MINI-HYDRO SYSTEMS USING INDUCTION GENERATORS

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INDUCTION GENERATORS

by

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Abstract

This study has focused on developing and documenting a systems approach toward modern electrical design that minimizes the cost of building and operating a grid-connected mini-hydro plant. The thesis applied innovative electrical design to reduce capital costs, lower operating costs, increase efficiency, and maximize revenue. This was achieved by following a multi-diciplined engineering approach, selecting a standard three-phase squirrel cage induction motor as the grid-connected induction generator, automating and remotely controlling the plant to eliminate the cost of a full-time operator, and incorporating an innovative diagnostic expert system to quickly assist in isolating the cause of a plant shutdown.

It was clearly established that a significant reduction in the capital cost of electrical equipment is achievable if the squirrel cage induction motor is used as the induction generator. The "off-the-shelf" induction motor and standard solid-state motor starter are relatively inexpensive in comparison to custom induction or synchronous generators. Since standard three-phase, 575V induction motors have ratings less than 200 kVA, the focus was on grid connected mini-hydro developments with an installed capacity of less than 200 kVA. Stand-alone plants,

similar to those found in isolated communities and mining sites, were not considered.

Knowing when to use an induction generator, and the type of control philosophy to implement, is based on the assumption the electrical designer has an understanding of the complete mini-hydro development process, consequently the thesis also covered the general design of mini-hydro systems. While this is not an exhaustive treatment of the subject matter, it is an indication of the level of understanding required for the electrical design.

The thesis documents the theory, performance characteristics, and design considerations associated with an induction generator, in an effort to evaluate the appropriateness of installing the induction generator at a grid-connected location. Also, a method was presented for selecting the standard squirrel cage induction motor to use as an induction generator. Induction generator protection requirements, utility protection, and mechanical systems protection were investigated, and modern solutions proposed. The PLC was used to automate the plant and cost effective remote control options were explored. An innovative and novel diagnostic expert system was developed and demonstrated. Finally, the systems approach and documentation of modern electrical design and operating methods was applied to a practical example, a 150 kW installation proposed for Nipper's Harbour.

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η	Efficiency
α	Locked rotor power factor angle
θ_1	Power factor angle
ω_S	Synchronous Speed, radians per second
AI	Artificial Intelligence
C	C programming language
CCA	Capital Cost Allowance
CEA	Canadian Electrical Association
CT	Current Transformer
DA	Drainage Area
DCS	Distributed Control System
DDE	Dynamic Data Exchange (Microsoft)
DRD	Drainage Density
DSG	Distribution System Generator
E_a	Air gap voltage
EIS	Environmental Impact Statement
EMAC	Electrical Manufacturers Association of Canada
EXSYS	Expert system programming shell
FSL	Full Supply Level
FVNR	Full Voltage Non-Reversing
h	Head
HP	Horsepower
Hz	Frequency
I_1	Stator current
I_2	Reflected rotor current
I_{base}	Base Current
ID	Inner Diameter of the Pipe
I_{FL}	Full load current
I_{LR}	Locked Rotor current
I_m	Magnetizing current
IRR	Internal Rate of Return
kVA	Kilo Volt-Ampere
kVA_{base}	Base kVA (3ϕ)
kW	Kilowatt
kWhr	Kilowatt-hour
LISP	Symbolic programming language
LSL	Low Supply Level

MAR	Mean Annual Runoff
MHz	Frequency, megahertz
MMI	Man Machine Interface
MPU	Magnetic Pickup Unit
MW	Megawatt
n	Normal turbine speed
n_r	Turbine runaway speed
n_s	Specific speed of the turbine at full output and best efficiency
NUG	Non-Utility Generator
p	Number of poles
P	Power
PC	Personal Computer
pf	Power factor
pf_{FL}	Full load power factor
pf_{LR}	Locked Rotor power factor
P_{fws}	Friction, windage and stray load loss
P_{IN}	Input power
$P_{IN@FL}$	Full load input power
$P_{IN\text{-}gen.}$	Generator mode input power
$P_{IN\text{-}motorL}$	Motor mode input power
PLC	Programmable Logic Controller
P_m	Core I^2R loss
$P_{m@FL}$	Full load core I^2R loss
P_O	Output power
$P_{O@FL}$	Full load output power
$P_{O\text{-}gen.}$	Generator mode output power
$P_{O\text{-}motor}$	Motor mode output power
P_{R1}	Stator I^2R loss
$P_{R1@FL}$	Full load stator I^2R loss
P_{R2}	Rotor I^2R loss
$P_{R2@FL}$	Full load rotor I^2R loss
PU	Per Unit
PV	Present Value
Q	Flow rate
Q_{mean}	Average stream flow
R_1	Stator effective resistance
R_2	Reflected rotor resistance
R_{2st}	Rotor Start resistance
RFP	Request for Proposals
R_m	Core loss/iron loss resistance
rpm	Revolutions per minute

RTD	Resistive Temperature Device
S	Slip
SCADA	Supervisory Control and Data Acquisition
SF	Service factor
S_R	Rotor Speed, rpm
S_S	Synchronous Speed, rpm
$T_{gen.}$	Generator mode torque
T_{motor}	Motor mode torque
V	Voltage
V_{1_ϕ}	Base Voltage (1ϕ)
V_{3_ϕ}	Base Voltage (3ϕ)
VAR	Reactive volt-ampere
V_{FL}	Full load voltage
V_{LL}	Line-to-line voltage
V_t	Base Terminal Voltage
WSC	Water Survey of Canada
X_1	Stator leakage reactance
X_2	Reflected rotor leakage reactance
X_m	Magnetizing reactance
Z_{2st}	Locked Rotor impedance
Z_{base}	Base Impedance
Z_{LR}	Locked Rotor Impedance
Z_m	Magnetizing branch impedance
Z_{total}	Total impedance of the induction machine

Chapter 1

Introduction

1.1 Research Rationale

The problem of increasing demand for electricity is best addressed by encouraging energy conservation and the development of alternate energy sources. The other choice is to continue building large scale thermal, nuclear, and hydroelectric plants, all of which have major environmental, social and financial costs. Small-scale renewable sources of energy, such as solar, wind, wave and mini-hydro, hold promise. Actual development of these small scale energy sources depends on the level of advancement of each specific technology, and the climatic and physiographic features of the area where the technology is to be used. Eastern Canada, especially Newfoundland and Labrador, have the precipitation levels and geographic features which favour small and mini-hydroelectric developments[1].

In recent years, public utilities across Canada, and in Newfoundland, have called on private companies (NUG's - non-utility generators) to supply a portion of the grid-connected electrical demand using alternate energy sources. Developers have responded with proposals for cogeneration facilities and small-hydro projects (greater than 1 MW). Very little attention was given to grid-connected mini-hydro developments (less than 1 MW), mainly because the economies of scale tend to favour the larger developments.

Mini-hydro is an attractive energy source. A mini-hydro plant uses a renewable energy source which is environmentally benign, there is little disruption of fish habitat, no impairment of navigable waterways, and minimal flooding. A mini-hydro development can be brought on stream more quickly than larger hydro projects, usually within one construction season. Since no heat is involved in the process, equipment has a long life, minimal maintenance is required, and breakdowns are rare. A physical plant life greater than fifty years is normal. The hydraulic and civil engineering technologies are well-developed and proven, with recent advances in turbine design and construction methods resulting in increased efficiency and reduced capital costs.

Thus, an economically viable, grid-connected, mini-hydro project is possible when creative civil, mechanical and electrical designs are used to minimise the cost of building and operating the plant. Simplified and standardised design procedures must be used to avoid the high costs associated with the traditional approach of custom designing each hydroelectric plant.

The objective of this thesis is to develop a systems approach and documentation of modern electrical design and operating methods for a mini-hydro plant. This focus will lessen the capital cost of the electrical systems and reduce operating costs, contributing to the overall economic viability of the mini-hydro development. Further reduction in project cost is achieved when a multi-disciplined engineering approach is used during the mini-hydro plant design phase. The plant will be grid-connected, remotely controlled and automated, and will use a standard induction motor as an induction generator. Specifically, the induction generator significantly reduces the cost of the electrical equipment package, and remote control of the plant eliminates the full-time operator cost. In addition, an expert system decreases down-time and maintenance costs. The expert system quickly diagnoses the cause of a plant shutdown, and recommends remedial action.

Induction generators, in small sizes, are lower in cost than synchronous generators, require less complex controls, and are simpler in construction. Standard squirrel cage induction motors can be used as low-voltage induction generators in the smaller grid connected mini-hydro plants (less than 200 kW). The motors, used as generators, are significantly cheaper than similarly sized custom induction generators or synchronous generators.

The plant must be automated to eliminate the substantial cost of a full-time operator. As an example, a typical 150 kW run-of-river plant, with a capacity factor of 50%, will generate revenues of approximately $40,000 per year, assuming a blended rate for energy and demand of approximately 6 cents/kWhr. Obviously this plant cannot support a full-time operator, and will not be viable without automatic and remote control. Advances in small programmable logic controller (PLC) design, and a corresponding reduction in hardware costs, make it possible to implement automatic and remote control strategies previously only available to larger hydro plants. The PLC is also used to collect the necessary field data needed as inputs to the diagnostic expert system.

1.2 Literature Review

Now, and in the past, mini-hydro development has been regarded as a good source of hydroelectric power for isolated communities and remote industrial sites, yet grid-connected mini-hydro developments were generally not considered to be cost effective. The majority of the mini-hydro plants connected today to the Newfoundland grid started as stand-alone power plants, then were connected as the transmission system expanded into their geographic area. The exception, the Morris hydro plant[2], located on the Avalon peninsula in Newfoundland, was conceived as a grid-connected mini-hydro development. It is part of the Newfoundland Power system. Newfoundland Power originated from an amalgamation of isolated hydro plants, many with an installed capacity less than 1 MW.

During the peak hydro development years in Newfoundland, the 1960's and 1970's, consumer demand, economies of scale, and a lack of public awareness of environment effects encouraged the development of the larger hydroelectric facilities. Grid-connected mini-hydro developments could not compete. Today, the public is aware of the environmental and social costs of large scale hydro developments, consequently there is renewed interest in grid-connected mini-hydro. The most recent environmental regulations governing hydro development, specifically in the province of Newfoundland & Labrador[3], recognises the environmental attractiveness of mini-hydro. The regulations state that any proposed development less than 1 MW (mini-hydro), which does not infringe on a special area, is automatically exempt from the environmental review process.

Even though research and development efforts in the mini-hydro field focused on making stand-alone plants more efficient and cost effective, the resultant improvements in turbine design, hydrologic analysis and civil structures are equally applicable to grid-connected mini-hydro developments. Recent references, including textbooks and design manuals, have increased their effort to document the progression of design changes applicable to small and mini-hydro systems, regardless of whether the plant is grid-connected or stand-alone. Older standard textbooks, H.K. Barrows[4] in 1943 and W. Creager[5] in 1950, concentrated on the large hydro systems. More recent texts, specifically J.J. Fritz[6] in 1984 and J.S. Gulliver[7] in 1991, deal with small hydro developments and the concept of a multi-disciplinary approach to design and development. However, the smaller of the small-hydro projects, or mini-hydro, receive superfluous coverage in these texts.

Still, mini and micro-hydro systems were the recipients of considerable coverage during the 1980's, with documentation usually taking the form of design manuals. A. R. Inversin[8] published an excellent micro-hydro sourcebook in 1986, and in 1987, Energy, Mines and Resources Canada commissioned a small/mini hydro handbook for Newfoundland and Labrador[9]. Other reference materials were the result of small hydro workshops, conferences and demonstration projects[10 - 17]. However, none of the references view the mini-hydro systems and components from the electrical designer's perspective, which is critical, since the electrical designer will be expected to select the most appropriate generator type, protection system , and plant control strategy.

Recent electrical research concentrated on introducing alternatives to the traditional synchronous generator, the mainstay of stand-alone mini-hydro plants. Of course, the synchronous generator has the ability to maintain a constant voltage and frequency under varying loads. The self-excited single-phase synchronous generator, permanent magnet synchronous generator, and self-excited induction generator have been proposed as possible alternatives to the conventional stand-alone synchronous machine, mainly because recent advancements in power electronics and controller hardware made it possible to regulate the voltage and frequency of these generators in stand-alone applications.

In the area of self-excited single-phase synchronous generators, steady-state performance analysis technique were introduced by S. Nonaka[18, 19]. A.M. Osheiba and M.A. Rahman [20] presented a dynamic performance analysis of self-excited single-phase synchronous generators, using the d-q axis simulation technique, which yields significant improvement over the steady-state approach.

The permanent magnet synchronous generator concept, as reviewed by K. Binns and A. Kurdali[21], continues to receive significant research effort, with modelling techniques recently presented by Rahman and Osheiba[22]. Unfortunately, the three alternatives mentioned incorporate relatively complex control methods to solve the problem of controlling the system voltage and frequency. Such complexity and cost is unacceptable in a grid-connected mini-hydro application, especially when an induction generator, connected directly to the grid, requires no additional circuitry to maintain acceptable voltage, frequency and phase relationships.

Research in the area of self-excited induction generators for stand-alone applications has resulted in a better understanding of abnormal operating characteristics, conditions that are also a concern for grid-connected induction generators. The first analysis of self-excited induction generator characteristics was undertaken by C. Wagner[23] in 1939. It was recognised at that time that an induction machine, driven mechanically, may become self-excited if capacitors are connected across its terminals. It was forty years later before practical control of self-excited induction generators was possible, using static exciters. In 1979, M. Brennen and A. Abbondanti[24] proposed, and tested, a static exciter using fixed capacitors and thyristor controlled inductors. Since then a variety of static power control designs, analysis techniques, and testing methods have been published in the literature[25 - 34]. Variations on the standard static-controlled induction generator theme have also been presented., as in the case of R. Bonert and G. Hoops[35], who proposed an electronic impedance controller to control the voltage and frequency of a stand-alone induction generator. The stand-alone induction generator research has indirectly made a contribution to grid-connected induction generator applications, specifically with respect to understanding over-voltage conditions caused by generator overspeed.

The concept of using an induction machine as an induction generator is certainly not a new idea. It was originally investigated by H.M. Hobart and E. Knowlton [36] in 1912. Their review assumed a grid-connected induction generator, as opposed to a stand-alone system, since stand-alone operation was not technically feasible at that time. Still, there were few grid-connected induction generator installations until the 1940's. In 1948 farmers and small industries in northern California began installing engine driven induction generators to compensate for the shortage of power available from the grid. This spurred O.J. Smith[37], in 1950, to develop a method of calculating the generator rating of an induction motor, standard motors that were being used as generators by the farmers. Four years later, in 1954, J.E. Barkle and R.W. Ferguson [38] presented a paper discussing the theory of operation of the grid-connected induction generator, the self-excitation problem, and other application problems that should be considered when designing an induction generator installation. Unfortunately, there are no further references to induction generators in the literature until 1980, other than those previously mentioned which specifically refer to self-excitation and stand-alone induction generators. Thus, during the 1960's and 1970's the induction generator was ignored by manufacturers, researchers and industry.

An energy shortage in the early 1970's, due to the Middle East oil cartel, was the cause of renewed interest in the grid-connected induction generator. This time, the induction generator was being considered for waste-heat recovery and cogeneration schemes. Between 1980 and 1983, R.L. Nailen [39 - 41] wrote a series of articles highlighting the virtues of the induction generator for this type of application. The petroleum and chemical industries installed induction generators. E.L. Owen [42], in 1983, documented his experiences with a 13,000 HP induction motor/generator installation, while in 1984, J.R. Parsons [43] published a paper comparing an induction generator to a similarly sized synchronous machine in a typical cogeneration scheme. However, there are no references in the literature which document similar detailed experiences in the small or mini hydro field. L. Pererira[44] and L. Schafer[45], in 1981 and 1982 respectively, did publish articles in Water Power and Dam Construction which dealt with the general concept of induction generators in grid-connected small-hydro applications. Unfortunately, they did not present a comprehensive document which would take the informed reader from the theoretical analysis of induction machines, through to a practical design and implementation of an induction generator in a mini-hydro installation. As well, practical operational and installation considerations, with respect to using standard induction motors as induction generators, have not been concisely presented in the literature.

As recognized by R.L. Nailen[40], the grid-connected induction machine requires similar protection when operated as a motor or generator. Two excellent articles, one written by H. A. Breedlove[46] in 1983, and the other by J. D. Bailey[47] in 1988, review, in general terms, both the generator and utility protection requirements of a grid-connected induction generator. Recent developments in microprocessor controlled motor starters have made it possible to further improve the protection schemes for mini-hydro induction generators. However, the application of the new protection methods to grid-connected induction generators has not been documented.

A mini-hydro plant may not afford a full-time operator, thus implementing automatic monitoring and control is a key element in making any mini-hydro development economically viable. With the proliferation of small, inexpensive and powerful programmable logic controllers (PLC's), it is now feasible to automate even the smallest plant. However, actual experiences with PLC based control of mini-hydro plants have not been documented in the literature. References found on automatic control generally refer to hydro systems in excess of 10 MW. In 1989 J.P. Cross[48] described the STS Hydropower(USA) experience with implementing a remote monitoring scheme which, unfortunately, is much to costly to be considered for mini-hydro applications. Also in 1989, S. Isakson[49] reviewed computer based control systems for hydro power control, but again, the literature focused on the larger hydro installations, sites with the resources to purchase custom control hardware and software. Standard protection and control strategies for very small hydro generators, of all types, are documented in a 1984 CEA Report[50]. Obviously, the report does not incorporate the significant technological improvements of the last 10 years. Available today are motor starters capable of providing sophisticated generator protection, and inexpensive PLC's with the ability to be continuously monitored from a remote location.

Remote and automatic control of a grid-connected mini-hydro plant, using PC's and PLC's, introduces an opportunity to use expert system diagnostics to quickly identify the source of problems that may cause the plant to shut down. Expert system technology, as a component of the artificial intelligence field, came to the forefront in the mid 1980's, with subsequent publication of numerous articles and texts. L. Johnson[51], and D.A. Waterman[52], in 1985 and 1986 respectively, authored separate texts describing the development of expert systems and potential applications in business, medicine and industry. The software implementations of initial diagnostic expert system applications were written in FORTRAN, C, or Turbo Prolog. As interest developed, expert system shells appeared on the market, including EXSYS Professional[53]. The literature search found diagnostic expert system papers dealing with the power distribution field[54, 55], but few dealing with hydroelectric plants[56, 57], and no references to diagnostic expert systems being used to improve operations in small or mini-hydro plants.

1.3 Scope of Work

The stated objective is to develop a systems approach and documentation of modern electrical design and operating methods for a grid-connected, remotely controlled and automated mini-hydro plant, one which uses a standard three-phase induction motor as an induction generator. Since standard "off-the-shelf" three-phase, 575V induction motors have ratings less than 200 kVA, the focus is on mini-hydro developments with an installed capacity of less than 200 kVA. Stand-alone plants, similar to those found in isolated communities and mining sites, are not considered. The electrical design and operating methods presented assume the plant is grid-connected.

The electrical system should incorporate all mini-hydro components which affect and interact with the grid system, including the prime mover, induction generator, control system, interconnection requirements, and protection scheme. As well, knowing when to use an induction generator, the appropriate prime mover to select, and the type of control philosophy to implement, is based on the assumption the electrical designer has an understanding of the complete mini-hydro development process. Regulatory issues, environmental regulations, site selection, hydrology, power and energy estimates, physical components, and economic evaluation will impact on the electrical design and operating methods of the mini-hydro plant. Consequently, Chapter 2 covers the general design of mini-hydro systems. While this section is not an exhaustive treatment of the subject matter, it is an indication of the level of understanding required for the electrical design.

The induction generator is an obvious choice for a small grid-connected mini-hydro installation. It is rugged, inexpensive, and simple to protect and control. Chapter 3 introduces the induction generator concept, as well as selection, protection and control of the standard squirrel cage induction motor used as an induction generator. This induction generating part is not covered adequately in the standard textbook. Also included is a technical analysis of the induction generator, and performance prediction of the induction motor when run as a generator. Modern electrical design methods are applied and documented to produce reliable, cost effective generator and utility protection. The sum of the information presented is Chapter 3 is sufficient to evaluate the appropriateness of installing an induction generator at a grid-connected location.

Automatic operation of a grid-connected mini-hydro plant will eliminate the annual cost of a full-time operator. Thus, Chapter 4 documents the design process of automating the plant, using cost effective PLC's, PC's, motor starters, power monitoring equipment, man-machine interface (MMI) software, and expert system shells. Modern methods and systems for the protection, control and automatic operation of a mini-hydro plant are researched, selected, and documented. Unfortunately, the lack of a full-time operator means an on-site expert is not available to diagnose the cause(s) of a plant shutdown, when it occurs. Thus, a diagnostic expert system is presented in Chapter 4, one which constantly monitors the operation of the plant. The expert system assists maintenance personnel in detecting the cause of a plant shut-down, thus minimizing downtime. Decisions are made based on the status of plant sensors when the shutdown occurred, and maintenance personnel intervention is activated by modern telecommunications.

Chapter 5 applies the systems approach and documentation of modern electrical design and operating methods. Three potential grid-connected mini-hydro sites on the island of Newfoundland are compared in Chapter 2 and one, Nipper's Harbour, selected for development. The detailed electrical design is completed for the Nipper's Harbour site, using the systems approach documented in Chapter 3 and Chapter 4. First, the appropriate three-phase induction motor, which will operate as a generator, is specified. Then, operational procedures are identified and protection and control systems designed.

The summary, conclusions, innovative aspects of the research, and suggestions for future work are presented in Chapter 6.

Chapter 2

Design of Grid Connected Mini-Hydro Systems

Chapter 2 covers the general design of mini-hydro systems. Knowing when to use an induction generator, and the type of control philosophy to implement, is based on the assumption the electrical designer has a good understanding of all aspects of a mini-hydro development. This includes the regulatory process, environmental issues, site selection, site hydrology, power and energy estimate, rates, and economic evaluation. While this section is not an exhaustive treatment of the subject matter, it is an indication of the level of understanding required of the electrical engineer.

2.1 The Regulatory Process in Newfoundland

2.1.1 Non-Utility Generators (NUG's)

Any successful grid-connected hydro development must have a buyer for the energy produced, and satisfactorily address all local, provincial, and federal regulatory issues. Recent Newfoundland and Labrador legislation (1989) [58] permits private development of small and mini hydro resources, typically sites with an installed capacity of less than 15 MW. Through the legislation the private developers, called Non-Utility Generators (NUG's), have access to the water rights of streams located on the island of Newfoundland. Before the legislation, Newfoundland and Labrador Hydro Corporation (Nfld. Hydro) held the exclusive rights to all hydro developments on the island, regardless of size. Nfld. Hydro will now waive their rights to the small and mini hydro sites. The provincial Department of Environment and Lands regulates the development process by issuing Preliminary Water Use Authorization to qualifying parties.

2.1.2 The Market

Currently, the only buyer for power produced by NUG's is Nfld. Hydro, who issues request for proposals (RFP) when expected consumer demand exceeds system capacity. The successful bids are awarded a long term 25 year power contract, with an option to renew for an additional 25 years. Only one RFP, for 50 MW of installed capacity, has been issued to date [59].

2.1.3 Water Rights

Any NUG interested in developing a mini-hydro site in Newfoundland has to adhere to a specific regulatory process. The developer must first identify the holder of the water rights of the stream of interest. On the island of Newfoundland, water rights are held by Nfld. Hydro, Newfoundland Power, Deer Lake Power Co., and Abitibi-Price Inc.. Developers interested in water rights held by Newfoundland Power, Deer Lake Power, or Abitibi-Price, must negotiate directly with those companies. Water Rights held by Nfld. Hydro are controlled by government legislation, Section 21 of the Department of Environment and Lands Act, 1989[58].

The legislation states that Nfld. Hydro must waive its rights to the development of the hydro potential of any stream, with a capacity of 15 MW or less, if Nfld. Hydro has no immediate plans to develop that stream. The first NUG to apply to have the water rights waived will be accepted. In the meantime, the NUG must also apply to the Department of Environment and Lands, Water Resources Division, Water Rights Section, and request to have the waived water rights to the stream transferred to the NUG. This type of request to the Water Resources Division is called an Application for Water Use Authorization. An example is given in Appendix A.

The specific legislative authority, procedures, and guidelines for Water Use Authorization are given in the government publication "*Guidelines Regarding Application for Water Use Authorization (Water Use Licence) for A Hydroelectric Project*" [60]. The purpose of the water use licence is to enable the applicant to secure the water resources at the proposed site necessary for the operation of the project, and to generate hydroelectric energy for a specific period of time. No other rights to water use are conferred. Assuming equivalent quality of two competing applications for development at the same site, the first proposal submitted will have precedence.

A preliminary licence is issued for a one year period, giving the proponent authorization to undertake relevant surveys and field investigations in the area, prepare the feasibility study, and undertake environmental impact studies. An application for Water Use Licence must be filed before expiration of the preliminary licence. The issuance of a Water Use Licence will depend on the quality of the proposed project, in terms of multiple and optimum utilization of the available water resource, minimal environmental disruption, and land use conflicts. As mentioned, Appendix A includes the Nipper's Harbour mini-hydro Application for Water Use Authorization, and preliminary licence, as an example.

2.2 Environmental Issues

Electricity is an integral part of our society, powering our lights, washers, stoves, and computers. If we are not willing to totally forsake these necessities and conveniences, then we must accept the fact that there will always be some environmental damage caused by power generation equipment. To minimize that damage we should first reduce our demand for electricity, then select small-scale, renewable power sources which have the least effect on the environment.

A mini-hydro plant, being a small development, is one of the most environmentally sound methods of producing electricity. It is inconspicuous, uses a renewable resource, and has a negligible impact on the environment. Existing ponds are used for storage, no land is flooded, the dams are small concrete and timber crib structures, and it does not disturb the fish habitat. Scheduled salmon rivers are avoided.

While mini-hydro is recognized as being environmentally friendly, the proposed developments still must adhere to all regulations and follow the correct regulatory process. Thus, concurrent with obtaining a waiver from Nfld. Hydro, and applying for Preliminary Water Use Authorization, the proposed project must be cleared from the requirements of the *Environmental Assessment Act, 1980* [3]. The Regulations of the Act list all undertakings which must be registered. All proposed developments, large or small, which involves land use, forests, water or animal life must be brought to the attention of the Minister of the Environment. If it is determined the project, including mini-hydro developments, will have a significant impact on the environment, the undertaking will have to be registered. If the undertaking is not listed in Schedule 1 of the Act, "Undertakings Subject to Registration"[3], the project will not have to be registered.

Mini-hydro developments (less than 1 MW) are not considered to be an undertaking subject to registration if the following conditions are met; the plant capacity is less than 1 MW, the area to be flooded is less than 500 hectares, no flooding will occur in a special area, no development is located within a special area, and no transmission line or road is to be located at a distance greater than 500 metres from an existing right-of-way. "Special Areas" are listed in Schedule 2 of the Regulations[3] and include scheduled salmon rivers, waste disposal sites, wildlife reserve areas, provincial parks, protected water supply areas, and others. Any mini-hydro undertaking required to register may have to prepare a complete Environmental Impact Statement (EIS) [3]. The cost of an EIS would make most mini-hydro developments uneconomical.

Once the undertaking has been cleared from the requirements of the Environmental Assessment Act, 1980, [3] other provincial and municipal authorities are free to grant approvals as required. The federal Department of Fisheries and Oceans must be contacted whenever fish habitat is affected by the undertaking. The proponent must submit an "Application for Authorization for

Works or Undertakings Affecting Fish Habitat"[61] before proceeding with any work at the site. Stringent regulations apply when the stream of interest is a scheduled salmon river, thus development on these rivers should be avoided. Due to lack of economies of scale for a mini-hydro plant, the cost of meeting all environmental requirements at such a site are prohibitive.

2.3 Site Selection

The site selection process for a mini-hydro development begins with noting the geographic region where development is permitted, listing the desirable characteristics of the ideal location, undertaking a map survey to identify favourable sites, then following up with a site visit. Sites with existing infrastructure, typically reservoirs, dams, and pipelines, are scrutinized first. Any site characteristic which reduces capital costs, usually easy access, small dams, and short penstocks, will make the proposed development more appealing.

Desirable physical characteristics of a grid-connected mini-hydro site include medium to high head, sufficient stream flow, close to a suitable transmission line, proximity to passable roads, short penstock length, natural head pond, upstream storage, access to telephone lines or cellular telephone, and located near a gauged stream. Other factors to consider include land ownership, and other users of the stream. Water Rights and environmental concerns must be considered concurrently with the initial map survey and site visit. There is no point in pursuing the undertaking at a particular site if water rights are not available or obvious environmental issues preclude development.

2.3.1 Map Survey

The map survey shows the obvious, such as the distance of the site from the nearest road, transmission line length, penstock length, gross head, and drainage area. The data from the 1:50,000 topographic map survey is sufficient to give an indication of the energy generation capacity of the site, approximate capital cost, and to complete a preliminary feasibility study.

A value for gross head (h) and stream flow (Q) is needed to calculate the power (P) production capability of the site.

$$P = 9.81 \times \eta \times h \times Q \tag{2.1}$$

The gross head is the difference in elevation between the normal water level at the intake and the water level at the turbine outflow. It does not take into account the losses occurring throughout a hydro generation system. With practice, the gross head estimate taken from the 1:50,000 map is within 10% of the surveyed gross head. The accuracy improves as the gross head increases[8]. The stream flow (Q) usually is not available from direct measurement. It must be derived by prorating the drainage area and Mean Annual Rainfall (MAR), using a nearby gauged stream as the reference. The 1:50,000 map is used to find the drainage area.

The map survey provides preliminary estimates of penstock length and distance from existing roads and transmission lines. The length of the penstock should be as short as possible. A site may have sufficient flow and adequate head, but the rise in elevation is very gradual, requiring a long penstock. A long penstock is expensive and it is the main cause for making a site economically unattractive. Also, heavy equipment must have access to the site during the construction phase. Roads to the powerhouse, intake structure, and along the penstock route are necessary. Obviously, the closer the site is to any passable road, the less road the developer has to build. Since power has to be delivered to the utility grid, the site must also be close to a three phase distribution line. The high voltage transmission line is of no use here, as they require an expensive transformer and switch yard to make the connection to the low voltage generators (600V) typical in mini-hydro. Distribution lines are not necessarily shown on the topographic maps, but they normally parallel secondary roads that lead to small communities. Any site close to a community will most likely have access to a distribution line. A check with Nfld. Hydro, or Nfld. Power, will confirm the type and size of the distribution line in the area of interest.

For maximum energy production, the development requires a method of capturing and storing the excess water flowing during the high run-off periods. During the map survey, look for locations on ponds upstream of the intake where low lying timber crib dams could be built. Consider that the dam should block off a natural basin and should be easily accessible via road or cat-track.

2.3.2 Site Visit

Assuming the water rights are available, the 1:50,000 topographic map survey results will indicate whether a site visit is warranted. The site visit will identify factors normally not available from the map survey, which might affect the viability of a development. Those factors include the possibility of the stream being used as a municipal water supply, the presence or absence of migratory fish, access to the construction site, the location of the intake dam, land ownership, and potential downstream effects.

Many of the promising streams are located close to communities, mainly because that is the most likely place of finding a three-phase power distribution line. Unfortunately, the stream of interest may be the community water supply. According to Ministerial policy[60], applications for Water Use Licence shall have precedence in the following order; domestic purposes, municipal purposes, commercial and industrial purposes, hydroelectric generation purposes, recreational purposes, and other prescribed purposes. If the stream is used as a municipal water supply, the town has exclusive rights to the complete watershed of that stream. Nothing further can be done until the permission of the town is secured. The provincial department responsible for Environment cannot overrule the municipality. Yet, a hydro plant can be built on the same stream as a municipal water supply. If the plant is downstream of the water supply intake it will not degrade the water supply. If it is upstream of the intake, special precautions have to be taken to ensure that the water supply is not contaminated during construction or operation of the mini-hydro development.

A hydropower project cannot interfere with migratory fish, be it salmon, arctic char, or trout. If the stream of interest flows into the sea, check the area to see if a falls blocks the path of the migratory fish. Next, check with the local people to see if they are aware of the type of fish that use the stream. Finally, contact the Federal Department of Fisheries and Oceans to see if it is a scheduled river, or is protected in any way.

While the map survey will give an idea of the proximity of the site to a passable road, a site visit will confirm the type of terrain, the existence of new roads not shown on the map, and the existence of any old roads or tracks that could easily be upgraded. If the terrain does not permit the building of a road to the intake or powerhouse, consider the additional cost of bringing the equipment in by a winter road, boat, or helicopter. Also, since a short penstock is the most desirable option, check the terrain to ensure that the penstock can be built over the cliffs and steep sections. Perhaps a slightly longer but more accessible route would be cheaper to build. As for the dam, select a location that is in a natural basin with a narrow outlet and steep walls. This keeps the dam short and small, minimizing the cost. A solid rock foundation is another important consideration when selecting a dam site.

While the watershed area of the development is usually crown land, the power-house is often located close to a community, and may be on privately owned land. Acquiring private land is difficult, not because of cost, but because of the problems tracing ownership and obtaining clear title. One method of avoiding private land is to have the penstock route parallel the stream-bed. Early land grants left a narrow strip of land along the banks of the stream. Recent grants have a wider buffer zone, 15 metres, along each bank. Check the provincial Crown Lands and Registry of Deeds to see how much land is available along the banks of the stream in question, and whether penstocks can be built on this land. Also, beware of building a hydro plant upstream of a community or farm. If flooding does occur, the owner of the plant may be blamed for the flooding, even if the hydro plant was not responsible for such flooding.

2.3.3 Site with Existing Infrastructure

As an illustration of the site selection process, the author focused on the island of Newfoundland, where legislation (1989) [58] now permits private development of hydroelectric sites less than 15 MW. Only mini-hydro sites, 1 MW or less, are considered.

As per the selection processes outlined previously, initial investigations focused on identifying sites with existing infrastructure. Three interesting sites surfaced, specifically; the Marble Mountain ski area snow-making water-line, which is capable of developing 120 kW of output power when not being used to make snow; the now defunct ERCO (Long Harbour) phosphorus water supply system, including dam, reservoir, and penstock, which could be converted to a 500 kW mini-hydro plant; and finally, the excess capacity of the Corner Brook Pulp & Paper Ltd. mill water supply (Glynmill Inn Pond), capable of generating 250 kW.

While all of these sites are economically attractive, none have been developed because of water rights issues, uncertainty about infrastructure ownership, and conflicts between multiple users. The Marble Mountain site development has not progressed because the water rights are held by Deer Lake Power, and there is concern about the effect the plant will have on the Steady Brook municipal water supply. Both the water supply and hydro plant would draw water from the same stream. The ERCO water supply site holds promise, and is currently being investigated by a number of companies. While the water rights to the ERCO site appear to have been settled, ownership of the infrastructure is still an issue, consequently no development has taken place. The Glynmill Inn Pond site would have to be a joint effort between Deer Lake Power and the interested party, since the water rights are held by Deer Lake Power and the dam is owned by Corner Brook Pulp & Paper Company Ltd.. No known activity or development is planned for this site.

The favourable sites selected must be ranked to determine the preferred development. A spreadsheet was used to implement a ranking system, and to ascertain which site(s) has the best chance of being developed. The sites were rated on all issues, including technical, environmental, regulatory and operational. The results of the rating process for sites with existing infrastructure are shown in Table 2.1.

The ERCO water supply is obviously the most attractive site, mainly because of the existing dam and penstock, and excellent long term storage. The spread between the ERCO site and the remainder of the sites is not as great as one would expect. The uncertainty associated with the ERCO "Land/Facilities Ownership" and "Other Users/Interests" categories kept its overall rating down. While the ERCO site should be pursued, the developer must be aware of the risk of not gaining access to the infrastructure.

In reference to the information given in Table 2.1 and Table 2.2, the "RANK" column assigns a weight (0-5) to each category. The higher number reflects the relative importance of each category, with respect to all other categories. As well, each category is rated according to it's effect on each individual project. The “RATING” can range from 0 to 10. Ratings greater than 5 are used to account for existing infrastructure or unusual circumstances. As an example, an undeveloped site requiring a very short penstock would receive a rating of 5, while a site with an existing penstock might receive a rating of 9.

Table 2.1: Ranking of Sites with Existing Infrastructure

		ERCO WATER SUPPLY 500 kW		MARBLE MOUNTAIN 120 kW		GLYNMILL INN POND 250 kW	
CATAGORY	RANK (0-5)	RATING (0-10)	TOTAL	RATING (0-10)	TOTAL	RATING (0-10)	TOTAL
PENSTOCK LENGTH	5	7	35	10	50	3	15
DAM LENGTH	4	9	36	9	36	10	40
TRANSMISSION LINE LENGTH	3	3	9	9	27	6	18
ACCESS TO INTAKE	3	10	30	10	30	10	30
ACCESS TO POWERHOUSE	3	10	30	10	30	9	27
ACCESS TO PENSTOCK ROUTE	3	9	27	10	30	10	30
WINTER ACCESS	3	6	18	8	24	8	24
WATER RIGHTS	5	7	35	2	10	2	10
ENVIRONMENTAL APPROVAL	5	9	45	7	35	3	15
MIGRATORY FISH	4	8	32	10	40	3	12
STORAGE	4	10	40	2	8	6	24
FLOW VARIABILITY	2	10	20	9	18	3	6
WINTER OPERATION	2	7	14	8	16	7	14
INTERCONNECTION COSTS	4	3	12	8	32	5	20
REMOTE CONTROL COSTS	3	4	12	5	15	7	21
LAND/FACILITIES OWNERSHIP	5	2	10	2	10	2	10
VISIBILITY	2	8	16	3	6	4	8
OTHER USERS/INTERESTS	4	2	8	2	8	2	8
TOTAL POINTS			429		425		332
PRIORITY			1		2		3

2.3.4 Green Site

While the sites with existing infrastructure are very attractive, the complications caused by water rights and ownership issues usually mean the site is not available for development by private individuals or companies. Thus the site selection focus must shift to sites where the water rights are owned by the provincial government, and available to be transferred to private developers. Usually these sites are called green sites, sites where no civil structures are currently in place. Based on the map survey criteria outlined, three of the most favourable grid-connected mini-hydro sites on the island of Newfoundland were selected. They include Western Brook and Eastern Brook near Little Coney Arm, and Nipper's Harbour. All have good access via road, medium to high head, short penstock length, and are close to a distribution line. None were located on scheduled salmon rivers, or near municipal water supplies. The results of the ranking process for the green sites are given in Table 2.2.

Nipper's Harbour is the best green site alternative available, where water rights and access are not an issue. The site has a number of attractive physical features, including no other users of the water supply, no salmon or sea trout migration, short penstock length, natural head-pond, extremely small dam required, existing road access to powerhouse and lower penstock, short transmission line (0.7 km), direct connection to the Nfld. Hydro system, access to telephone line, and proven energy potential and drainage basin characteristics. The major disadvantages of the site are the difficult access to the upper penstock route and minimal long-term storage. The Nipper's Harbour site will continue to be used as an example throughout Chapter 2. A summary of the project features of the Nipper's Harbour site is listed in Appendix F.

Table 2.2: Ranking of Green Sites

		NIPPER'S HARBOUR 650 kW		WESTERN BROOK 600 kW		EASTERN BROOK 500 kW	
CATAGORY	RANK (0-5)	RATING (0-10)	TOTAL	RATING (0-10)	TOTAL	RATING (0-10)	TOTAL
PENSTOCK LENGTH	5	4	20	3	15	4	20
DAM LENGTH	4	4	16	3	12	2	8
TRANSMISSION LINE LENGTH	3	2	6	4	12	5	15
ACCESS TO INTAKE	3	2	6	8	24	2	6
ACCESS TO POWERHOUSE	3	7	21	4	12	5	15
ACCESS TO PENSTOCK ROUTE	3	2	6	3	9	2	6
WINTER ACCESS	3	4	12	1	3	1	3
WATER RIGHTS	5	10	50	5	25	5	25
ENVIRONMENTAL APPROVAL	5	5	25	5	25	5	25
MIGRATORY FISH	4	5	20	3	12	4	16
STORAGE	4	3	12	2	8	1	4
FLOW VARIABILITY	2	3	6	3	6	2	4
WINTER OPERATION	2	4	8	2	4	2	4
INTERCONNECTION COSTS	4	4	16	1	4	1	4
REMOTE CONTROL COSTS	3	5	15	1	3	1	3
LAND/FACILITIES OWNERSHIP	5	4	20	4	20	3	15
VISIBILITY	2	5	10	4	8	4	8
OTHER USERS/INTERESTS	4	4	16	3	12	2	8
TOTAL POINTS			285		214		189
PRIORITY			1		2		3

2.4 Site Hydrology

The site hydrology information is used to select the installed capacity of the turbine and generator, and to predict the average annual energy production of the plant. Then the energy estimate, in conjunction with a capital and operating cost estimate derived from the installed capacity, is used to perform an economic evaluation of the proposed project. Completing the initial hydrology work in-house, using available manpower and application software, significantly reduces project costs. It also gives the developer more control over the type of prime mover, generator, and control system to select to ensure maximum energy production. The author has researched methods of performing a simplified and cost effective hydrologic analysis of a mini-hydro site. Public domain literature, historical stream flow data, and software are used throughout. The process is documented in Appendix B, using the Nipper's Harbour site as a working example. A summary of the hydrology data is given in Table 2.3.

Table 2.3: Hydrology Information - Nipper's Harbour

Nipper's Harbour Hydrology Information Summary	
Drainage Area	33.8 km^2
Annual Mean Flow	0.772 m^3/s
Mean Annual Run-off	720 mm
100-Year Design Flood	25 m^3/s
10-Year Diversion Flood	19 m^3/s
Est. 2-Year 7-Day Low Flow	0.066 m^3/s
Est. 10-Year 7-Day Low Flow	0.005 m^3/s
Forebay Pondage	38,700 m^3

2.4.1 Flow Duration Curve

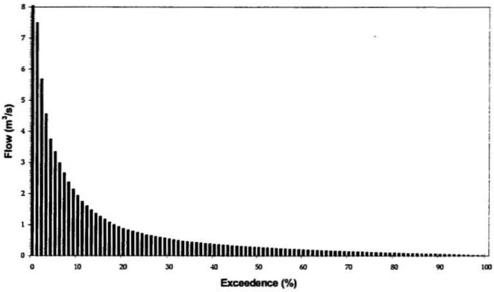

Figure 2.1: Flow Duration Curve - Nipper's Harbour

Energy calculations require knowledge of the mean flow of the stream and the shape of the flow duration curve. The curve indicates the expected frequency of all flow rates, high, average and low included, at the site selected for mini-hydro development. Of course, a constant flow rate at all times is not the norm, unless significant storage is available, thus flow rates vary and depend on the season, weather patterns, physiographic features and site characteristics. The hydrological analysis is used to calculate the annual mean flow, derive the flow duration curve, and estimate flood flow and low flow.

The historical flow records published by Environment Canada are essential to calculating the mean flow and flow duration curve for a particular site. The Water Survey of Canada Streamflow Toolkit [68] software was used to generate the flow duration curve data table for Nipper's Harbour. The curve was defined using 100 points, one for each percentage of flow exceedence. The flow duration curve data file was exported to a spreadsheet, to be used later in an analysis of the power and energy available at the site.

2.4.2 Flow Synthesis

If the mini-hydro site is on a gauged stream the hydrological analysis is straightforward. However, if it is located on an unguaged stream, the critical step is creating synthesized flow records. Synthesized flow records for an unguaged stream are created using either of the two methods recommended in a series of studies completed in 1988 by Acres International for the Inland Waters Directorate, Environment Canada [62, 63]. The methods are proration on Drainage Area and Mean Annual Run-off (MAR), and Regional Non-dimensional Flow Duration Curves. The Nipper's Harbour example, described in Appendix B, generates the synthesized time series of daily flows by prorating on drainage area and mean annual run-off (MAR). Both the gauged and ungauged site is assumed to have similar physiographic features and site characteristics. If this is true, and both sites are relatively close to each other, then both have a similar MAR. The MAR of the gauged stream, given in millimetres (mm), is calculated directly from the annual mean flow (m^3/s) and drainage area (km^2). Drainage area is determined by planimetry from the 1:50,000 scale maps. The hydrology results described in Appendix B indicate the MAR for the Nipper's Harbour mini-hydro site is 725 mm and the drainage area is 33.8 km^2. The closest gauged stream is South West Brook, Station No. 02YM003 of the Water Survey of Canada, and is 90 miles away.

2.4.3 Flood Flow Estimate

Estimates of flood flows must be determined to assist in the safe design of the dam and to reduce the risk of damage caused by flooding. The design flood and diversion flood return periods are selected based on the perceived risk. The Nipper's Harbour site is classified as low risk, since there is no risk of damage to downstream property or loss of life, the timber-crib dam can be safely overtopped, and reconstruction costs would not be excessive. Thus, the recommended design flood return period is 100 years, and the recommended diversion flood return period is 10 years. The design flood and diversion flood for Nipper's Harbour were estimated using the procedures and software outlined in the report "*Regional Flood Frequency Analysis for the Island of Newfoundland*"[64]. The report recommends using regional flood frequency analysis at ungauged sites and single station flood frequency analysis at sites near a hydrometric station on the same stream. Since Nipper's Harbour is not on a gauged stream, regional flood frequency analysis was used. The results of the spreadsheet analysis (software being provided with Reference 6), indicated the 100-year design flood for Nipper's Harbour is 25 m^3/sec, and the 10-year diversion flood is 19 m^3/sec.

2.4.4 Low Flow Estimate

An estimate of the low flows expected at the site is important in determining the firm capacity of a run-of-river mini-hydro installation. The estimated 7-day low flow over 2-years, and the estimated 7-day low flow over 10-years, are also needed for the Water Use Authorization application[60] required by the Water Resources Division of the Department of Environment and Lands.

Unless the proposed site is on a gauged stream, it is difficult to estimate the low flows. Sometimes the initial estimate of the low flow is taken as the 95% exceedence flow shown on the flow duration curve. A better estimate of the low flows is found using the procedures and software outlined in the report "Estimation of Low Flows in Newfoundland " by A. K. Beersing[91]. The report presents a series of regional regression equations, which are derived from the analysis of thirty-nine gauging stations on the island of Newfoundland. A spreadsheet uses the equations to estimate the low flows of several duration and return periods at unguaged streams. For the Nipper's Harbour location, the software produced an estimated 2-year 7-day low flow of 0.066 m^3/s and an estimated 10-year 7-day low flow of 0.005 m^3/s.

2.5 Power and Energy Estimate

Table 2.4: Site Parameters - Nipper's Harbour

Nipper's Harbour Energy Calculation Spreadsheet Results		
Installed Capacity	650	kW
Annual Mean Flow	0.772	m^3/s
Rated Turbine Flow	0.906	m^3/s
Capacity Factor	41	%
Net Head	86	m
Energy Available	4,668,061	kwh
Spillage Loss	2,342,765	kwh
Actual Energy Production	2,325,295	kwh

The previously mentioned site hydrology information is used to select the installed capacity of the turbine and generator, and to predict the average annual energy production of the plant. A flow duration curve was created and the critical flows were graphically extracted from the curve. Current software, available from the Water Survey of Canada (WSC)[68], creates a table of percentage exceedence versus flow, a total of 100 points from 0% exceedence to 100% exceedence. While this information can be used to create an accurate flow duration curve (Figure 2.1), the pictorial curve no longer serves any useful function. Instead, the data points are transferred to a spreadsheet called the Energy Calculation spreadsheet. The spreadsheet is described in detail in Appendix C, while Table 2.4 summarizes the pertinent results.

The spreadsheet calculates the annual mean flow and the mean annual run-off (MAR), for both the gauged stream and the stream of interest. Then, given a specific annual mean flow, the designer manipulates the installed capacity (kW) value in the spreadsheet to produce a plant capacity factor (C.F.) in excess of the minimum required by Nfld. Hydro. If the development is a "run-of-river" installation, the absolute minimum capacity factor allowed is 40%. The final installed capacity of the mini-hydro plant is a compromise, one which minimizes spillage at flood flow levels, meets the minimum capacity factor, yet maximizes energy production. The spreadsheet also considers the effects of other variables, including minimum and maximum turbine flows, turbine efficiency, plant efficiency, transformer efficiency, head losses caused by friction, and dam height. All variables can be changed to observe their effect on the capacity factor and net annual energy production.

2.6 Physical Components

The next stage in assessing the economic viability of the project is accurately estimating the capital cost. The engineer must be aware of the differences in the physical components that make up a mini-hydro plant, and how those components interact and affect each other. Thus, the information in this section is an overview of the different components comprising a mini-hydro plant. It is not meant to be an all-encompassing treatment of the material, which is best left to the references [4-9], but does give the multi-disciplined engineer an insight into what is appropriate in the Newfoundland environment. The major items here include the dam, penstock, turbine and generator.

2.6.1 Dam

Dams are expensive, thus the location of the intake dam should be selected to minimize it's size. There are three basic types of dams used with the existing small hydro plants in Newfoundland. They are the concrete dam, rock dam with concrete face, and timber-crib dam. If the dam site is accessible via road and close to a cement plant, give serious consideration to cement. It is expensive, but durable, and has a long life. Partial developments are most suited to concrete since a small intake weir/dam is usually all that is required. Many intake dams are located at a point that is inaccessible by road, preventing the use of quality pre-mixed concrete. Mixing large quantities of cement on site is labour intensive, expensive, and is of questionable quality.

The rock dam with a concrete face has been the choice at a number of small hydro plant locations in Newfoundland. The two hydro plants that were built in the mid-fifties to service the Tilt Cove mine, Snook's Arm and Venam's Bight were of this type. Rock was blasted from a site nearby (20 meters away), hauled to the dam site, and used to build a rock dike. The slanted upstream face of the dam was covered with a four-inch layer of cement. Both dams are still in good shape 35 years later.

The timber-crib dam is the cheapest and easiest to build. It is almost as good as the concrete and rock dam, if built properly. Treated wood is used to increase the life of the structure. If the dam is on a stream used as a water supply, or a stream containing migratory fish, treated lumber may not be permitted. Natural wood that is rot resistant, such as Douglas Fir, or local "Juniper", could be used instead. The timber crib dam requires rock of the proper size to fill the cribs. Blasting may be necessary to acquire the correct size of rock. Most references [8, 9] suggest that the upstream face of the dam should be built with a slope to ease the pressure caused by ice. The Roddickton dam [15] has a vertical face and has been problem free to date. A solid foundation is important for any dam, more so for a timber-crib dam. A concrete foundation, the width of the timbers, should be laid on clean bedrock. Anchor bolts secure the crib to the foundation and bedrock. The bolts ensure that the lateral forces caused by ice and spring floods will not cause the structure to slip downstream.

2.6.2 Penstock

The four main types of penstock materials that have been used in Newfoundland, in order of the number presently in service, are woodstave, steel pipe, polyethylene pipe, and Fiberglas pipe. Woodstave is the most common type of penstock in use in Newfoundland, mainly because it was easy to construct in remote locations and is not affected by freezing. It is above ground, does not have to be buried, and is made of pressure treated tongue and grove Douglas Fir, usually two inches in thickness. With regular maintenance it has a life span of 50 years. The only supplier of wood penstocks is a Canadian company, Canbar Inc.. The woodstave penstock is an excellent choice for small hydro. While it is labour intensive to have it installed, it is unskilled labour. The foundation is simply a bed of rough gravel and the penstock can follow any curve or contour. Certainly this is an advantage when you consider the detailed lay-out and cement anchors/supports required for a steel penstock.

Steel is an excellent penstock material that requires very little maintenance and can easily handle the pressures involved, but it is expensive to buy and to install. Expansion joints are required to deal with the significant thermal expansion encountered in the Nfld. climate. If a large quantity of used steel pipe can be found and shipped to the site at a reasonable cost then it is an alternative worth considering [9, 12].

Polyethylene is a good penstock material, one that has minimum head loss due to pipe friction. It is installed quickly and does not require expansion joints. It should be buried to minimize freezing problems, and perhaps more importantly, to minimize vandalism. It is expensive to buy, requires heavy equipment to handle, and needs a special jointing machine to weld the sections of pipe [9]. As for Fiberglas, there has been only one of this type installed in Nfld. to date, that being located at the Newfoundland Light & Power Morris Plant on the Avalon Peninsula. It was buried and required major civil work. Initial cost estimates indicated that it was marginally cheaper than any of the other three alternatives [2].

2.6.3 Turbine

Once plant capacity and turbine size has been selected, a decision has to be made as to the type and quality of the turbine to use at the site. There are two options, namely either to purchase a new turbine, or purchase a used turbine. The price and quality of new equipment varies dramatically, but generally speaking, you get what you pay for. In most cases new equipment is the best option since it is expected to be dependable.

"Used" turbines are a definite option. The older turbines, many having been taken out of service in recent years, are of excellent quality and still have many years of dependable service life left. If an appropriate turbine can be located, the original manufacturer, or a reliable company in that business, should refurbish it at reasonable cost. The main problem with using a used turbine is finding one that operates efficiently under the new head and flow conditions.

When a turbine is initially designed, the manufacturer strives to produce the highest possible overall efficiency. Designing the turbine to run at the same speed as the generator eliminates the gearbox, thus the overall plant efficiency is increased by 2% - 3%. Also, given that the frequency of the grid and the number of poles in the generator dictate the speed of the generator, the speed of the direct coupled turbine is fixed by the generator speed. Consequently, the head, average flow, and power output of the direct coupled turbine is fixed. Now that all variables have a fixed value, only one physical shape of turbine runner will produce the required speed.

If one is willing to use a geared system to match the speed of the turbine with the speed of the generator then a "used" turbine can be installed at a different site and still maintain respectable efficiency levels. Selection of the correct gear box permits the original turbine to run at its design speed, maintaining the turbine efficiency, but also permits the developer to manipulate and match the turbine to the new head, flow and power output conditions. A lower overall plant efficiency should be accepted, due to the losses in the gearbox.

2.6.4 Generator

As previously mentioned in the Literature Review in Chapter 1, the traditional generator used in all hydro plants, until recent years, was the synchronous generator. It was preferred because the speed, and hence the frequency, could be controlled to match the line frequency and help stabilize the system. The synchronous generator is capable of independent operation, but governor, complex controls, and elaborate protective relaying is required [39, 42, 43]. Since this thesis is concerned with grid connected mini-hydro, a synchronous generator is not a necessity. The small grid connected plant is not built to operate independently, or to control the frequency of the grid. As mentioned, the induction generator was selected for the application described in this thesis because it is inexpensive, reliable, and rugged, requires minimum maintenance, and does not require a governor and the associated controls. The speed of the induction generator is dictated by the grid frequency. The main disadvantage of the induction generator is the slightly lower operating efficiency. In summary, the induction generator has the advantage in grid connected applications when it is small in size., thus an excellent choice for mini hydro development.

Electrically, an induction motor is identical to an induction generator, thus the motor can be run, and used, as a generator. However, there is one important limitation. An ordinary induction motor is built to withstand the centrifugal forces created in a typical industrial setting, which is 125% of rated speed. A generator application may see an overspeed condition of 200% of rated speed. Custom induction generators are built to withstand these temporary over-speed. Induction motors will do the job as well, but overspeed conditions should be kept to a minimum. The application of induction generators will be treated in detail in Chapter 3.

2.7 Rates and Economic Evaluation

Knowing the pricing structure, energy production, capital costs, and annual operating costs allow for a reliable economic evaluation of the project. The economic evaluation attempts to clearly identify all associated costs, and minimize the number of variables. The following sections give details on the capital cost estimate, the pricing structure used, and a description of the structure of the economic evaluation spreadsheet. The Nipper's Harbour mini-hydro project is used as an example.

2.7.1 Capital Cost Estimate

After the physical components have been selected and sized, the preliminary capital cost estimate is completed. The cost estimate includes the cost of the powerhouse structure, turbine, generator, controls, interconnection, penstock, dam and intake structure, access roads, telemetering, installation, commissioning and engineering. The results of the capital cost estimate for Nipper's Harbour are presented in Table 2.5. Further details are found in Appendix D.

Table 2.5: Preliminary Capital Cost Estimate - Nipper's Harbour

Nipper's Harbour Capital Cost Summary		
DESCRIPTION		**COST**
Power House Building	$	53,925
Turbine / Generator Set & Controls	$	438,150
Penstock	$	198,625
Dam & Intake	$	55,000
Access Roads	$	40,000
Switch yard	$	65,000
Connection to Hydro Grid	$	40,000
Upgrade Transmission Line	$	17,500
Telephone Connection	$	3,000
Telemetering	$	15,000
Stream Guage	$	15,000
Installation / Commissioning	$	38,000
Total Direct Construction Costs	$	979,200
Engineering	$	146,880
Sub-Total	$	1,126,080
Contingency (15%)	$	168,912
GRAND TOTAL	**$**	**1,294,992**

2.7.2 Pricing Structure

The utility, Newfoundland and Labrador Hydro, has developed a pricing structure for grid-connected small hydro projects [59]. The pricing structure has both a demand and energy component and offers an incentive for winter production. The demand portion of the rate will be escalated to the in-service date of the plant and then remain constant over the life of the power contract. The escalation index proposed for the demand is the Statistics Canada Hydroelectric Generating Station Index [68]. The energy portion of the rate will be escalated annually using the Statistics Canada Consumer Price Index [69]. This increase will be limited to a maximum of 6% in any year.

Table 2.6: Nfld. Hydro Pricing Structure

Period	**Energy Component** (cents/kwh)	**Demand Component** (cents/kwh)	**Total Amount** (cents/kwh)
Winter Nov.1 - Mar. 31	3.58	4.5	8.08
Summer Apr. 1 - Oct. 31	3.58	2.11	5.69

It is possible to increase revenue by storing water during the summer season, then operating at full capacity in the winter until all stored water is depleted. The stored water has an increased value of 2.39 cents/kWh, or 42% more than the summer price. To take full advantage of winter rates the site must have a large storage capacity, plus a larger turbine has to be installed. The increased cost of the extra storage and larger turbine must be weighed against the increased revenue from winter rates.

2.7.3 Economic Evaluation Spreadsheet

The purpose of the economic evaluation spreadsheet is to determine whether the proposed mini-hydro development has an acceptable internal rate of return (IRR) on investment. It was also designed to demonstrate to investors the positive effect of the Capital Cost Allowance, and to calculate the present worth of the undertaking when built. All variables were included and can be modified to demonstrate their effect on the IRR. The variable categories include technical specifications, annual costs, tax rates, discount rate, CCA, pricing structure, winter and summer capacity factors, escalation index, capital cost, and percent equity investment required.

All of the variables are used in a series of spreadsheets, which in turn contribute essential information to the final spreadsheet that calculates the corporate and personal IRR. The series of spreadsheets, covering the 20 year economic life of the project, includes revenue calculations, annual operating expenses, debt financing, CCA effects, and IRR and after tax income. The results obtained from the spreadsheet provide prospective investors, bankers, or developers with the essential numbers required to make informed investment decisions. The Nipper's Harbour mini-hydro Economic Evaluation spreadsheet is given in Appendix E.

Chapter 3

Induction Generators

While the induction generator is cost effective, especially in small sizes, it does have disadvantages, which must be considered before final selection of the generator type. Consequently, the purpose of this chapter is to document the theory, performance characteristics, and design considerations associated with an induction generator installation at a mini-hydro site. Induction generator problem areas are identified, specifically power factor correction and self-excitation concerns. The sum of the information required to evaluate the appropriateness of installing an induction generator at a grid-connected location is presented in Chapter 3.

3.1 Introduction

Nikola Tesla invented the induction machine between 1882 and 1887. Shortly after, modifications to the design resulted in the rugged squirrel cage rotor becoming an integral part of most induction machines [42]. Today, squirrel cage induction motors are the most commonly used devices of the induction machine. They are used to drive a variety of industrial and commercial equipment, including pumps, fans and conveyors. The popularity of the squirrel cage induction motor is a result of its rugged and simple form of construction, dependable operation, and minimal maintenance required. Since the machine excitation is accomplished through induction, field windings, brushes, and associated controls are not necessary, thus increasing reliability and decreasing maintenance. The lack of field windings also means the utility mains must supply the magnetization current.

The induction generator is simply an induction machine driven by a prime mover, with a rotor speed slightly faster than the machine's synchronous speed. The difference in speed between the rotor and rotating stator field is referred to as negative slip. When negative slip exists, mechanical energy is transferred from the prime mover to the electrical system. To increase the power output from the induction generator, the prime mover has to rotate faster, increasing the induction generator rotor speed and increasing the negative slip. At maximum power output the slip will most likely be in the range of 1% to 3% higher than synchronous speed. The higher the starting torque capabilities of the induction machine the larger the slip at rated load. As with the induction motor, the actual change in rotor speed from no-load to full-load is not significant. Also, induction machines with a lower slip at rated load are more efficient because the internal mechanical power developed is greater with lower slip values. I^2R losses are also less since less current is required to produce rated power.

The operating principle of the induction generator is exactly the same as that of an induction motor, the only difference being the speed of rotation of the shaft with respect to the synchronous speed. When motoring, the shaft speed is slightly slower than synchronous speed (positive slip), while in generator mode the shaft speed is slightly faster (negative slip). Since the electrical design and physical construction of an induction motor and generator are identical, it is possible to use a standard squirrel cage induction motor as an induction generator. The only constraint is the over-speed capability of the induction motor used as a generator; can it handle the sustained over-speed encountered in mini-hydro applications?

The widespread use of induction motors has resulted in reduced cost and improvements in design and reliability. Since the same machines can operate as generators, the initial cost savings, as well as a reduction in maintenance costs, make the induction generator an attractive alternative for a grid connected mini-hydro development. Yet, before the plant designer decides between the synchronous or induction generator, careful consideration must be given to the advantages and disadvantages of both [39, 40, 41, 44]. The advantages of the induction generator include lower purchase cost; lower maintenance cost; the control and protective devices are basically the same as for a similarly sized induction motor; the control and protective devices are less complex and less costly than those for a synchronous machine; induction generators are simpler to operate since there is no excitation control or synchronisation equipment; the squirrel cage rotor has the simplest, most rugged construction of any electrical machine; the induction generator has no effect on system frequency; the induction generator cannot feed a sustained short circuit current into a system fault; the generator does not produce harmonics; and "off-the-shelf" units are available in small sizes.

The induction generator also has disadvantages. These are; the basic induction generator cannot operate as a stand-alone unit; the efficiency of the induction generator is less than the equivalent sized synchronous type, especially in the smaller sizes; the excitation current required to magnetise the machine must be provided by the grid, resulting in a lagging power factor load; the power factor of the induction generator is always less than one, and gets progressively worse as the actual load drops below the rated load; and the induction generator does not have the inherent ability to contribute towards maintaining the system voltage and/or frequency.

After reviewing the advantages and disadvantages of induction generators, it is obvious that induction generators are particularly well suited to grid connected mini-hydro developments that have access to a relatively constant flow of water, either through long term storage or partial use of the available stream flow. Having enough mechanical energy constantly available to operate at the rated power output ensures maximum efficiency and operation at the preferred power factor. If the available flow is variable, several machines can be installed to comprise the total capacity. The number of operating machines can vary with water conditions, allowing each machine to operate close to its rated value [38, 69].

In summary, the ideal conditions for an induction generator application, in the context of grid connected mini-hydro, include [39]; the induction generator size should be small in comparison to the total system capacity; the generator is not considered to be a base load installation thus energy is produced when water flow is available, not when there is a system demand; the constant flow conditions ensure a high power factor, or the utility will not penalise a plant for operating at a low power factor, thus power factor correction capacitors are not required; and the proposed installation is located at a point in the distribution system which will not sustain self-excitation conditions when the generator over-speeds.

Of the sites considered in the site selection example in Chapter 2, four are suited for an induction generator application. They including Nipper's Harbour, the ERCO water supply, the Marble Mountain snowmaking water line, and the Glynmill Pond site. ERCO and Marble Mountain, with a constant water flow available to the prime mover, would be ideal examples of where to install an induction generator. Nipper's Harbour could maintain a relatively constant flow to the turbine and induction generator by either reducing the installed capacity of the proposed development or installing multiple units of smaller size.

3.2 Principles of Operation

The standard three-phase induction machine consists of a stator and squirrel cage rotor. The windings mounted on the stator create pairs of poles, with the most common machines having two, four, six, or eight poles. The squirrel cage rotor is formed from laminated electrical steel punchings, with the rotor winding made from bars located in slots punched in the laminations. The bars are short-circuited at both ends by short-circuiting rings.

The operation of the well-known induction motor is described first to illustrate how the induction principle is used to create a torque on the squirrel cage rotor. When the three-phase stator is connected to the system supply, a rotating magnetic field is created in the stator. 120^0 separate each phase and the vector sum of the magnetic fields from each field, at any instant in time, produces a net magnetic field with a constant magnitude. The direction of the combined field changes as the instantaneous system phase voltage levels change. The net result is a rotating magnetic field, which travels around the stator at a speed called the synchronous speed. The synchronous speed of a three-phase induction machine is dependent on the system frequency and the number of poles in the stator. The synchronous speed, S_s, in rpm is

$$S_S = \frac{120 \cdot f}{P} \quad \text{rpm} \tag{3.1}$$

and in rad/sec

$$\omega_S = \frac{4 \cdot \pi \cdot f}{P} \quad \text{rad/sec} \tag{3.2}$$

This is not to be confused with the slip S as described in Equ. (3.3). Typical induction machine synchronous speeds when connected to a 60 Hz system are 3600 rpm, 1800 rpm, 1200 rpm, and 900 rpm.

The rotating magnetic field cuts across the squirrel cage rotor bars, inducing a voltage and causing current to flow through the bars and short-circuiting end rings. The rotor current produces its own magnetic field which interacts with the rotating stator field, producing a torque on the rotor. The resultant torque causes the rotor to turn in the same direction as the rotating field. As the rotor picks up speed and approaches synchronous speed, the rate at which the rotor bars cut the rotating flux decreases, reducing the induced rotor voltage and current and decreasing the torque.

Of course, the squirrel cage induction motor rotor speed will never reach synchronous speed, due to the need to produce a small amount of torque to overcome the friction and windage losses. When a load is applied to the motor the rotor will slow down, resulting in greater relative motion between the two fields and producing more torque. Thus the power drawn from the source is a combination of the real power transferred across the air gap to the load, via induction, and the reactive power needed to set up and sustain the rotating stator field.

The difference in speed between the synchronous speed and the rotor speed, expressed as a percentage of synchronous speed, is referred to as slip, where the slip is

$$S = \frac{S_S - S_R}{S_S} \tag{3.3}$$

Positive slip occurs when the rotor speed is less than the synchronous speed (motoring), while negative slip equates to generator mode.

If the induction machine is connected to a prime mover, the rotor speed can be increased to match the synchronous speed. At this point there is no relative motion between the rotating stator field and the rotor bars, thus no voltage is induced in the bars, no current will flow, and no torque is produced. The prime mover supplies the energy to overcome the frictional and windage losses. The only current drawn from the system is that which is required to sustain the rotating stator magnetic field and overcome copper losses.

As soon as the prime mover drives the rotor speed higher than synchronous speed (negative slip) the induction machine is operating as an induction generator. The rotor bars are cutting through the stator field in the opposite direction relative to motoring action, thus the rotor current direction and magnetic field interaction are reversed. Power is transferred from the prime mover to the electrical system.

The excitation current required to establish the rotating stator field is still drawn from the connected system. Consequently, the basic induction generator cannot operate as a stand-alone unit.

When the induction machine is operating as a motor, an increase in mechanical load causes an increase in slip and a corresponding increase in torque. At some point the torque demanded by the load is beyond the capacity of the motor to deliver and the motor stalls, hopefully tripping the protection device since the current drawn from the source will rapidly increase to six to seven times its normal value. This operating point on the induction machine speed-torque curve is referred to as the breakdown torque.

A similar situation arises when operating as an induction generator. The power generated will increase as the prime mover increases the speed of the rotor beyond synchronous speed. At some point the induction generator can no longer produce a large enough resisting torque. This point is referred to as generator breakdown , commonly called pushover. Once past this point on the speed-torque curve, resisting torque falls away quickly, creating a dangerous situation called runaway. The prime mover will carry the generator up to the prime mover runaway speed, typically twice the normal operating speed for mini-hydro installations, sometimes higher. If the induction generator is not designed to withstand this over-speed condition, major physical damage may result.

3.3 Steady State Analysis of Induction Machines

When considering an induction generator installation at a mini-hydro site, the designer must carefully consider how the generator will perform under normal loads, during short circuit conditions, and while experiencing an over-speed situation. The induction machine performance characteristics under normal load, both as a motor and a generator, can be predicted using standard steady-state analysis techniques, the single phase equivalent circuit, and the machine data supplied by the manufacturer. Results of the analysis include how the stator current, torque, efficiency and power factor change with speed and slip. Expected values for rated load, maximum efficiency, breakdown torque and maximum power output are also calculated, for both the motor mode and the generator mode.

3.3.1 Equivalent Circuits

The equivalent circuits shown in Figs. 3.1 - 3.2 represent one phase of a three phase induction machine operating in motoring mode and generating mode. It is assumed the machine is Y-connected. Rotor currents and voltages reflected to the stator side are at stator frequency. The components of the equivalent circuit in Fig. 3.1 include stator winding effective resistance R_1, stator leakage reactance X_1, equivalent core loss/iron loss resistance R_m, magnetising reactance X_m, rotor leakage reactance X_2 reflected back to the stator, rotor resistance R_2 reflected back to the stator (representing rotor I^2R losses), and $R_2(1\text{-}S)/S$ representing the internal mechanical power reflected back to the stator. Figure 3.2 shows R_2/S replacing $R_2(1\text{-}S)/S$ and R_2. R_2/S is the combined effect of shaft load and rotor resistance reflected to the stator side.

Since the rotor current is produced by induction, the induction machine operates in a similar manner to the transformer, thus the transformer analysis method of reflecting current, voltage and impedance back to the stator side is valid. In the case of the induction machine, the reflected rotor current, voltage, and impedance will change as the relative rotor speed, or slip, changes. Of course, with a transformer the reflected quantities are dependent on the turns ratio only.

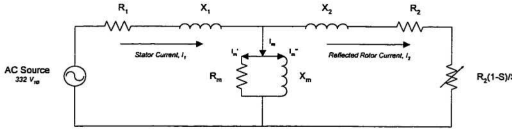

Figure 3.1: Induction Motor Equivalent Circuit typically used for power calculations.

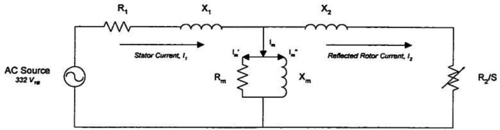

Figure 3.2: Induction Motor Equivalent Circuit

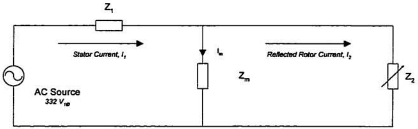

Figure 3.3: Induction Motor Equivalent Circuit - Impedance Diagram

3.3.2 Fall River Example - 500 kW Induction Generator

A number of circuit analysis techniques and methods have been used by the references [71, 72] to calculate the steady state performance characteristics of the induction machine. They include manual derivation of quantities using Thevenin's theorem, circle diagrams accompanied by manual calculations, and basic circuit analysis techniques used in conjunction with mathematical analysis software to simplify the solution of the equations. In an attempt to adhere to the thesis objective of documenting modern design methods to be used by multi-disciplined engineers, basic circuit analysis techniques and MathCad software were employed. MathCad is well documented, user friendly and widely available.

Table 3.1: Fall River Example - Induction Motor Nameplate Data

@ Rated Load	Value	Unit
Horsepower	670	HP
Voltage	575	V
Current	639	A
Efficiency (η)	94.5	%
Power Factor	0.843	p.u.
Torque	5943	lb-ft
Synchronous speed	600	rpm
Full Load Speed	592	rpm
Slip	0.0133	p.u.
Locked Rotor Current	3800	A
Locked Rotor pf	0.29	p.u.

The induction machine design constants required for the analysis are available from the manufacturer, with a typical listing given in Table 3.2 [72]. In this example, the manufacturer (Westinghouse) is using a standard induction machine as a 500 kW hydroelectric generator at the Fall River facility in Nova

Scotia. This particular induction machine was used in the analysis since nameplate data and machine parameters were readily available.

Table 3.2 Fall River Example - Induction Machine Design Constants

Component Name	Symbol	ohms	pu
Stator Resistance	R_1	0.0132	0.0254
Stator Reactance	X_1	0.0480	0.0924
Rotor Run Resistance	R_2	0.0070	0.0135
Rotor Reactance	X_2	0.0490	0.0943
Magnetizing Resistance	R_m	0.0570	0.1097
Magnetizing Reactance	X_m	1.0920	2.1019

In the region of normal induction machine operation, the "run" resistance values were used and assumed to be constant. The "run" values are sufficient for investigating the normal operating characteristics of the induction machine in a mini-hydro application, given that the range of slip values from no-load to the breakdown region will not vary beyond the 0 to 0.1 slip range. But if an estimate of breakdown torque/speed and pullout torque/speed is being investigated, the "start" value of rotor resistance should be included in the analysis to ensure a more accurate representation of the machine constants when not operating close to the normal machine load. Also, the equivalent circuit was not modified/simplified by bringing the magnetizing branch impedance, Z_m, out to the machine terminals mainly because the magnitization current, I_m, of the induction machine is very high in comparison to a transformer magnetizing current. I_m for the induction motor will be 30% to 50 % of full load current, while the transformer I_m is in the range of 2% of full load current. Thus analysis of the induction machine has been carried out based on the equivalent circuit shown in Figure 3.2.

Table 3.3: Fall River Example - Per Unit (P.U.) Base Values

	Symbol	Value
Base Voltage (3ϕ)	V_{3_ϕ}	575
Base Voltage (1ϕ)	V_{1_ϕ}	332
Base kVA (3ϕ)	kVA_{base}	636
Base Current	I_{base}	639
Base Impedance	Z_{base}	0.5195
Base Terminal Voltage	V_t	1.0

3.3.3 Starting Resistance Considerations

As previously mentioned, the starting resistance should be taken into consideration when the analysis requires the calculation of an induction machine parameter which occurs outside the normal operating range, as in the case when calculating the maximum power and breakdown torque in both generator mode and motor mode.

The induction motor has a rotor design allowing for high starting current on startup and an associated high starting torque. This value of current decreases as the rotor picks up speed (slip becomes less), thus the effective rotor resistance is different at each value of slip. This resistance is maximum at zero slip, called the "start" resistance, and minimum at rated load, called the "run" resistance. The "start" resistance is derived from the manufacturer's specified locked rotor current and locked rotor power factor, where

$$\alpha = a\cos(pf_{LR}) \tag{3.4}$$

is the power factor angle, and

$$\bar{I}_{LR} = |I_{LR}| \angle\alpha \tag{3.5}$$

is the locked rotor current vector. Since the terminal voltage, locked rotor current magnitude and phase angle are known, the total locked rotor impedance Z_{LR}, is

$$\bar{Z}_{LR} = \frac{\bar{V}_t}{\bar{I}_{LR}} \tag{3.6}$$

Given that the stator and magnetizing branch impedance are fixed, the reflected rotor impedance Z_{2st}

$$Z_{2st} = \frac{Z_{LR} - Z_1}{Z_{m-}Z_{LR} + Z_1} \cdot Z_m \tag{3.7}$$

and "start" resistance R_{2st} are derived using the equivalent circuit in Figure 3.2. The Fall River induction machine example calculations yielded a "start" resistance of $R_{2st} = 0.0213\,\Omega$.

3.3.4 Motor Mode and Generator Mode Analysis

With reference to the Fall River 500 kW induction machine, the normal operating characteristics are calculated using the parameters listed in Table 3.2, along with basic nodal analysis techniques and the Mathcad software. The standard equivalent circuit is represented by three impedances, Z_1, Z_2, Z_m, as shown in Figure 3.3. Solving for I_1, I_2 and I_m produces an expression for the current in all three branches, on a per unit (p.u.) basis. The equations are set-up in Mathcad, and solved for values of slip ranging from -0.5 (generator mode) to +0.5 (motor mode). Losses, output power, efficiency, power factor, speed and torque are also calculated. The results are plotted and max/min points identified.

Certain motor mode calculations differ from those in generator mode. The stator current I_1 is derived the same way in both modes; calculate the rotor-reflected impedance

$$Z_2 = \frac{R_2}{S} + jX_2 \tag{3.8}$$

for a given value of slip, then calculate the impedance Z_{total} of the induction machine,

$$Z_{total} = Z_1 + \frac{Z_2 \cdot Z_m}{Z_2 + Z_m} \tag{3.9}$$

finally, calculate the stator current I_1.

$$\bar{I}_1 = \frac{\bar{V}_t}{\bar{Z}_{total}} \tag{3.10}$$

It is assumed the induction machine terminal voltage V_t is fixed by the grid, consequently V_t is constant, and the same, for both motor mode and generator mode.

In motor mode, the current divider principle is used to find the reflected rotor current I_2.

$$I_2 = I_1 \cdot \left(\frac{Z_m}{Z_2 + Z_m} \right) \tag{3.11}$$

In generator mode, the current divider approach is not valid. The generator mode reflected rotor current I_2 is found by first finding the air gap voltage E_a. The air gap voltage in generator mode is

$$E_a = V_t + I_1 \cdot Z_1 \tag{3.12}$$

resulting in a generator mode reflected rotor current of

$$I_2 = \frac{E_a}{Z_2} \tag{3.13}$$

The magnetizing current I_m is also dependent on the air gap voltage E_a. The air gap voltage in motor mode is the terminal voltage minus the voltage drop across the stator impedance Z_1,

$$E_a = V_t - I_1 \cdot Z_1 \tag{3.14}$$

resulting in the motor mode magnetizing current I_m.

$$I_m = \frac{E_a}{Z_m} \tag{3.15}$$

In generator mode E_a is given by Eqn. (3.12), and

$$I_m = \frac{E_a}{Z_m} \tag{3.16}$$

is the generator mode magnetizing current. Both generator mode I_m and motor mode I_m have a magnitude and phase which is close, but not exact. The grid supplies the magnetizing VARS both in generator mode and motor mode, but the core losses are supplied by the grid in motor mode and by the induction machine in generator mode.

Values for stator current I_1 , rotor current I_2 , and magnetizing current I_m have been calculated for the full range of slip. Also, the power factor pf is

$$pf = \cos(\theta_1) \tag{3.17}$$

where

$$\theta_1 = \arg(\bar{I}_1) \tag{3.18}$$

3.3.5 Losses

Induction machine losses, both in generator mode and motor mode, include stator and rotor copper losses, core loss, friction, windage and stray losses. The copper losses are known for any operating point because all branch currents have been calculated. The full load stator I^2R loss

$$P_{R1@FL} = 3 \cdot (I_1)^2 \cdot R_1 \tag{3.19}$$

full load rotor I^2R loss

$$P_{R2@FL} = 3 \cdot (I_2)^2 \cdot R_2 \tag{3.20}$$

and full load core I^2R loss

$$P_{m@FL} = 3 \cdot (I_m)^2 \cdot R_m \tag{3.21}$$

are used to calculate windage, friction, and stray load losses. Windage, friction and stray losses are assumed to be fixed and the same for all normal operating loads, thus the lumped value for these losses, P_{fws}, is calculated at rated load where both input power

$$P_{IN@FL} = \frac{\sqrt{3} \cdot I_{FL} \cdot V_{FL} \cdot pf_{FL}}{1000} \tag{3.22}$$

and output power

$$P_{O@FL} = (Full\ Load\ HP) \cdot 0.746 \tag{3.23}$$

are found using the manufacturer's rated load nameplate data. Thus the constant lumped friction, windage and stray losses are

$$P_{fws} = P_{IN@FL} - P_{R2@FL} - P_{R1@FL} - P_{m@FL} - P_{O@FL} \tag{3.24}$$

Stray load losses are comprised of the additional core losses and eddy and load dependant current losses, caused by increased air gap leakage flux at load and by the high frequency pulsation of these fluxes.

3.3.6 Input Power, Output Power and Efficiency (η)

In motor mode, the induction machine input power is

$$P_{IN-motor} = \frac{\sqrt{3} \cdot I_1 \cdot V_{LL} \cdot pf}{1000} \tag{3.25}$$

which is the electrical power available at the machine terminals. In generator mode, the input power is the mechanical energy available at the shaft of the induction machine, which is equal to the output power plus losses, thus

$$P_{IN-gen.} = P_O + P_{R1} + P_{R2} + P_m + P_{fws} \tag{3.26}$$

The output power of the induction machine in generator mode is the electrical power available at the machine terminals, which equates to

$$P_{O-gen.} = \frac{\sqrt{3} \cdot I_1 \cdot V_{LL} \cdot pf}{1000} \tag{3.27}$$

while the output power in motor mode equals the mechanical power delivered to the shaft.

$$P_{O-motor.} = P_{IN} - P_{R1} - P_{R2} - P_m - P_{fws} \tag{3.28}$$

The magnetizing branch power loss, generally referred to as core loss, P_m, is larger in generator mode than motor mode. This is to be expected since the air gap voltage E_a must be higher in generator mode in order to maintain the fixed grid terminal voltage V_{LL}, given that the stator voltage drop and V_{LL} must add to produce E_a. The higher air gap voltage E_a translates into a higher real magnetizing current component and subsequent higher magnetizing core losses. If the rotor current in generator mode remains the same as the motor mode rotor current, less slip is needed to produce the air gap power since E_a is larger. Generator slip is less than motor mode slip when rotor currents are equal. The generator power factor is less because losses are supplied by the turbine, reducing kilowatts, and VARs are increased due to the larger air gap voltage, E_a.

In generator mode the generator supplies the copper losses thus the reflected rotor current is higher than in motor mode. Consequently, the differences in losses between modes, given the same rated stator current, means the generator mode efficiency is slightly less than the motor mode efficiency. Friction, windage and stray losses are assumed to be the same and constant in both modes and at all operating points.

3.3.7 Torque

The equivalent circuit representation of the induction machine is used to calculate the power and torque in both motor mode and generator mode. In motor mode the torque is

$$T_{motor} = \frac{P_{O-motor} \cdot 33000}{0.746 \cdot 2 \cdot \pi \cdot rpm} \quad \text{lb-ft} \tag{3.29}$$

and in generator mode it is

$$T_{gen.} = \frac{P_{IN-gen.} \cdot 33000}{0.746 \cdot 2 \cdot \pi \cdot rpm} \quad \text{lb-ft} \tag{3.30}$$

The operating points of interest are at full load and at breakdown, both in motor mode and generator mode. The maximum and minimum points on the torque versus slip graph are the breakdown and pushover torque values. These points are identified and the associated slip/speed noted. For the Fall River 500 kW induction machine example the calculated breakdown torque of the motor is 16,565 ft-lb, and it occurs at 550 rpm. The calculated pushover torque in generator mode is 24,634 ft-lb and it takes place at a speed of 680 rpm.

3.3.8 Summary of Motor Mode and Generator Mode Calculations

Table 3.4 summarizes the induction machine parameters calculated for the Fall River Example. The details of the Mathcad analysis of this particular induction machine are explained in Appendix G. Figure 3.4 to Figure 3.10 are graphs of the Fall River induction machine parameters over a range of slip.

Table 3.4: Fall River Example - Computed Values of Machine Parameters for Steady-State Operation.

@ Rated Load	Motor	Generator
Voltage	575 V	575 V
Current	636 A	641A
Efficiency (η)	93.0%	92.5%
Power Factor	0.822	0.794
Synchronous Speed	600 rpm	600 rpm
Full Load Speed	593 rpm	607 rpm
Slip	0.0124	0.0124
Output Power	648 HP	507 kW
Input Power	520 kW	735 HP
Maximum Power	1312 kW	1547 kW
Breakdown Slip	0.081	0.1193
Breakdown Torque	16,696 ft-lb	23,644 ft-lb
Breakdown Speed	551 rpm	671 rpm

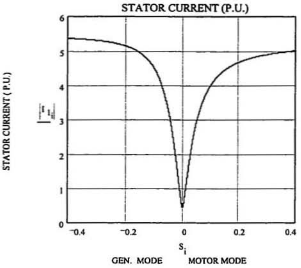

Figure 3.4: Fall River 670 HP Induction Machine - Stator Current , I_1

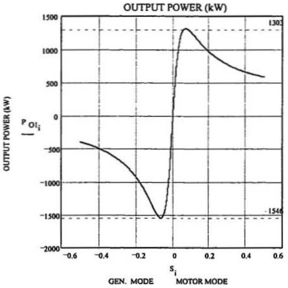

Figure 3.5: Fall River 670 HP Induction Machine - Output Power , P_{O1}

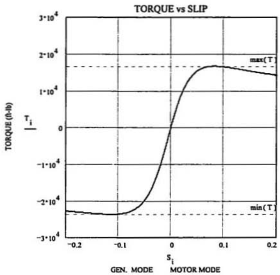

Figure 3.6: Fall River 670 HP Induction Machine Torque

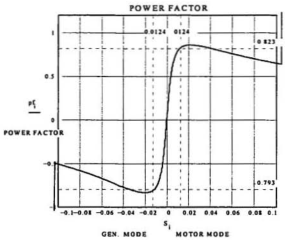

Figure 3.7: Fall River 670 HP Induction Machine - Power factor

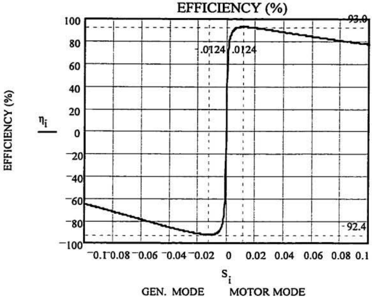

Figure 3.8: Fall River 670 HP Induction Machine - Efficiency, η

3.3 Short Circuit Performance

Induction generator short circuit considerations are simpler than those for a synchronous generator. As previously mentioned, the induction generator magnetizing current comes from the grid. Unlike the synchronous generator, the induction machine does not have a separate field control and energy source, thus when a fault occurs the energy normally flowing toward the induction generator field is diverted to the fault. The generator magnetic field will quickly collapse as the energy stored in the field dissipates to feed the fault. Thus the induction generator cannot sustain fault currents caused by system short circuits.

When the induction generator is exposed to a fault, such as a bolted three-phase fault, the initial fault current contributed by the generator is determined by the sub-transient reactance of the machine. At the instant the fault occurs, the fault current will be equal to the locked rotor current, or approximately six times the full load current. The fault path *X/R* ratio and short circuit time constant dictate the decay rate of the fault current contributed by the induction generator. Typically the fault current will disappear in a few cycles. Any power factor correction capacitors connected will slow down the decay [40].

Induction generators may be subjected to any of the three principle types of faults, phase-to-ground, phase-to-phase or three-phase fault [73]. The most common fault occurrence is the phase-to-ground while phase-to-phase and three-phase faults are usually the end result of the phase-to-ground fault not being cleared quickly enough. The location of the fault could be at the generator, on the bus, or on the system side. Thus with respect to short circuit considerations, the induction generator installation should be handled the same as an induction motor installation. The starter /breaker and switchgear must still be sized to handle the potentially high fault current from the electrical power system, which can be much larger than that contributed by the induction generator. A starter rated for a similar sized induction motor will meet these requirements [47]. Details of induction generator protection are covered in Chapter 4.4.

3.4 Over-speed & Self-Excitation

The induction generator must be designed to withstand overspeed conditions. As an example, when a protective trip occurs, the electrical load on the generator is lost, yet the turbine continues to transform the hydraulic energy into mechanical energy. The sudden energy imbalance translates into a rapid increase in speed as the prime mover accelerates to its runaway speed, sometimes twice the full load speed. Depending on the inertia of the system, runaway speed can be reached in seconds, yet it takes much longer to divert or stop the water flow and remove the torque. Consequently, the prime mover and generator must be capable of continuous operation at the runaway speed. Induction motors used as generators are usually rated for 25% overspeed [70], although most are capable of much higher sustained speeds [9].

Accurate numbers for defining runaway speed values must be based on model tests conducted by the turbine manufacturers. Imperical formule to estimate runaway speed have been developed based on model tests of installed units [6,7]. The runaway speed n_r is defined as

$$n_r = 0.85 \cdot n \cdot n_s^{0.2} \tag{3.31}$$

where n_r = runaway speed of the turbine at best efficiency, rpm

n_s = specific speed of the turbine at full output and best efficiency

n = normal rotational speed of the turbine, rpm

The specific speed n_s is

$$n_s = \frac{n\sqrt{P}}{h^{5/4}} \tag{3.32}$$

where P = turbine output, kW

n = rotational speed of the turbine, rpm

h = net head, meters

An induction generator will become self-excited when there is enough capacitance connected to supply the required VARS for the generator excitation, and the connected load is less than the rated capacity of the generator. The self-excitation capacitance consists of power factor capacitors and/or the capacitance of the connected transmission line. On load rejection the prime mover accelerates the generator causing an increase in frequency and terminal voltage. Significant variations in frequency or voltage may cause damage to customer loads. Thus, the connected load must be quickly isolated from the generator. The over/under frequency relay, over/under voltage relay and an over-speed switch detect the self-excitation conditions.

Opening the generator breaker protects the connected loads, but the generator is still exposed to a high voltage resulting from the self-excitation process. The only way to avoid damage is to remove the capacitance before the voltage reaches dangerous levels. Self-excitation voltages occur instantly when the connected load is removed thus the initial self-excitation voltage must be kept to a safe level [69]. This is possible by ensuring that the speed increase is not large enough to produce dangerous voltage levels. The power factor capacitors have to be quickly isolated from the generator. It will take a finite amount of time for the speed switch to activate and the breaker to trip. Once the capacitance has been removed the generator loses its source of excitation, causing the voltage to gradually collapse.

3.5 Using Standard Induction Motors as Generators

The preferred machine for use as an induction generator is the squirrel cage induction motor. The two most common concerns when trying to select the correct motor to be used as a generator are selecting a safe generator kW rating and determining the realistic overspeed rating. The rating of the induction machine in generator mode is normally taken to be the HP of the motor expressed in kW, where

$$P_{O-generator} = P_{O-motor} \times 0.746 \tag{3.33}$$

and $P_{O\text{-}motor}$ is in horsepower. As an example, a 200 HP squirrel cage induction motor has a generator rating of 150 kW.

This approach is based on the assumption the rotor current in both modes are equal [37, 70]. If this is true, in generator mode the stator current is lower, stator I^2R losses are smaller, core losses are larger. The change in core loss will be less than the change in I^2R losses. Also, the friction and windage loss is slightly larger in generator mode. Under the described conditions the overall generator efficiency is the same, or slightly less, than the motor mode efficiency. Thus, the induction generator temperature rise will be within the limits specified for the motor.

A generator rated in this fashion runs cooler than it does in motor mode and will safely handle slightly higher kW output when demanded. Depending on the class, temperature rise, and service factor of the motor, it may be possible to safely run the induction generator with a stator current equal to the motor mode stator current. Generator output is increased at the expense of higher temperatures and reduced efficiency.

The overspeed rating of squirrel cage induction motors used as generators is not adequately addressed by the literature [9, 70], other than to note the typical overspeed rating as a motor is 25%. Attention to bearings, using the best possible, and balancing the rotor will help in safely handling sustained overspeeds. Machines with lower synchronous speed will have a lower absolute runaway speed, thus will be less susceptible to bearing and balancing problems. Obviously a 900 rpm machine with a runaway speed of 1800 rpm will have fewer problems than a 3600 rpm machine with a runaway speed approaching 5000 rpm to 6000 rpm. As the references suggest, consult the manufacturer. Increasing inertia with the addition of a flywheel can reduce acceleration rate and overspeed. Also, certain turbines, the impulse type as an example, can use deflectors to quickly remove the flow from the turbine.

Once the kW and overspeed rating of the generator are established, the generator is expected to operate safely under normal conditions. The next consideration, of course, is efficiency. The induction machines with the highest efficiencies are those with low starting torque, high speed (3600 rpm), large size, low full-load slip, lots of iron and steel, and high power factor. The high-speed requirement contradicts the overspeed limitation of the generator, which obviously takes priority.

Low torque machines have low resistance rotors, less rotor losses, thus a higher efficiency and smaller slip. EMAC Design A and B have relatively low starting torque. Design B is the most common while Design A would be preferable if starting torque is not necessary, as is the case in a hydroelectric installation. The turbine is used to bring the induction generator up to synchronous speed, thus

Design A motors can be used as generators. While the low torque characteristic of the induction machine brings higher efficiency, it also results in lower slip. This is not a problem as long as the turbine flow is relatively constant. The low slip means the system is sensitive to small speed variations, and this translates into load variations.

An induction generator with a high power factor will be more efficient. This does not mean adding power factor capacitors will improve the efficiency of the machine. Higher generator power factors are achieved by reducing the VARs required. For a given machine this is accomplished with more iron and steel, longer cores and better design. The induction generator should be installed in an application where the load will be relatively constant and equal the full load rating, since the power factor deteriorates rapidly at partial loads.

To summarize, in most cases the best squirrel cage induction motor to select as an induction generator would be one that is a stock item, thus relatively inexpensive in comparison to a custom machine. Typically the ideal "off-the-shelf" machine would have low speed (1200 rpm), normal to low starting torque (EMAC Design B, or A), 1.15 Service Factor, a minimum of Class B insulation, high temperature rise, high efficiency rating (larger size, more copper, iron and steel), spherical roller bearings, and a drip-proof enclosure.

Chapter 4

Plant Control, Operation and Protection Requirements

Chapter 4 introduces the standard flow control and load control methods encountered in a mini-hydro plant equipped with an induction generator. The important plant operational procedures, including manual start-up, normal shutdown, and emergency shutdown, are reviewed in light of their effect on the induction motor used as a generator. Induction generator protection requirements, utility protection, and mechanical systems protection are also presented. In Section 4.6 the PLC is used to automate the plant by incorporating the control and protection schemes. Cost effective remote control options are also explored. Finally, a diagnostics expert system is demonstrated using the Roddickton mini-hydro plant as an example.

The mini-hydro design process is focused on induction generators used in the low end of the mini-hydro scale, up to 150 kW. Applications in this range are usually low voltage, 575V, three wire machines, and use a motor starter rather than a power circuit breaker as the main switching device. The equipment selected and protection applied is based on these criteria.

4.1 Flow Control Equipment

Most new mini-hydro developments will be the run-of-river types that do not depend on large, expensive reservoirs to regulate the flow. Under these conditions, the turbine must be capable of running efficiently over a wide range of flows, thus will require some form of variable flow control equipment. Wicket gates, guide vanes and valves, or a combination of these, are used to control the flow of water to the turbine.

The flow control equipment serves two functions, to safely shut down the turbine without causing excessive over-speed or water-hammer, and to continuously adjust the turbine flow as requested by the load control signal or level control signal. The wicket gates or guide vanes can act as the continuous flow control device, as well as provide the shutdown function normally performed by the turbine stop valve. Eliminating the redundancy of the turbine stop valve is only acceptable if the generator and turbine can withstand a continuous over-speed condition. As discussed in Chapter 3.6, when using standard induction motors as induction generators every effort must be made to reduce the possibility of runaway, thus it is recommended that the turbine stop valve remain as an integral part of the flow control scheme.

Continuous control of the turbine flow during start-up, run, normal shutdown, and emergency shutdown require turbine wicket gates or guide vanes, a turbine stop valve, bypass valve, wicket gate servo-motor or hydraulic actuator, and a fail-safe gravity based counter weight.

4.2 The Control Strategy

A mini-hydro control system, controlling either a synchronous or induction generator connected to the grid, has two main functions. First, the control system must interlock the protective devices to ensure a safe start-up, run, and shutdown sequence. Second, a method of controlling generator output (kW) is necessary. The generator load is directly related to the available flow, assuming head remains constant. The load control scheme implemented at a particular mini-hydro plant is dependant on local conditions, including available flow, minimum stream flow levels, and ice cover, etc.. The control schemes are described in Sections 4.2.1 - 4.2.4, and include on/off control, level control, on/off level control, and manual load control.

The control scheme for a synchronous and induction generator will differ. Large synchronous generators connected to the grid are capable of assisting in controlling the grid frequency, voltage, and power factor. A mini-hydro synchronous generator is too small compared to the overall power system to have any significant effect on the grid frequency or voltage, but it can control the amount of reactive power draw or contributed to the grid. Consequently, the mini-hydro synchronous generator will have both kW and kVAR load control. A governor for speed control is not a requirement unless the synchronous generator is expected to supply the local load when isolated from the grid.

An induction generator installation does not need a governor for speed control. The induction generator frequency is fixed by the grid frequency. The grid supplies VARS, eliminating the need for both kVAR control and excitation control. Control of the generator load (kW) by varying the turbine flow is the only control mechanism required in an induction generator installation, greatly simplifying the overall control scheme.

4.2.1 On/Off Control

There are situations where the flow to the turbine is constant at all times, and under these circumstances there is no need to incorporate flow control, other than simple on/off control. The generator operates either at no load or full load. The flow to the turbine is constant only if the rated turbine flow is a small percentage of the average stream flow, or if the hydro plant is located on a stream which already has a large existing storage reservoir. The Marble Mountain snowmaking waterline mini-hydro proposal is an application where only on/off control is adequate.

4.2.2 Level Control

The flow to the turbine is regulated to maintain a constant level at the intake. As the intake level stabilizes, the generator output matches the rate of flow currently available from the stream. This control scheme is best suited to low head sites where a change in head cannot be tolerated, since it will have an adverse affect on the turbine efficiency.

Level control is also the best operating scheme for medium to high head sites during the winter period. It will ensure a partial flow of water through the turbine at all times, preventing freeze-up of the penstock. Also, the constant water level at the head pond does not disturb the ice cover, minimizing frazil ice problems. Accepting level control as the exclusive form of flow control means the turbine must be capable of maintaining a relatively high efficiency over a wide range of flows. A cross-flow or Pelton turbine would be more appropriate in this situation rather than a Francis turbine.

4.2.3 On/Off Level Control

When on/off level control is used, the turbine is started when the head pond level reaches the full supply level (FSL). The flow is increased until the turbine output corresponds to the point of highest efficiency, which is usually at the full-load rating. The turbine continues to run at full-load until the head pond level reaches the lower supply level (LSL). The turbine then shuts down, allowing the stream flow to refill the head pond.

The advantages of on/off level control are the simple control scheme (on/off) and the increased energy production resulting from always operating at the highest possible efficiency, regardless of the stream flow. The variation in head, usually a maximum of 2 meters for most mini-hydro sites, has minimal effect on medium and high head installations. The disadvantages of the control scheme are the increased number of stops/starts required, the need for an automatic start-up capability, the possibility of no flow through the penstock for short periods during the winter, and the disruption of the ice cover in the head pond. Consequently, the risk of a penstock freeze-up and the possibility of aggravating frazil ice problems means that on/off level control is not acceptable during the winter months.

4.2.4 Load Control

The control system must be capable of disconnecting the level control and/or the on/off level control, allowing the operator to manually set a desired generator output. This is called load control and is advantageous during unusual operating conditions. There are times when a specific amount of flow is needed to ensure safe operation. As an example, when freeze-up starts in late fall the turbine flow should be set at a minimum, regardless of available stream flow, to prevent frazil ice problems. Also, during the high run-off period in the spring the operator may wish to increase the load beyond 100% to minimize spillage losses and increase production.

4.3 Operating Procedures

The function of standard operating procedures is to ensure safe start-up and shutdown, and to effectively deal with emergency shutdown situations. The control system and protection scheme were designed in conjunction with the requirements incorporated in the safe operating procedures. Safety of personnel, plant equipment, the utility equipment, and connected customers is paramount. The typical hydro-plant operational cycle begins with a manual start-up procedure, then the plant runs automatically without operator intervention using one of the control methods described in Section 4.2. Finally, at some point the plant shuts down, using either the emergency shut-down procedure or the normal shut-down procedure. A description of the manual start-up procedure, normal shut-down procedure and emergency shut-down procedure follows [73].

4.3.1 Manual Start-up Procedure

When all protection interlocks are satisfied the start switch activates the bypass valve, equalizing the pressure differential across the turbine stop valve. It also turns on the cooling water for the speed increaser, if required. The turbine valve and wicket gates are opened to the speed/no-load position, indicated by a limit switch on the turbine stop valve or the wicket gates. The main contactor closes when the speed exceeds 95% of the synchronous speed. If the turbine does not reach the desired speed in a specific time period, the valve and wicket gates close, shutting down the turbine. If the start sequence was successful a "raise kW" command can be issued to the servomotor, opening the wicket gates and increasing the load.

4.3.2 Emergency Shutdown Procedure

The turbine/generator will experience a temporary over-speed condition whenever an emergency shutdown procedure is initiated. The local emergency stop, all of the electrical protection devices, the utility cutout interlock, and the overspeed switch de-energize the starter seal-in coil, thereby quickly removing the electrical load. The turbine overspeeds until the water flow is stopped.

The main function of the turbine stop valve is to quickly reduce the flow to limit the overspeed time, yet not to reduce the flow too fast such that water-hammer problems occur. The wicket gates also close, but not as fast as the turbine stop valve. The turbine, speed increaser, and generator must be capable of withstanding a 100% over-speed condition. The main source of emergency stop signals is from the electrical protection devices. Every effort should be made to coordinate the electrical protection scheme to minimize nuisance trips.

4.3.3 Normal Shutdown Procedure

Whenever possible the generator is shutdown by first reducing the turbine flow. This is accomplished by initiating a "lower kW" signal, which closes the wicket gates. When the flow has been reduced to the speed/no-load level the main contactor opens, removing the electrical load. The system will not over-speed.

The normal shutdown procedure is initiated by bearing over temperature, excessive vibration (if required), reverse power, low inlet pressure, loss of cooling water flow, local stop, or remote stop. The mechanical protection devices do not cause an emergency stop because the resulting over-speed condition may aggravate the mechanical problem. The turbine speed does not have to be below synchronous speed before the main contactor can be opened. The speed/no-load position limit switch gives positive indication of when it is safe to open the main contactor.

4.4 Generator Protection

The complexity of the protection scheme is dependent on the size of the installation. Generally speaking, the induction generator protection should be similar to the protection applied to an induction motor of the same size. The protective circuits trip the starter/contactor when an electrical fault or mechanical problem occurs, preventing damage to the generator. The generator has instantaneous over-current fuses to protect from short circuits and severe ground faults, an overload device, phase loss and phase unbalance detection, ground fault protection, and a speed switch to prevent sustained over-speeds.

4.4.1 Switching Device - Motor Starter (52)

As mentioned, an induction generator requires the same protection and control as a similar sized induction motor. A three-phase full voltage combination starter will be used as the main switching and protection device for the 150 kW (200 HP) induction generator at Nipper's Harbour. Full voltage starters are available in EEMAC Size 00 (2 HP) up to Size 9 (1600 HP). Sizes greater than Size 5 (200 HP/150 kW) are considered non-standard and expensive. A Size 6 (400 HP/300 kW) starter is three times more expensive than a Size 5 starter, thus induction generator installations greater than 150 kW should consider medium voltage generators and switchgear.

A combination starter includes a disconnect switch, fuses or moulded case circuit breaker, magnetic contactor, overload relays c/w heater elements, control transformer and a general purpose enclosure. The fuses are used for short circuit protection of the generator and magnetic contactor. Standard heater elements protect against generator overload.

Standard motor starters provide adequate protection but do have deficiencies. They do not protect against phase unbalance or loss of phase, which is one of the major causes of motor/generator failure. Also, the holding coil will drop out when low-voltage or brownout conditions occur. As well, the overload heater elements are sensitive to ambient temperature, possibly causing premature or late trips [47].

All of these problems have been overcome by the new generation of solid-state motor starters, first introduced by Westinghouse in 1992 [75]. The Westinghouse "Advantage" motor starter features integrated current sensors coupled to a built-in microprocessor, which provides accurate current measurement. Consequently, the heaters and their associated problems, low accuracy, ambient temperature dependence, and minimal adjustment, have been eliminated. The current sensors and microprocessor combination are also capable of detecting phase loss, phase unbalance, and Class II ground faults. The integrated microprocessor controls the contact closure, resulting in minimum contact bounce and elimination of coil drop-out caused by brownout conditions.

The "Advantage" starter is available in EEMAC Size 00 to Size 6 and costs the same as traditional starters.

4.4.2 Short-Circuit Protection (50)

An instantaneous over-current device is required to protect against severe faults. The device will be the same as the current limiting fuses used to protect the contactor on low-voltage 600V starters. Fuses allow for flexible short circuit protection design, but moulded case circuit breakers can be used instead of fuses. The fuse selection must allow for the large magnetizing inrush current, typically up to 6.5 times full load current. It is advisable to consider differential protection on larger medium voltage installations. The differential relay provides better protection, especially for low level internal machine faults, but it requires an induction machine with access to all six leads.

4.4.3 Overload Protection (51)

Overload heaters, either connected directly or through current transformers, traditionally provided standard overload protection. The size and type of heater element used would be similar to that used on an induction motor installation. The heater elements simulate motor temperature by passing current through the heater, causing the bimetallic strip to expand from the heat produced. The time lag associated with this action means the heater element does not accurately model the heat produced by the motor. Current sensors on each phase to measure the actual current, at any instant, would be more accurate. In the past dedicated electronic relays, combined with CT current measurement, were the only option available for accurate overload protection. Small motors or small generator installations could not justify the additional cost of this type of overload protection, thus thermal heater elements prevailed.

The Westinghouse Advantage starter has three current sensors built-in. The current measured is modified by the electronics to provide accurate I^2t modelling of the motor heating. Trip Class 10, 20, and 30 are selectable and the actual overload protection can be set to within 2% accuracy. This level of protection was not available at reasonable cost until this starter was introduced. Other manufacturers have since followed Westinghouse and introduced electronic overload relay replacements for the conventional heaters found in the standard motor starter [79].

The best overload protection is provided by temperature sensing devices, either RTD's or thermocouples embedded in each phase of the motor windings. For generators less than 150 kW, thermocouple detectors connected to an external tripping unit provide the most affordable protection [80]. Resistance measurement device (RTD) protection schemes are more accurate than thermocouples but are expensive. RTD thermal protection is only cost effective in large induction generator installations.

4.4.4 Ground Fault Protection (50G)

It is common practice to ground the neutral of electric power systems and not to ground the neutral of loads. Because the induction generator is not capable of supplying sustained short-circuit current, it is not necessary to ground the neutral of small induction generators. Consequently, the induction motor operating as a generator should be regarded as a motor load for purposes of neutral grounding [42]. The 600V bus on the generator side must be grounded, and is usually connected to the transformer secondary ground [72].

Ground fault protection is not normally applied to the small three-wire induction generators that use traditional motor starters. The solid-state Westinghouse "Advantage" motor starter has built-in Class II ground fault protection. Low-level ground faults are below the fuse or circuit breaker rating and therefore go undetected until a much larger problem develops. Class I protection is designed to trip the switching device regardless of the current level. Class II protection includes a high current inhibit circuit which prevents the contactor from opening if the fault current exceeds the contactor interrupting capacity. Ground fault current exceeding the interrupting capacity is designed to be cleared by the short circuit protection device.

Larger generators may have access to the generator neutral. If so, the power system on the generator side can be grounded through a high resistance ground [47, 73]. The high resistance ground reduces the ground fault to a safe level. A voltage relay (59G) detecting a voltage change across the ground resistor is the ground fault sensor [73].

4.4.5 Phase Unbalance Protection (46)

When the line voltages applied to the induction generator are not equal, unbalanced currents in the stator windings will result. The current will change as a square of the voltage, causing a significant temperature rise in the motor. The traditional bimetallic overload heaters barely provided adequate phase unbalance protection. The new electronic starters and solid-state overload relays have built-in phase loss or phase unbalance protection at no extra cost. As an example, the Westinghouse Advantage starter will trip if any two phases have a current difference greater than 30%. This set point is not adjustable. All induction generator applications less than 150 kW should take advantage of this type of protection.

The induction generator should be de-rated if a continuous distribution voltage difference is expected, and the generator shutdown if the voltage unbalance is greater than 5%. Adjustment of the main transformer taps may eliminate the distribution voltage unbalance. A temporary 3% voltage unbalance and a 10% current unbalance are conditions normally encountered [47, 74], but a consistent occurrence of a 3% voltage unbalance indicates the generator should be de-rated by 10%.

4.4.6 Over-Speed Protection (12)

As discussed in previous sections, the most troublesome problems encountered when applying an induction motor as an induction generator, namely the threat of sustained runaway and over-voltage caused by self-excitation, are a direct result of excessive over-speeds experienced after a load rejection. An over-speed condition must be detected immediately and the flow control valve closed. A shaft mounted centrifugal switch, or tachometer with an over-speed set point, detects the over-speed.

4.4.7 Protection of Mechanical Systems

Every mini-hydro installation using a standard induction motor as a generator should specify the best bearings possible. A second line of defence against major mechanical failure are bearing temperature (38) sensors and vibration monitors (39), one of each installed at every bearing. When activation of the sensors is detected by the PLC, a normal shutdown procedure starts. Using the PLC to monitor the protection features is acceptable since the plant will only be remotely operated and unmanned if the PLC based remote control system is functional. If the PLC is down, the plant is either off-line or running with an operator on site. The operator's routine on-site checks will detect unusual bearing temperature or excessive vibration.

If cooling water is part of the plant systems, adequate flow must be available at all times. Installed strainers should have automatic backwash activated by pressure differential across the strainer [76]. A fail-safe, low flow switch detects loss of cooling water and initiates a normal shutdown procedure.

4.5 Utility Protection

The minimum protection demanded by the utility for an induction generator installation includes over-voltage, under-voltage, over-frequency, and under-frequency protection [77]. Lightning arrestors, reclosure considerations, and the selection of main transformer also assist in protecting the utility, customers, and mini-hydro plant.

Voltage and frequency protection are required to disconnect the power plant from the distribution line when an islanding condition occurs. Islanding occurs when a Distribution System Generator (DSG) and the local load are disconnected from the utility supply [23]. Such a condition may have been caused by a line fault, lightning strike, or substation breaker opening. Under certain conditions the isolated DSG may continue to feed the connected load. This can be dangerous to utility personnel and can damage customer equipment. An islanded induction generator is normally not able to sustain an output voltage at rated frequency. The problem occurs when there is enough capacitance, either power factor correction capacitors and/or line capacitance, still connected to the generator during the islanding condition to cause self-excitation. If the connected load equals generator capacity, the turbine may not overspeed enough to initiate an overspeed trip. Under these conditions, the protection scheme depends on the over/under frequency and over/under voltage relays to trip the generator.

Unless careful site specific analysis is performed, a full compliment of protective relaying must be provided to detect the islanding condition and disconnect the generator. The utility will insist on over/under frequency and over/under voltage protection. It is the responsibility of the utility to set the protection standards, but the private plant owner must ensure that he is not liable for any damage to customer equipment or injury to utility personnel in the event of an undetected islanding problem. For complete protection the plant owner should install protective relaying as outline in Sections 4.5.2 - 4.5.4.

4.5.1 Power Factor Correction Capacitors and Self-Excitation

Induction generators should be operated as close as possible to their rated power output in order to produce the best power factor. Hydro requires an induction generator installation to install power factor correction capacitors to maintain a power factor of 90%. The main concern related to power factor correction capacitors is the possibility of an over-voltage condition caused by over-excitation. The over-voltage will occur instantaneously upon disconnection of the electrical load, assuming that there is enough capacitance connected at the generator terminals to cause self-excitation.

The main protection against self-excitation problems is to connect power factor correction capacitors through a separate contactor, and never directly across the terminals of the induction generator. An accurate overspeed detector will trip the generator before an over-voltage can develop. The size of the capacitors should be limited to the rating which will not lead to self-excitation at the calculated overspeed [69].

When an induction generator suddenly loses it's electrical load the turbine will drive the generator into an over-speed condition. The generator requires less magnetizing VARS at higher speeds, making it easier to produce an over-voltage problem. The generator can also encounter an over-speed condition if the applied torque exceeds the pullout torque of the generator. This is typically 325% of the full load torque. The maximum pullout torque occurs at approximately 10% overspeed [72].

The best way to protect against over-excitation problems is to reduce or eliminate the connected capacitance, and to install accurate overspeed protection. When an islanding condition occurs, a section of transmission line capacitance and/or power factor capacitors may still be connected to the generator, as well as a portion of the customer load. The potential over-voltage problem continues to exist until the generator contactor opens. The contactor will open if an over/under-frequency, over/under-voltage, or over-speed condition has been detected, but utilities have expressed concern that frequency and voltage protection may not be fast enough to trip the generator before an over-voltage occurs. Tests reported by R. Nailan [40] indicate that the over-voltage relay does indeed act fast enough.

4.5.2 Over-Voltage Relay (one per phase)

The over-voltage relay will protect other loads on the feeder from damage caused by high over-voltages. The over-voltage should not exceed 1.5 times normal voltage. The relay should be set at 10% over-voltage and it should be capable of operating in 10 cycles or less. Induction disk relays cannot meet the 10 cycle criterion and should not be used. There should be one relay per phase since the level of over-voltage on each phase may differ. Averaging the three phases may work but it is not reliable.

4.5.3 Under-Voltage Relay (one per phase)

The purpose of the under-voltage relay is to detect a sustained or slowly decaying under-voltage condition. This condition is hazardous to utility personnel and can cause generator damage if the reclosure connects the utility when it is out-of-phase with the generator. After the under-voltage trip, the relay also prevents the generator starter from reclosing until the feeder is energized from the utility source. Nuisance trips may be caused by an under-voltage condition resulting from a fault on an adjacent line. This problem is overcome by lengthening the under-voltage trip time. Special consideration must be given to the reclosure timing to ensure the voltage and frequency protections have enough time to react and trip the generator before the reclosure tries to restore power.

4.5.4 Over/Under Frequency Relay

If the self-excitation voltage is between 0.9 and 1.1 per unit during an islanding condition, the over/under voltage relays will not trip the induction generator. The over-frequency relay will trip as the frequency increases, where the frequency increase is caused by the imbalance between the feeder load and the induction generator output. The under-frequency will trip when the feeder load is greater than the generator rating. The over-frequency relay is usually set at 60.5 HZ and the under-frequency at 59.5 HZ.

4.5.5 Reclosure Effects

The protection scheme must ensure that the isolated generator and the system are not out of phase when reconnected by the reclosure. The out of phase condition will produce large currents, sudden torque and possible mechanical damage. With a well designed induction generator installation the over/under voltage or over/under frequency relay will detect the loss of the distribution feeder and trip the generator breaker. After the system has been restored, the generator will be started in the normal manner.

Distribution lines with standard reclosures cause a problem because they attempt to reconnect the system shortly after a fault has been detected. The induction generator installation can be protected from out-of-phase reclosure by extending the reclosure times. Also, the voltage and frequency relays must have enough time to detect and trip the generator before reclosing. As mentioned at the beginning of Chapter 4, the voltage and frequency relays are usually mandatory.

Alternate schemes would include upgrading the reclosure to include out-of-phase or generator voltage detection, but this is expensive. Since induction generators are best suited to small hydro developments, most installations will be connected to the grid through a distribution line that includes a reclosure.

4.5.6 Lightning Arrestors

The lightning arrestor protects the insulation on the transformer and motor windings from excessive voltage caused by lightning or switching problems. The lightning arrestor is also called a distribution arrestor [15]. It should not be confused with the surge protector, which consists of a voltage-limiting device in parallel with a capacitor, usually found on larger generators. Lightning arrestors must be installed between any transformer/generator and a transmission line, one per phase. If the transformer has a transmission line on both sides, arrestors must be installed on both sides. The effectiveness of the lightning arrestor is totally dependant on a good connection to ground [78]. The lightning arrestors have a rating that is about 25% above the nominal line voltage.

4.5.7 Main Transformer

Transformers associated with a typical induction generator installation have a kVA rating which assumes a 0.8 power factor. As an example, a 150 kVA transformer is capable of supplying a 150 kW load at a 0.8 pf. or 187 kW at unity power factor. The transformer must be large enough to handle the generator rating minus the station service load. The greatest load would occur when the generator is at maximum load and the station service load is low. Using another example, the Roddickton mini-hydro plant [15] has three single phase transformers, with a combined rating of 3 x 167 kVA = 501 kVA. The generator is rated at 531 kVA, thus the largest normal load would be 531 kW at unity power factor. The transformers are capable of handling 501 kVA at 0.8 power factor, or 626 kVA at unity power factor.

The transformer connection is usually selected to ensure adequate protection of the transformers and transmission line from system faults. This is best accomplished by having the high side of the transformer a grounded wye, enabling the relay on the ground connection to detect any abnormal current, which is an indication of a ground fault on the distribution line [47]. The larger induction generator installations use the wye connected generator stator winding as a ground source for the 600 V secondary system.

The standard squirrel cage induction generator does not have an external neutral. In this case, the solution to the 600 V grounding problem is to use a 25kV/600V wye-wye or delta-wye transformer. The neutral of the transformer secondary is used as the 600 V ground source [72]. For small sizes, usually less than 500 kVA, the only transformer protection required is fuses on the primary side. The fuses can be integrated with a ganged disconnect switch if desired.

4.6 Automation of the Plant

The level of automation required in a small or mini hydro plant depends on the complexity of the flow and load control, the remoteness of the plant, and technical skills of the local operator. Small plants with on/off control and easy access, located close to a technically competent owner/operator, can get by with a hard-wired control scheme that does not utilise a PLC. A larger plant with a complex control scheme, one that is remotely located and dependent on technical expertise based at a distant site, not only needs hard-wired control, but also a PLC.

The PLC provides flexible control options, eliminates the need for dedicated controller hardware, and can act as the communications medium for remote monitoring and control. The loss of a PLC in a mini-hydro plant must not affect the ability of the plant to run under manual control. When this happens the plant will have to be started locally and the load adjusted manually. Automatic start up and level control will not be possible while the PLC is out of service.

While it is desirable to have every mini hydro plant, regardless of size, automated and equipped with remote monitoring and control capability, fancy control, PLCs, PCs and an abundance of software will not increase revenue, yet the automation costs quickly add up [82]. The proposed mini-hydro plant has to make money, thus common sense must prevail through-out the design process. The criteria for the level of automation is initially based on the minimum requirements for safe operation of equipment and personnel, the level of metering and protective relaying demanded by the utility, and the minimum level of control acceptable. The cost of additional automation features, regardless of how desirable or enticing, must be carefully weighed against the expected benefits.

As mentioned, different developments require varying degrees of automation. Section 4.6 describes the minimum requirements for the control of a mini hydro plant, then introduces the various levels of automation made possible because of the hardware and software technologies available today. Wherever possible, utility and plant protection, control, and metering requirements are integrated to minimize cost.

4.6.1 Minimum Automation

The automation of every mini-hydro plant, regardless of size, should take advantage of the latest technology to ensure the best possible protection, metering and control scheme is implemented with least cost. The minimum protection requirements for personnel, equipment, and the utility were identified in Section 4.5. The minimum level of automation must allow for unattended operation of the plant and automatic emergency shut down. Two additional features normally included in all plants, and covered in detail in Section 4.7, are remote access to the utility revenue meter, and a remote trip alarm signalling the operator when the plant goes off-line.

The simplest plant has on/off hard-wired control. To get the plant on-line, the operator goes to the site and runs through the normal pre-start checklist. If all is satisfactory, the start push-button is held down, causing the main flow control valve to slowly open. The turbine runner will start to rotate, increasing speed as the valve continues to open. When the valve opening reaches the speed-no-load position, as indicated by a limit switch, the turbine is near synchronous speed. The speed-no-load contact closure causes the starter contactor to close, connecting the induction generator to the grid. At this point the operator can release the start push-button, since the contactor auxiliary contacts seal in the start signal. If contactor closure via direct unit speed measurement is demanded, a speed switch will be installed and the contacts set to close at 95% of synchronous speed. The contacts are wired in series with the speed-no-load switch. The solenoid valve controlling the flow valve is fail-safe, thus if power to the solenoid valve is lost, the flow control valve will close slowly [73].

The field devices and interlocks needed to implement this basic control scheme include local start and stop push-buttons, utility switching interlock, over/under voltage and frequency protection interlock, trash-rack water level interlock, speed-no-load limit switch, 95% speed-switch, and over-speed. The over-speed and under-speed contacts are activated by the same speed switch. Overload, instantaneous over-current, phase unbalance, and ground fault protection are provided by the solid-state starter and automatically trip the main contactor and/or fuses. Thermistors are optional but provide excellent generator overheating protection at minimal cost. Bearing temperature and vibration monitors are not normally included.

Significant cost savings are possible if the utility approves of combination meters, similar to Power Measurements models ION 7300, ION 7700 and 3720 [83], which have revenue accurate metering capability and fast over/under frequency/voltage set points with output contacts. The remote trip alarm, via modem alarm dialler, would use an auxiliary contact from the starter for positive indication of plant shutdown. Again, to ensure reliability, all of these interlocks are hard-wired, regardless of whether a PLC is used or not.

Optional equipment would include a micro sized fixed I/O PLC. These PLCs are available with a high speed counter for tachometer input, enough fixed inputs to record the status of all plant interlocks and contacts not covered by the power monitor/metering device, outputs capable of implementing remote start functions, ASCII message display, RS232 port for local programming and remote access, and programming software. Price, less than $500 for the PLC Direct Model 105 [84]. The final item needed for full remote monitoring and control capability is a three-port telephone line-sharing device, similar to the industry standard TelTone model. The single telephone line entering the powerhouse is shared between the power monitoring device, the PLC, and the operator telephone. The prices are included here as an example to demonstrate the seductive nature of computer hardware and software, and our constant desire for more information. The two prices quoted are amazingly low for the features provided, but already the cost of these optional automation devices exceeds $1000. This is significant when compared to the cost of the required solid-state starter ($4900 for Size 5) and the power monitor/revenue meter ($995). Yet if the plant is distant from the owner/operator, this is truly low cost remote monitoring and control.

4.6.2 Full Automation

Full automation capability is usually justified for larger and more remote mini-hydro plants. Also, if remote or local diagnostics using expert systems are to be used, then more operational parameters must be available to the expert system software. A modular PLC is more appropriate in this case, using analog I/O cards to capture parameters like intake water level, and using third party PLC interface cards to gather information from the power monitor/revenue meter and solid-state starter [85, 86].

The "on/off" control described in Section 4.6.1 assumes constant flow at all times. The only control interlock is the field device used to detect a low water level behind the trash rack, caused by ice or debris clogging the intake. "On/off level" control uses similar instruments in front of the trash rack, one set to activate at the low supply level (LSL), and the other to activate at the full supply level (FSL). A normal start procedure is initiated when the water level rises to FSL, then the plant runs at rated capacity until the LSL switch is activated, causing the plant to begin a normal shutdown sequence. Obviously, for "on/off level" control the plant must be capable of an unattended start. This function is handled by the PLC. Since the FSL and LSL signals are discrete, the fixed I/O PLC is still adequate.

For an unattended start sequence, parameters normally checked by the operator, typically cooling water, oil pressure, and bearing temperature, are fed to the PLC as discrete inputs. If these pre-start interlocks are o.k., and all other standard interlocks described in Section 4.6.1 are normal, the closed FSL contact input to the PLC is captured, producing an output pulse long enough to give the turbine time to ramp up to the 95% synchronous speed [73]. The FSL output from the PLC is wired in parallel with the local start push-button. The LSL contact is connected to a PLC input, activating a normally-closed PLC output, which is wired in series with the local stop push-button. The LSL contact could be wired direct, but the PLC acts as a sample and hold to produce a positive signal when actual level is very close to the LSL set point.

All but the simplest and smallest mini-hydro installations will have a backup turbine stop valve. The stop valve is fail-safe and usually fast acting in comparison to the turbine flow control mechanism. From a control perspective, a normal shutdown sequence will initiate both the stop valve and wicket gate closure at the same time. This is adjustable, depending on the type of turbine and site parameters. An unattended start sequence also includes a time-out limit on the start signal. If the turbine speed does not reach the 95% level to close the main contactor before the pre-set time limit, a normal shutdown sequence is invoked. If the start sequence is successful, the PLC will output a maintained discrete signal to the servo-motor/solenoid, causing the turbine gates to continue opening, thus loading the generator. The gates will stop opening when the high load limit switch, mounted on the gate, is reached. The Manual/Automatic switch in conjunction with the Local/Remote selector switch, selects the operational control mode.

"Level" control requires a continuous head-pond level signal. The signal is sent to the PLC located at the powerhouse via dedicated telephone line, twisted pair RS-485, 900 MHz spread spectrum radio, or a fibre transmitter/receiver. Fibre and spread spectrum are the optimum choice since they eliminate ground potential problems caused by lightning strikes. Another consideration is the availability of AC power at the intake structure. While this is taken for granted at larger sites, it may be too costly for smaller installations, like the Marble Mountain snow making water line project.

The fully automated plant has the capability of implementing all control modes, from the simple on/off mode to load control, and gathers information about the operating status of the plant from the power monitor/revenue metering device and the PLC. This information is transferred to a PC, located either on-site or at a remote location, where it is used by SCADA/MMI software and expert system diagnostic software. The PLC still makes all control decisions while the PC performs the data collection and supervisory function. The detail of the various configurations of software and hardware required to collect information from different sources is presented in Section 4.7. An example of the actual design of control schemes, diagrams, and equipment lists are presented in Chapter 5.

4.7 Remote Monitoring and Control

As discussed at the end of Section 4.6.1, remote monitoring and control is possible for even the smallest sites. There are different levels of remote monitoring and control, ranging from basic to complex. The simplest is a plant-activated signal, via modem dialler, alerting off site operators of a plant shut. Next, the PLC and power monitoring device are interrogated remotely, and separately, through the line sharing switch. The on site equipment do not share information. Last, the information from all sources at the plant are collected and shared with any hardware or software that needs the data. This could be an on site data collection system or a remote data collection system.

Figures 4.1 - 4.4 describe the different powerhouse communication networks that provide the remote monitoring and control functions. Option 1, Figure 4.1, described in detail in Section 4.6.1, permits remote monitoring and control of the PLC, as well as remote PLC programming.. The scheme also provides a remote connection to the power monitoring equipment, but not at the same time the PLC is being monitored. There is no provision for on-site sharing of data between the PLC and the power monitor. Off-line expert system diagnostics is still possible, but cumbersome.

Figure 4.2 shows the ION 7300 [83] sharing its information with the PLC. With this arrangement the PLC uses the shared information and PLC set points to detect phase unbalance and reverse energy flow. Also, there is one common source for all pertinent data coming from the plant, that being the PLC. Unfortunately an interface card is needed to achieve the communication link. With this scheme it is easier for the expert system to get the information needed, especially if the remote PC is running the server software for that brand of PLC that supports Microsoft

Dynamic Data Exchange (DDE). The cost of the DDE server also has to be considered.

Option 3, shown in Figure 4.3, assumes an on-site graphical operator interface (SCADA or MMI). The DDE server for the PLC will run on this computer, gathering the plant data on a regular basis then distributing it to the Windows based MMI and expert system software. Set-point changes are transferred easily to the PLC, and analog data form the PLC and ION 7300 are displayed on the MMI screen. If information is needed remotely, the communication link is via the line sharing switch, modem, and COM port on the PC.

The last option, outlined in Figure 4.4, eliminates the direct link between the PLC and the ION 7300 power monitor. The advantages include easy access to all set points, historical data, and measured parameters available in the ION 7300, and the PLC interface card is eliminated. The information from the power monitor is still available to the PLC, but indirectly via the PC and DDE servers. The disadvantage is the need for two separate DDE servers, one for the Ion 7300 and the other for the PLC. The MMI has to gather information from two servers now. Also, two-way communications for the ION 7300 is now possible. The master/slave arrangement of the Modbus protocol controlling the direct link to the PLC, as shown in Option 2 and Option 3, only permitted one way communication. Option 3, described in Figure 4.3, is the preferred arrangement, mainly because the control system can function without the PC being operational.

Using DDE servers to gather and distribute information to other software packages is much easier than trying to find or write custom drivers, which is what had to be done in the past. The system designer no longer has to be a programming expert, or depend on non-standard interface tools. Any Windows based program that supports DDE, such as Excel, Access, MMI software, SCADA software, or the expert system software, can request any information from the PLC or ION 7300 [83]. Unfortunately the Westinghouse Advantage starter [75] does not have a RS-232 or RS-485 communications port. Their propriety hardware communication link requires a $2500 black box to convert the starter information to RS-232 format. Also, a DDE server is not currently available.

In conclusion, it is understood the utility requires a communication link to all hydro plants, regardless of size, for revenue meter interrogation. Since a communication link is a given, it is recommended the minimum remote monitoring and control system, even for the smallest plant, include a line sharing device. This provides an on-site telephone for the operator, a connection to the revenue meter, and remote monitoring of the small PLC. This minimum system can be expanded, as outlined in Figures 4.1 - 4.4. Chapter 5 provides the details of a full fledged remote monitoring and control scheme, one which takes advantage of Microsoft Windows standardisation and Dynamic Data Exchange (DDE) to collect and distribute relevant information.

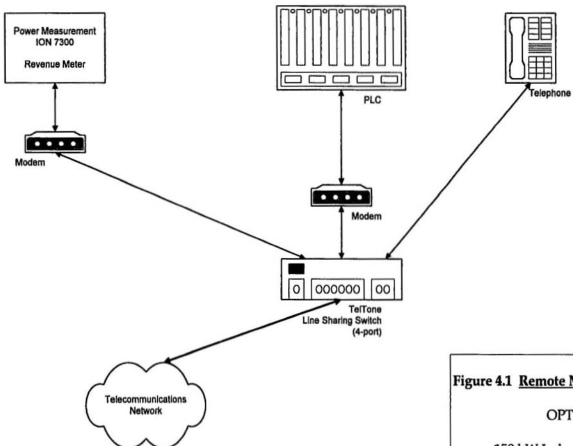

Figure 4.1 __Remote Monitoring & Control__

OPTION 1

150 kW Induction Generator

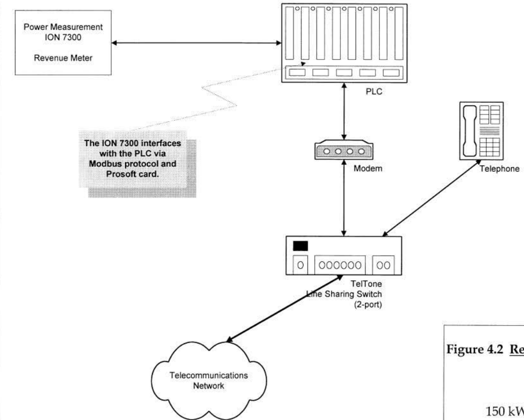

Figure 4.2 <u>Remote Monitoring & Control</u>

OPTION 2

150 kW Induction Generator

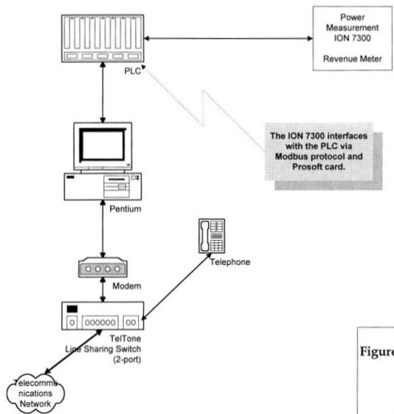

Figure 4.3 **Remote Monitoring & Control**

OPTION 3

150 kW Induction Generator

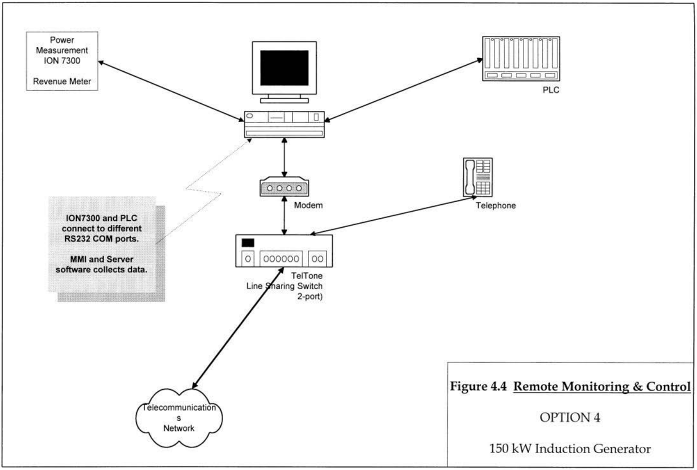

Figure 4.4 <u>Remote Monitoring & Control</u>

OPTION 4

150 kW Induction Generator

4.8 Expert System Diagnostics

4.8.1 Introduction

Small hydroelectric plants connected to the electrical distribution grid are not economical unless remotely controlled, because the small plant does not generate enough revenue to cover the cost of a full-time operator. When an operational problem does occur, the cause of the shutdown must be quickly identified, a technician dispatched to fix the problem and the plant restarted. Quick identification of the cause of a small hydro plant shutdown will reduce lost revenue and minimize the troubleshooting manpower costs.

While automation eliminates the full-time operator cost, it also eliminates the expertise. The remaining operators will continue to apply their experience and expertise to a large number of remotely operated small-hydro plants. As they retire, their intimate understanding of the plants will be lost. The next generation of operators and technicians will have to deal with a more complex control system, will be responsible for a larger number of plants, and may have other duties not directly related to the power generation process. Under these conditions it is unlikely they will be able to acquire the level of expertise of their predecessors. Also, the independent operator will be working on his own, and will not have access to the technical resources of a large company such as Newfoundland Power.

Thus, a diagnostic expert system, even at an advanced beginner level, would be an asset to utility personnel and independent owner/operators.

Consequently, an expert system to diagnose the cause of the mini hydro plant shutdown was developed, one that required minimal input from the operator/technician. The knowledge base for the expert system comes from the PLC data table which stores the status of the various contacts and sensors. An expert system has a number of benefits, including reduced troubleshooting time and downtime costs, and reduced dependence on the available experts in the area. It also captures the detailed knowledge of the experienced operators and assists in the training of new technicians and operators.

From a practical point of view, diagnostic expert systems are technically feasible, but as with other aspects of mini hydro development, the cost of implementing the technology has to be carefully examined. Good plant instrumentation, a PLC, and remote access are a necessity for seamless transfer of sensor status to the expert system software. As mentioned in Section 4.7 on remote monitoring and control, even the very small plants will have remote access to the on-site PLC, thus some form of expert system is possible. The most practical application of an expert system occurs when all instrumentation data are available to the expert system through DDE servers.

4.8.2 Review of Expert Systems

Expert systems are computer programs that embody human knowledge and understanding and use this information to imitate the human thought process in decision-making [87]. Regardless of whether the computer programs are interactive or embedded in other software, all expert systems have a knowledge base of rules and facts that are used to incorporate judgement, experience, and rules of thumb, intuition and other expertise.

An expert system differs from algorithmic programming in a number of ways. An algorithmic program uses a small amount of knowledge repeated over many cycles, whereas an expert system typically has to search a large amount of knowledge at each cycle, and a particular piece of knowledge may only apply once. Expert system problem solving techniques are separated from the knowledge base. Also, there is some form of explanation feature in an expert system that explains to the user why a certain inference was made. Conventional "Help" facilities are not the same. Another feature of expert systems is the domain dependent knowledge, and it is coded in the program in a readable form.

Expert systems have evolved with the computer. Shortly after the computer was invented, numerical programming was born with the introduction of "Fortran". Symbolic programming, via "LISP", was created at about the same time by John McCarthy [88]. Fortran was an outgrowth of numerical analysis while LISP was an outgrowth of abstract mathematics. Expert systems are considered to be a branch of artificial intelligence (AI), which in turn is a sub-field of computer science. During the 1960's and early 1970's AI researchers developed a number of general problem-solving mechanisms, which were applied to "real" problems. The results were not good. Researchers realized that what was needed was knowledge, enough knowledge information to understand the problem at hand. "Pattern-directed inference" was also developed in the early 1970's. Pattern-directed inference provided a way to represent knowledge inside a computer and how to use it. The twin themes of extensive domain-specific knowledge and pattern-directed inference dominate today's expert systems.

Early AI efforts concentrated on the processing of symbols, understanding information processing, and the ways in which humans learn. Experts systems arrived when problem-solving techniques were combined with well-defined areas of knowledge, often referred to as domains [89]. The problem solving techniques were separated from the knowledge base, resulting in an expert system shell, also called an inference engine. Today's expert systems are comprised of the knowledge base, inference engine, user interface and other utilities. The knowledge base must be configured for each expert system application.

The knowledge base is an assembly of knowledge that a human might use to conceptualize information and make decisions in a particular domain [87]. The knowledge base consists of factual information, rules that describe the complex relationship between the facts and procedures. The procedures direct the application of the rules using a predefined order. As previously mentioned, rules can represent concepts, rules-of-thumb, or mathematical expressions. Most commercial expert system shells use the IF-THEN-ELSE format to write the rules. "EXSYS Professional" writes the rules in a natural language format which is very easy to understand [53]. Others, like Comdale/X [87], are more cryptic, yet very powerful.

The expert system inference engine processes the knowledge contained in the knowledge base. When the inference process is started, the inference engine dictates whether forward or backward chaining will be used, and selects either a depth or breath approach to the reasoning process. Backward chaining is a common inference strategy. It is a reasoning process that starts with the outcome, then looks for facts and rules that support this result. Forward chaining uses known facts to produce new facts, which in turn help to reach a conclusion. An additional feature of an expert system is its ability to deal with uncertainty. Outcomes are not limited to either the TRUE or FALSE state, but can have a degree of uncertainty associated with them.

Expert system shells are available as shareware, typically used for educational and experimental purposes, and as commercial packages. The commercial packages usually have a graphical user interface, good documentation, and software support. The commercial expert systems used today have been applied to solve business and industry problems, either in real-time or off-line. While most expert systems are versatile enough to be used in a variety of applications, different packages have found a niche market for their product. As an example, EXSYS Professional is normally found in the business environment because of its English like structuring language. The Comdale expert system has found a market as a process control supervisory tool in the mining process industry, mainly because it operates as a real-time embedded expert system and has DDE servers for most brands of PLCs and DCS products [90]. Other commercial packages are available from Gensym Corporation, Inference Corporation, Asymetrix, Acquired Intelligence Inc., and Pavilion Technologies, to mention a few. Most of these expert systems work in conjunction with other AI technologies, including neural networks, fuzzy logic and chaotic principles [91, 92]. There is a tremendous range in price between products, but one worthy of note is Comdale/X, the off-line expert system. The student rate for the full commercial package is $100.

4.8.3 Expert System Diagnostics

The purpose of the expert system is to assist the operator in diagnosing the cause of the hydro-plant shutdown. When an input device, such as a speed-switch, detects an abnormal condition, it will send a signal to the PLC. Depending on the severity of the problem, the PLC will initiate a normal shutdown procedure or an emergency shutdown procedure.

The relays and sensors that can initiate the shutdown procedure include utility protection devices, electrical equipment protection devices, and mechanical equipment protection devices. The utility protection devices are the under-voltage relay, over-voltage relay, under-frequency relay, and over-frequency relay. The electrical equipment protection devices include instantaneous over-current relay, ground fault relay, speed switch, and overload relay. The mechanical equipment protection devices consist of low sump level, low governor solenoid pump flow, low bearing coolant flow, high bearing temperature, and high vibration. There are other conditions that will set off an alarm but are not important enough to initiate a shutdown. They are battery charger failure, charger fuse blown, and low head-pond level.

The first step in diagnosing the cause of a shutdown is to identify any relay or sensor that has tripped. This is recorded by the PLC, and provides most of the knowledge base required by the expert system. Relay and sensor tripping combinations point to a specific cause of the plant shutdown. Any additional information needed can be entered by the operator when prompted by the expert system program.

When a shutdown does occur, the PLC transfers the relay and sensor status to the microcomputer containing the expert system software, "EXSYS Professional" [53]. This software package was used because it was the only commercial package available from Memorial University (Faculty of Engineering and Applied Science). The EXSYS English language rule structure is easy to master, but the package is limited in its ability to easily import facts from industrial controllers (PLCs).

Consequently, the external program, HYDRO2.EXE, was written to transform the sensor data into a form that can be interpreted by EXSYS. The latest version of EXSYS still does not support DDE servers or industrial controller drivers.

4.8.4 Expert System Example

The actual hydro-plant used as a test case in the expert system was the Roddickton Mini-Hydro Development, built in 1980. The design guide [15], published by Energy, Mines & Resources Canada, had most of the detailed information needed to create the rules for the expert system, plus it is an actual built plant, and it uses a stand-alone synchronous generator. It has a more complex protection and control system than an induction generator, thus if the expert system works for the synchronous plant, it should definitely be able to handle the induction generator protection and control scheme.

As was mentioned previously, the sensors and relays were designed to detect abnormal conditions. These conditions are usually caused by operational problems or equipment failure. Hopefully, the sensors will trip before any major damage is done to the equipment. The process used to determine which problems caused specific sensors to trip was as follows: first, create a list of the plant equipment, then identify each piece of equipment which could cause a problem, and, finally, record each problem, its cause, and associated symptoms (i.e. sensors tripped).

A detailed list of equipment, problems, possible causes, and associated symptoms, is given in Appendix H. After reviewing the equipment list, the following major problem areas were identified. They include mechanical problems, governor problems, electrical problems, and utility problems. The mechanical problems are runner unbalance, rotor unbalance, stuck gates, and stuck butterfly valve. The governor problems include linkage broken or seized, hydraulic pump seized, hydraulic pump motor tripped, and hydraulic line blocked. The electrical problems are generator overload, ground fault, generator windings fault, and breaker damage. Finally, the utility problems include utility substation trip, unbalanced system load, and a lightning strike.

Once all possible causes of a plant shutdown were identified, a decision tree was constructed showing the cause and effect relationship between sensors activated and the source of the problems. The decision tree was then used as the model to write the rules for the expert system. The decision tree, qualifiers, variables, choices, rules, output screen information, and related EXSYS files are located in Appendix H. The output of the expert system indicates to the operator or technician the cause of the shutdown, list the sensors and relays that have been tripped, and recommend remedial action.

Chapter 5

150 kW Induction Generator Example

5.1 Introduction

The system approach and documentation of modern electrical design and operating methods, as developed in the previous Chapters, are applied to a grid connected mini-hydro site. The selected site, as identified in Chapter 2, is Nipper's Harbour. An installation using all of the available flow of the Nipper's Harbour stream would have had an installed capacity of 650 kW. The economic evaluation of this proposal (Appendix E) demonstrated that the 650 kW plant was not viable, mainly because of the 40% capacity factor. Consequently, the initial installed capacity was reduced to 150 kW, resulting in a capacity factor of 77%. The reduced revenue expected from the 150 kW plant is balanced by a major reduction in capital costs.

The scaled down Nipper's Harbour project is an excellent application for an induction generator because of the relatively constant flow associated with the 77% capacity factor. Thus, the load on the induction generator will be steady and the generator will operate at optimum power factor and efficiency. The remainder of Chapter 5 covers the specifics related to the selection, protection, operation, and control of the 150 kW induction generator planned for the Nipper's Harbour site.

5.2 Induction Generator Selection

As described in Ch. 3.5, the rating of the induction machine in generator mode is normally taken to be the HP of the motor expressed in kW, thus a 150 kW generator requires a standard 200 HP squirrel cage induction motor. To minimise overspeed problems, a low speed machine is desirable, but one must keep in mind the efficiency and power factor will also be lower. As well, the cost of the motor is higher at lower speeds. The most common squirrel cage induction motor is the 4 pole machine, operating with a synchronous speed of 1800 rpm. While the 1200 rpm and 900 rpm induction motors are stock items, the 1200 rpm costs twice as much as the 1800 rpm, and the 900 rpm version costs two and a third times more. Also, reconditioned low speed induction motors are readily available at significant cost savings. For the Nipper's Harbour site, the 1200 rpm machine is acceptable.

To summarize, in most cases the best squirrel cage induction motor to select as an induction generator would be one that is a stock item, thus relatively inexpensive in comparison to a custom machine. Typically the ideal "off-the-shelf" machine would have low speed (1200 rpm), normal to low starting torque (EMAC Design B, or A), 1.15 Service Factor, a minimum of Class B insulation, high temperature rise, high efficiency rating (larger size, more copper, iron and steel), spherical roller bearings, and a drip-proof enclosure. The best combination of efficiency and power factor occurs when the induction machine is operated between 80% and 100% of the full load rating. The high efficiency 200 HP, 1200 rpm motor has a full load efficiency rating of 95% and a power factor of 90%. High efficiency motors typically carry a 20% price premium over the standard motor. Most modern EMAC Design B motors have an efficiency which is equal to, or almost equal to, the EMAC Design A motors, consequently the more common Design B motor is specified. Class F insulation and a 1.15 Service Factor will allow the motor to safely operate at a 170 kW rating when extra flow is available, maximizing revenue. The bearings of the induction generator should have a B-5 minimum life expectancy rating of 50,000 hours. The typical life expectancy of direct coupled applications is five times the B-5 rating, or 250,000 hours (28 years of continuous operation). A roller bearing with a B-10 rating of 100,000 hours is also available, and common on many turbines. The complete specifications for the induction generator are listed in Table 5.1.

Table 5.1 Specifications for the 200 HP Squirrel Cage Induction Motor used as a 150 kW Induction Generator.

Characteristic	Specifics
Motor Horsepower	200 HP
Generator Output	150 kW
Voltage Rating	575 V
Synchronous Speed	1200 rpm
Torque Rating	EMAC Design B
Service Factor	1.15
Insulation	Class F
Efficiency Rating	High Efficiency Type
Enclosure	Drip-Proof
Bearing Type & Rating	Spherical - B5

5.3 Major Electrical Equipment

The major electrical equipment, starting from the sub-station and working towards the powerhouse, includes the substation disconnect, transmission line, lightning arrestors, main transformer, station service transformer, and the starter/contactor. The single-line diagram of Figure 5.1 shows the major electrical components included between the interconnection point at the Nipper's Harbour substation and the induction generator at the power plant. The components are sized based on the specified induction generator size of 150 KW, 600 V, 3-phase, 3-wire. The relay numbers are explained in Table 5.2.

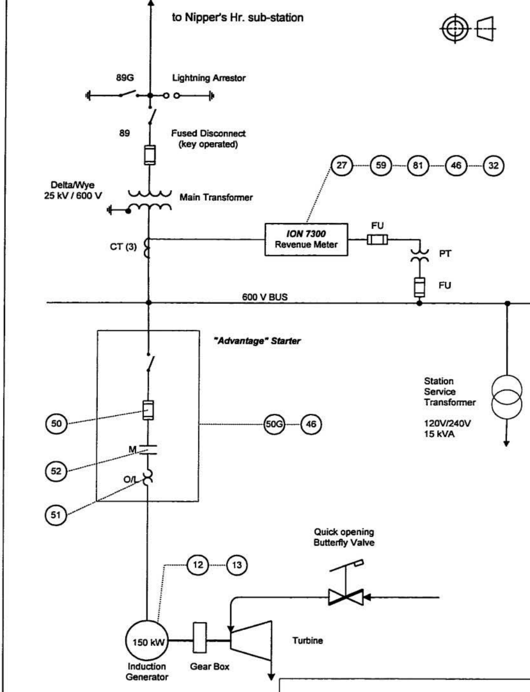

Figure 5.1 **Single Line Diagram**

Nipper's Harbour Mini-Hydro
150 kW Induction Generator

A three-phase gang-operated air-break load interrupting switch must be located at the point of interconnection to the distribution system [94]. The transformer used is connected to Hydro's standards to ensure the integrity of their line protection scheme. Ground fault protection for the distribution line is physically located at the Nipper's Harbour reclosure. Any variation from this connection scheme will be dictated by Hydro's standards applicable for the stated voltage and load.

Distribution transformers have a kVA rating which assumes a 0.8 power factor (pf). The transformer must be large enough to handle the induction generator rating plus a 25% safety factor. The station service load does not have to be included as part of the total load because the induction generator supplies the station load when on-line. If the stream has the potential to produce more power than 150 kW, a decision must be made with respect to the amount of spare transformer capacity to install. Nipper's Harbour is capable of supporting a 300 kW generator at 60% capacity factor. If Nfld. Hydro approves a staged development the extra capacity can be developed at a later date. At this point it is assumed that the installed capacity will remain at 150 KW, thus three single-phase, 50kVA, 25kV/600kV, ONAN, outdoor distribution transformers are specified.

The transformer connection is selected to ensure adequate protection of the transformers and transmission line from system faults. The 150 kW induction machine does not have an external neutral, thus the secondary of the main transformer will have to act as the grounded neutral for the power plant. A separate grounding transformer and grounding resistor are not warranted for a plant of this size. Given that a grounded secondary is necessary, the main transformer could have a wye-grounded primary/wye-grounded secondary or a delta-primary/wye-grounded secondary [94]. The former would apply when a 4-wire grounded feeder is used and the latter is preferred for three wire feeders. It is still uncertain as to the type of feeder (4-wire or 3-wire) to be used at Nipper's Harbour because the local fish plant may want to connect to the same feeder at a future date. For small transformers (i.e. 150 kVA) the only transformer protection required are fuses on the primary side and they are integrated with a ganged disconnect switch. Also, standard surge arrestors are needed on the high voltage side for surge protection. The surge arrestor protects the insulation on the transformer and motor windings from excessive voltage caused by lightning or switching problems. It should not be confused with the surge protector, which consists of a voltage limiting device in parallel with a capacitor and located in the motor terminal box.

The contactor/starter does double duty. It connects the induction generator to the grid and provides generator protection features. A Cutler-Hammer (Westinghouse) size-5 Advantage starter was selected. As described in Chapter 4, the solid-state starter circuitry minimizes contact bounce and drop-out problems. It also has accurate over-load protection, phase unbalance protection, and ground fault detection, yet costs the same as a standard motor starter with conventional over-load heaters. While the Advantage starter has communication capabilities, Cutler-Hammer has no immediate plans to offer this data to the user via a standard RS-232/RS-485 or DeviceNet port.

A 15 kVA station service transformer supplies the powerhouse lighting and heating load, using a 100 A single-phase 120V/240V distribution panel. There is no requirement for a three-phase station service for the Nipper's Harbour powerhouse. The optimum connection point, from a maintenance perspective, is on the primary side of one of the single-phase 50 kVA generator transformers. Such a connection point would only be appropriate if the transmission voltage was much lower (i.e. 4160 V) than the 25 kV at Nipper's Harbour. Separate revenue metering is required. The Nipper's Harbour station service transformer is connected to one phase of the 600V bus, between the generator breaker and the revenue metering. Power will not be available for transformer and/or substation maintenance work with this type of connection.

5.4 Protection Scheme

The overall protection scheme is shown in the single-line diagram in Fig. 5.1 and protective features listed in Table 5.2. It includes the required utility protection, generator protection, and mechanical protection. The Power Measurement ION 7300 meter is used as the approved utility kWh meter, and provides under-voltage

(27) over-voltage (59), under/over frequency (81), phase-unbalance (46) and reverse power (32) protection. As previously stated, the Advantage starter provides over-load protection (51), basic phase-unbalance protection (46), and ground fault detection (50G). Short circuit protection (50) and high level ground fault protection are handled by fuses located with the fusible disconnect in the combination starter. Power factor correction capacitors are not required since the full load power factor is close to 90%.

Table 5.2 Utility, Generator, and Mechanical Protection specified for the 150 kW Nipper's Harbour Mini-Hydro Plant.

Relay No.	Description	Device/Equipment
(12)	over-speed	MPU and Switch
(13)	under-speed	MPU and Switch
(27)	under-voltage	Power Measurement ION 7300
(59)	over-voltage	Power Measurement ION 7300
(32)	reverse power	Power Measurement ION 7300
(46)	phase unbalance	ION 7300 & Advantage Starter
(50)	instantaneous over-current	Westinghouse Advantage Starter
(50G)	Level II ground fault	Westinghouse Advantage Starter
(51)	sustained over-current	Westinghouse Advantage Starter
(52)	main contactor	Westinghouse Advantage Starter
(81)	over/under frequency	Power Measurement ION 7300

Mechanical protection consists of a magnetic pickup unit (MPU) and speed switch to detect the 95% synchronous speed condition and the 110% over-speed condition. A variety of speed switches and MPUs are available from Woodward Governor, Caterpillar and Thompson Technology. Vibration detection and bearing temperature sensors are not included. Neither Newfoundland Power, Newfoundland Hydro, nor Alberta Power implement vibration or bearing temperature monitoring on small grid connected plants.

5.5 Operational Modes

The Nipper's Harbour hydro plant will incorporate on/off level control, level control and manual load control, as described in Chapter 4.2. Water level sensors and a turbine level regulator are used to implement both forms of level control. Regulators, headwater level transmitters, and water level electrodes are available from a variety of sources, including ITT Flygt, Ossberger Turbines, and Woodward Controls. The operational procedures for safe start-up and shut-down are the same as described in Chapter 4.3.

5.6 Monitoring and Control Scheme

As described in Ch. 4.6 and Ch. 4.7, different levels of automation and remote monitoring are possible. Fig. 4.1 - Fig. 4.4 illustrate the configurations possible and all assume a PLC will be used to gather data and control the plant. Regardless of the level of automation desired, the mini-hydro plant control system must be designed to run without the PLC or SCADA system. The basic controls are initially hardwired, then advanced control and data acquisition features added as required.

As referenced in Ch. 4.6, the fundamentals of the control system are the Power Measurements ION 7300 meter and the PLC. The ION 7300 measures, detects and records kWh, kW, PF, I, V, phase unbalance, reverse power flow, under/over frequency, under/over voltage. The kWh totals from the meter must be available to the utility via the telephone system, consequently the single ION 7300 communications channel has to be connected to the telephone line switch. The ION 7300 will not be able to communicate directly with the PLC unless an additional communications port is added, at considerable expense. This is not a major drawback because the PLC doesn't need all of the information available from the ION. Also, the ION 7300 has four output contacts, configurable to be ON/OFF or pulsed. One contact is activated by either the under/over frequency, under/over voltage, phase unbalance, or reverse power flow. This contact is connected to both the hardwired control and the PLC. The second contact is a pulsed output, representing the kW load, which is connected to the counter input on the PLC.

The arrangement where the ION 7300 and the PLC do not communicate with each other directly corresponds to the layout outlined in Fig. 4.1. Also, a PC based graphical interface(MMI) located in the powerhouse is not essential, plus an automated system dependant on the PC to pass critical data to the PLC (Fig. 4.4) is not good design, thus a powerhouse PC is not included in the control scheme. The operator or technician takes the laptop PC when troubleshooting or interrogating the system on site. The laptop holds the PLC programming software, the ION 7300 configuration software, and in the future, the ION DDE server, PLC DDE server, and the expert system. It is also understood the off-site PC can dial in at any time to interrogate the ION 7300 or the PLC. Fig. 5.2 illustrates the preferred arrangement and equipment requirements. This automation scheme starts with the basic hardware and software, yet it can be easily expanded, mostly through software, to include the advanced features, including expert system diagnostics and a graphical operator interface(MMI).

As previously mentioned, the Nipper's Harbour control scheme includes on/off level control, level control and manual load control. The hardwired control scheme is specified in Fig. 5.3, and the PLC logic diagram is outlined in Fig. 5.4. Descriptions of the control system operation are recorded in Ch. 4.3, Ch. 4.6, and Ch. 4.7.

5.7 Special Considerations

There is an initial current of four to six times rated current when an EMAC Design B induction motor is started using an across-the-line motor starter. The startup current causes a voltage dip, which may affect the quality of the electrical supply to other utility customers. Nfld. Hydro has set a limit on the allowable voltage dip. Based on Newfoundland Hydro's voltage dip calculations, the maximum size of induction generator allowed on the 25 kV Nipper's Harbour feeder is 400 HP (300 kW).

When starting an induction generator the turbine/generator is brought up to 95% of synchronous speed before the contactor switch is closed. The duration of the resultant starting current is much less than that expected from a similar sized motor when started from stand-still. If the start-up procedure, as outlined in Ch. 4.3.1 is followed, the application of a full voltage non-reversing (FVNR) Advantage starter is acceptable to Newfoundland Hydro.

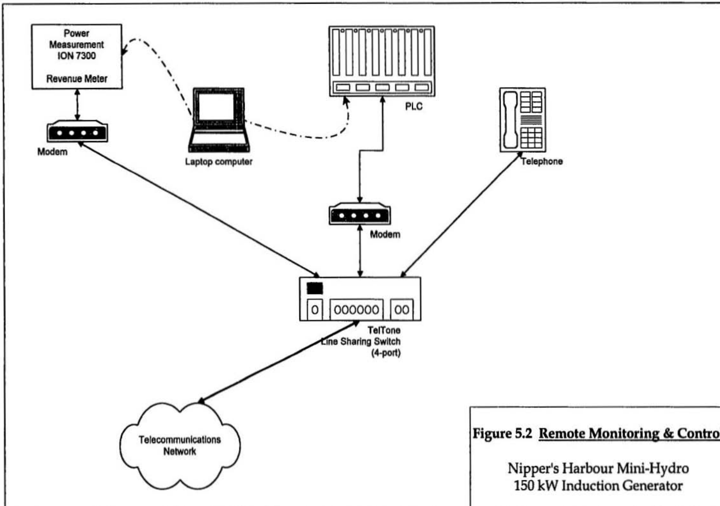

Figure 5.2 **Remote Monitoring & Control**

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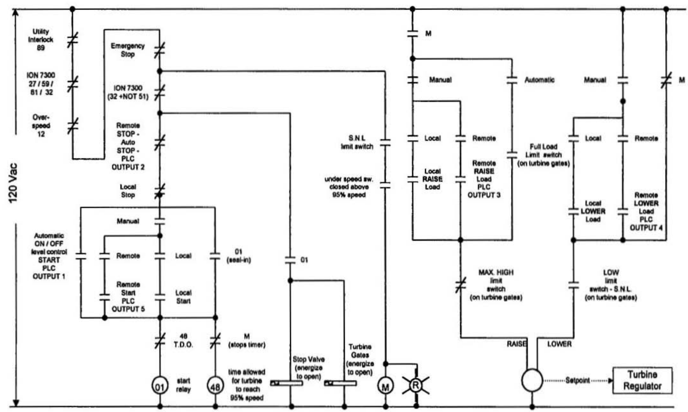

Figure 5.3 Control Schematic
Nipper's Harbour Mini-Hydro
150 kW Induction Generator

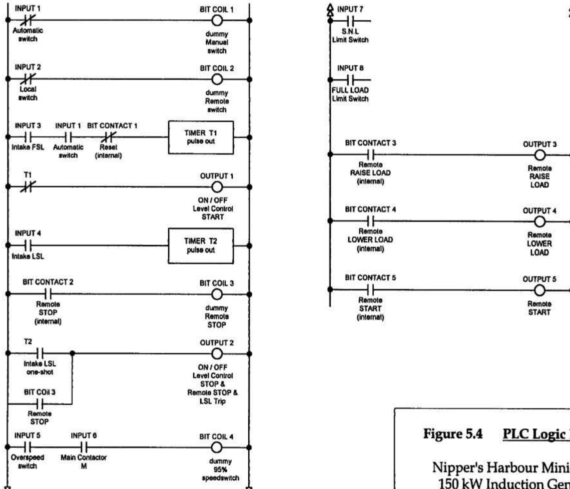

Figure 5.4 **PLC Logic Diagram**

Nipper's Harbour Mini-Hydro
150 kW Induction Generator

Chapter 6

Summary and Conclusions

The increasing demand for electricity is best addressed by first encouraging energy conservation, then developing small-scale renewable energy sources like solar, wind, wave, and mini-hydro. Very little attention has been given to grid connected mini-hydro because the economies of scale tend to favour larger developments. Therefore, in this study the focus was on developing and documenting a systems approach toward modern electrical design that minimized the cost of building and operating a grid-connected mini-hydro plant. Design costs are reduced by following a multi- disciplined engineering approach, the cost of the electrical equipment package is diminished by selecting a standard squirrel cage induction motor as the grid-connected induction generator, the operating costs are cutback by automating the plant to eliminate the cost of a full-time operator, and maintenance costs are reduced by incorporating a diagnostic expert system to assist in isolating the cause of a plant shutdown. To summarize, the stated objective was to develop a systems approach and documentation of modern electrical design and operating methods for a grid-connected, remotely controlled and automated mini-hydro plant, one which used a standard three-phase induction motor as an induction generator.

Chapter 2 covered the general design of mini-hydro systems. Knowing when to use an induction generator, and the type of control philosophy to implement, is based on the assumption the electrical designer has a good understanding of all aspects of a mini-hydro development. This includes the regulatory process, environmental issues, site selection, site hydrology, power and energy estimate, rates, and economic evaluation. While this section is not an exhaustive treatment of the subject matter, it is an indication of the level of understanding required of the electrical engineer.

The purpose of Chapter 3 is to document the theory, performance characteristics, and design considerations associated with an induction generator installation at a mini-hydro site. This information was required to evaluate the appropriateness of installing an induction generator at a grid-connected location. The advantages and disadvantages of a grid-connected induction generator were discussed and the principle of operation of the induction machine reviewed. Procedures were developed to perform a steady state analysis of an installed induction generator. The performance of the induction machine under normal load, both as a motor and as a generator, has been evaluated, with the results in close agreement with the stated manufacturer's machine parameters [72]. Values for stator current, torque, efficiency, power factor, rated load, maximum efficiency, breakdown torque and maximum power output were derived or calculated. The induction generator short circuit performance was reviewed, while over-speed and over-excitation problems were identified and remedial action proposed. Finally, a method was presented for selecting a standard squirrel cage induction motor to use as an induction generator. Common concerns, limitations, and favourable motor characteristics were documented.

Chapter 4 has introduced flow control and load control methods encountered in a mini-hydro plant equipped with an induction generator. The important plant operational procedures, including manual start-up, normal shutdown, and emergency shutdown, were developed and reviewed in light of their effect on the induction motor used as a generator. Induction generator protection requirements, utility protection, and mechanical systems protection were also investigated, and modern solutions proposed. In Section 4.6 the PLC was used to automate the plant by incorporating the control and protection schemes. Cost-effective remote control options were also explored. Finally, an innovative and novel diagnostics expert system was developed and demonstrated using the Roddickton mini-hydro plant as an example.

Chapter 5 applied the systems approach and documentation of modern electrical design and operating methods to a practical design example. Three potential grid-connected mini-hydro sites on the island of Newfoundland were compared in Chapter 2 and one, Nipper's Harbour, selected for development. The detailed electrical design was completed for the Nipper's Harbour site, using the systems approach documented in Chapter 3 and Chapter 4. First, the appropriate three-phase induction motor, which operates as a generator, was specified. Then, operational procedures were identified and protection and control systems designed. The single line diagram, remote control layout, and control logic diagram were finalized for the Nipper's Harbour site and all electrical equipment, control hardware and software specified.

To summarize, the major contributions and innovative aspects of this thesis are:

- applies innovative electrical design to reduce capital costs, lower operating costs, increase efficiency, and maximize revenue of a grid-connected mini-hydro plant,

- has produced a comprehensive document which takes the informed reader from the theoretical analysis of induction machines through to a practical design and implementation of an induction generator in a grid-connected mini-hydro installation,

- documents a simple procedure to be used by multi-disciplined engineers for predicting the induction machine performance characteristics under normal load, both as a motor and as a generator. The method incorporates basic circuit analysis techniques, the widely available MathCad software, and the machine data supplied by the manufacturer,

- clearly establishes the characteristics and limitations associated with using a squirrel cage induction motor as an induction generator,

- applies new protection methods and equipment to grid-connected induction generators,

- demonstrates the effectiveness of using micro-PLCs to implement inexpensive remote monitoring and control capability,

- introduces an innovative diagnostic expert system to quickly determine the cause of a plant shutdown.

The major conclusions of this study are;

- A significant reduction in the capital cost of electrical equipment is achievable if a squirrel cage induction motor is used as induction generator. The "off-the-shelf" induction motor and standard solid-state motor starter are relatively inexpensive in comparison to custom induction or synchronous generators.

- Induction generators are the most cost effective when the installed capacity of the mini-hydro plant is less than 150 kW.

- The efficiency of the induction machine as a generator is almost equal to the efficiency when operating in motor mode, assuming the generator rating is equal to the motor HP rating.

- The ideal "off-the-shelf" induction motor to select as an induction generator has low speed (1200 rpm), normal to low starting torque (EMAC Design B), 1.15 Service Factor, a minimum of Class B insulation, high temperature rise, high efficiency rating (larger size, more copper, iron and steel), spherical roller bearings, and a drip-proof enclosure.

- Automatic operation and control is a necessity, even for the smallest plant, because the cost of a full-time operator would make the mini-hydro plant uneconomical.

- The basic mini-hydro plant control system still has to be hard-wired, to ensure continued production in the event of a PLC or communications failure.

- Expert system diagnostics is an important monitoring feature since problems only occur occasionally (hopefully), preventing the plant operator from gathering and retaining useful troubleshooting experience.

- It is important to have expert system shells (i.e. Comdale/X) that integrate drivers which allow easy access to data from PLCs and field instruments. The natural language expert system shells (i.e. EXSYS Professional) are easier to program but typically have cumbersome methods of collecting real-time field data.

Suggestions for future work are;

- Research and test the overspeed capability of "off-the-shelf" squirrel cage induction motors. The manufacturers are hesitant to endorse an overspeed rating greater than 125% of rated speed, yet experienced field personnel report sustained overspeed of 200% without problems.

- Investigate and test running multiple RS-485 protocols, at the same time, using different manufacturers equipment connected to the same RS-485 loop.

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Appendix A

Application for Water Use Authorization - Nipper's Harbour

GOVERNMENT OF NEWFOUNDLAND AND LABRADOR
DEPARTMENT OF ENVIRONMENT AND LANDS
P. O. Box 8700
St. John's, NF
A1B 4J6

Water Resources Management Division

March 30, 1993

Mr. Norris Eaton
Hydropower Resources Inc.
7 Welldale
Pasadena, NF.
A0l 1KO

Dear Mr. Eaton:

RE: Preliminary Licence # 93-08 (Preliminary Water Use Authorization)

Your application for preliminary water use authorization for the proposed hydroelectric project in Nipper's Harbour has been approved pursuant to Section 21 of *The Department of Environment and Lands Act*. Please find enclosed the Preliminary Licence (Water Use Authorization # 93-08) which is subject to the terms and conditions as set out in Appendix A. Also enclosed is a copy of "*Guidelines Regarding Application for Water Use Authorization (Water Use Licence) for A Hydroelectric Project*".

Please feel free to contact me at 729-4795 if you have any questions.

Yours truly,

SHAHBAZ MIAN
Water Rights Section

Enclosure

GOVERNMENT OF NEWFOUNDLAND AND LABRADOR
DEPARTMENT OF ENVIRONMENT AND LANDS

PRELIMINARY WATER USE AUTHORIZATION (PRELIMINARY LICENCE) FOR A HYDROELECTRIC DEVELOPMENT PROJECT

Issued in accordance with the provisions of the *Department of Environment and Lands Act*

e: March 9, 1993

No: 93-08
File No: 179-91

ensee: Hydropower Resources Inc.
7 Wellsdale
Pasadena, NF
A0L 1K0

ention: Mr. Norris Eaton

Hydroelectric Development Project in the Electorial District of Baie Verte-White Bay, Newfoundland

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eference to the application dated November 10, 1992, authorization is hereby given, for eriod of one (1) year, to secure data and undertake relevant surveys and field estigations in the area described in Appendix B, for the purposes of evaluating the ibility of the project and subsequently filing an application for a Final Water Use horization (Water Use Licence) for the proposed hydroelectric development project on stream flowing into Nipper's Harbour, which includes the drainage system fed by Pine d, Buskam Pond, Gulf Pond, Greenwood Pond, Saddler Pond, Nippers Harbour Pond Noble Pond (Schedule A).

s Preliminary Licence is subject to the terms and conditions indicated in Appendix A ached).

lure to comply with these terms and conditions will render this licence null and void, e the Licensee and its agent(s) in violation of the *Department of Environment and Lands* , and make the Licensee responsible for any remedial measures which might be prescribed this Department.

MINISTER

GOVERNMENT OF NEWFOUNDLAND AND LABRADOR
DEPARTMENT OF ENVIRONMENT AND LANDS

APPENDIX A

No: 93-08 File No: 179-91

TERMS AND CONDITIONS FOR PRELIMINARY WATER USE AUTHORIZATION (PRELIMINARY LICENCE)

1. This Preliminary Licence will expire on April 1, 1994, or earlier if suspended or cancelled by the Minister of Environment and Lands upon notification to the Licensee, its agent or the person designated by the Licensee.

2. This Preliminary Licence only provides permission for the Licensee to have access, to the extent necessary, to the watershed (Appendix B) in order to undertake field investigations, surveys and other related studies required to file an application for water use licence.

3. This Preliminary Licence does not release the Licensee from the obligation to seek appropriate approvals or permits from other concerned federal or provincial agencies, municipalities or individuals to enter upon, investigate and survey the Crown or private lands for the exclusive purpose incidental to hydropower potential of the proposed site.

4. This Preliminary Licence is subject to rights of water use conferred by or under any statute of the province or a valid grant, lease or other instrument and the Licensee shall inform all existing water users within the watershed of the proposed hydropower development and to the extent possible resolve any conflict that might emerge and appropriate notification of such resolutions shall be provided in writing to the Water Rights Section of this department.

5. This Preliminary Licence cannot be sold, transferred, assigned or otherwise alienated by the Licensee.

6. This Preliminary Licence does not confer the right and liberty to explore, prospect, search for, carry away and dispose of any mineral or use of any other natural resource in the watershed during the term of this Preliminary Licence.

7. The Licensee or its agents shall immediately proceed with relevant investigations, comprehensive surveys and data collection to accurately define hydrologic characteristics of the watershed, examine alternative conceptual designs and undertake environmental impact studies and complete the required assessment before the expiry of this Preliminary Licence.

GOVERNMENT OF NEWFOUNDLAND AND LABRADOR
DEPARTMENT OF ENVIRONMENT AND LANDS

APPENDIX A

No: 93-08 File No: 179-91

TERMS AND CONDITIONS FOR
PRELIMINARY WATER USE AUTHORIZATION (PRELIMINARY LICENCE)

8. The Licensee shall provide to this department a synopsis of the planned surveys, investigations and activities, name(s) of consultant(s) engaged for the feasibility study, terms of reference and its tentative date of completion within three months from the date of this Preliminary Licence.

9. The Licensee shall submit a report every three months containing information on the progress of various components of the feasibility study.

10. The feasibility study shall be completed and an application for water use licence be filed with the Water Rights Section before expiration of Preliminary Licence.

11. The issuance of a water use licence shall depend on the quality of the proposed project in terms of multiple and optimum utilization of the available water resource, minimal environmental disruption and land and water use conflicts, and any other factors that the Minister may consider pertinent in the public interest.

12. The Licensee shall submit the general plans, specifications and other information of the works comprising the development in such form and detail as required by the Minister under Section 27 of the *Department of Environment and Lands Act*, before the expiry of this Preliminary Licence.

13. The Licensee shall pay any administrative fees that the Minister may assess for the issuance of the preliminary and water use licence and charges for using water based on rates approved by government any time in the future.

14. The Licensee or its agents shall not undertake construction of any works until a Water Use Licence is issued by the Minister.

GOVERNMENT OF NEWFOUNDLAND AND LABRADOR
DEPARTMENT OF ENVIRONMENT AND LAND

APPENDIX B

LEGAL DESCRIPTION OF PROPOSED
HYDROELECTRIC DEVELOPMENT IN NIPPERS HARBOUR WATERSHED

The drainage area, subject to **Preliminary Licence 93-08** in the Electorial District of Baie Verte - White Bay, is herein defined by metric coordinates, as referenced to the North American Datum of 1927, in Zone 21 of the Universal Transverse Mercator mapping projection. The said drainage area is bounded as follows:

Beginning at a coordinate point number 1 being the proposed dam site at Nippers Harbour and having coordinates **581610** East, and **5516710** North; thence by sequential clockwise lines as defined by the following coordinates:

To Point	East Coordinate	North Coordinate
2	581510	5516770
3	581300	5516850
4	580560	5516760
5	580100	5516560
6	578680	5516440
7	577270	5516090
8	577040	5516620
9	576580	5516730
10	576040	5516930
11	575300	5517820
12	575950	5518160
13	576060	5518570
14	576400	5518810
15	576230	5519150
16	576280	5520140
17	576630	5520570
18	576660	5521130
19	577120	5521260
20	577500	5521560
21	577530	5522030
22	578040	5522220
23	579090	5522090
24	579180	5522300
25	579720	5522710
26	580180	5522550
27	581150	5522960

GOVERNMENT OF NEWFOUNDLAND AND LABRADOR
DEPARTMENT OF ENVIRONMENT AND LAND

APPENDIX B

LEGAL DESCRIPTION OF PROPOSED
HYDROELECTRIC DEVELOPMENT IN NIPPERS HARBOUR WATERSHED

To Point	East Coordinate	North Coordinate
28	581020	5523450
29	581620	5523770
30	581680	5524110
31	582220	5524200
32	582550	5523920
33	582460	5523400
34	582150	5522790
35	582240	5522170
36	581730	5521450
37	581840	5520890
38	582230	5520290
39	581780	5519960
40	581830	5519720
41	582120	5518830
42	581820	5518580
43	582490	5518170
44	582530	5517870
45	582720	5517550
46	582610	5517030
47	581790	5516910

and thence by a line to the point of beginning. The drainage area is illustrated on the attached diagram as plotted on a portion of NTS map 2E/13.


Schedule "A"
Proposed Dam Site
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North Yak Lake
South Yak Lake
Nippers Harbour Pond
Greenwood Pond
Gull Pond
Saddler Pond
Buskam Pond
Noble Pond
Pine Pond
Burtons Big Pond
Father Sheehan Pond
Burtons Pond
Black Lookout
Nippers Harbour
Jigging Head
Harbour Point
Candlemas Head
Bluff
Noble C
Noble Head
Green I
Alexander Rock
Riding I
Gull Rocks
NIPPERS ISLANDS
Fox I
Duck I
Seal I
Welshs Bight
Bear Cove Head
Bear C
Green Head
Northwest Arm
Hammer Head
Rogues Harbour
Rogues Harbour Point
Sawmill
Dump
172

GOVERNMENT OF NEWFOUNDLAND AND LABRADOR
DEPARTMENT OF ENVIRONMENT AND LANDS

APPENDIX C

No: 93-08
File No: 179/91
First Approved: March, 1993

QUARTERLY PROGRESS REPORT TO DEPARTMENT OF ENVIRONMENT AND LANDS

This report must be filed with the Water Resources Division, Department of Environment and Lands, on a quarterly basis or the authorization will be cancelled. Please provide the information required below:

1. Name of Applicant: ______________________________

2. Is this a new or changed name? (Y/N) ______________________________

3. Name and title of (natural) person responsible for administering the Preliminary Licence.

____

4. Mailing address: ______________________________

5. Office address or location for service (if different from mailing address):

____

6. Telephone no: ______________________________

7. Fax no: ______________________________

8. Has the Licensee carried out any investigations during the past three (3) months? If so, please submit a detailed report.

9. Is there any other matter the Licensee wishes to inform the Department of Environment and Lands about with regard to this Preliminary Licence? (Y/N). If yes, explain.

____

____

10. Person named in #3 shall sign and date this form. Send to:

Department of Environment and Lands
Water Resources Division
P.O. Box 8700
St. John's, NF A1B 4J6
(709) 729-4795

Signature: ______________________________

Title: ______________________________

Date: ______________________________

Appendix B

Hydrological Analysis - Nipper's Harbour

The Nipper's Harbour development is a run-of-river project located on an ungauged stream near Nipper's Harbour on the Baie Verte peninsula. Energy calculations require knowledge of the mean flow and the shape of the flow duration curve. A synthesized time series of daily flows is generated using stream flow data from the South West Brook gauging station (No. 02YM003).

The stream-flow analysis methodology used follows the procedures outlined in a series of studies completed in 1988 by Acres International for the Inland Waters Directorate, Environment Canada [62,63]. The studies recommend generating the synthesized time series of daily flows by prorating on drainage area and mean annual run-off.

The production records of the near-by Snook's Arm plant were used to calculate the mean annual run-off (MAR). It is located 13 kilometres from Nipper's Harbour and has similar site characteristics and physiographic features. The MAR for Nipper's Harbour was assumed to be the same as the Snook's Arm MAR.

The flood flow estimates were calculated using the methods outlined in the report, ***Regional Flood Frequency Analysis For The Island of Newfoundland*** [64,65,66]. The techniques given in a similar report, ***Estimation of Low Flows in Newfoundland*** was used to predict the expected low flows at the Nipper's Harbour site [67].

B.1 Drainage Area

The drainage area is 33.8 km^2, determined by planimetry from the 1:50,000 scale topographical map 2E/13 (Nipper's Harbour).

B.2 Flow Synthesis

Synthesized flow records for an unguaged stream can be created using two methods, as outlined in the references [62,63]:

- proration on Drainage Area and Mean Annual Run-off.
- Regional Non-dimensional Flow Duration Curves.

The Acres report[62] recommends the proration method or the regional flow duration curve method for sites of interest in Newfoundland. The proration method was used at Nipper's Harbour. The hydrometric station at South West

Brook near Baie Verte (No. 02YM003), was selected as the reference station based on proximity, exposure to a similar climatic zone, and similar physiographic characteristics. Fifteen years of daily flow records (1980-1994) are available for South West Brook. The next closest unregulated gauged stream with a long period of record is Sheffeld Brook (No. 02YK005). It was not used as the reference station because of the distance from the Nipper's Harbour site (90 km), the drainage area (391 km^2) is much larger than the Nipper's Harbour catchment area (33.8 km^2), and the large natural storage provided by Sheffield Lake will cause Sheffield River to exhibit significantly different flow behaviour.

Mean daily discharges for South West Brook (No. 02YM003) were obtained as an ASCII file, on disk, from the Water Survey of Canada (WSC) [68]. The WSC Streamflow Toolkit software was used to generate the flow duration curve data table. The curve was defined using 100 points, one for each percentage of flow exceedence. The flow duration curve data file was exported to a spreadsheet, to be used later in an analysis of the energy available at the site.

It is assumed that the flow duration curve shape for Nipper's Harbour is similar to the flow duration curve produced for South West Brook. The data points defining the curve at Nipper's Harbour were derived by prorating each of the South West Brook flows on the basis of drainage area and mean annual run-off (MAR).

B.3 Determining the Mean Annual Run-off

The standard procedure to determine the MAR at the unguaged site is to refer to the Newfoundland Mean Annual Run-off (MAR) map, produced by Inland Waters Directorate, Environment Canada. The 500 mm isoline intersects the centroid of the drainage area at both the Nipper's Harbour and the existing hydro plant at Snook's Arm. The map shows South West Brook near Baie Verte with a MAR of 650 mm. An analysis of the production records at Snook's Arm produced a MAR of 725 mm. The MAR at South West Brook, calculated from the 1980-1990 stream flow records, is 842 mm.

The discrepancy between the values from the MAR map and the calculated values are caused by the inherent errors in the MAR map, which is a result of the lack of data at the time the MAR map was produced in 1984. According to Mr. Don Ambler, (Regional Hydrologist, Water Resources Branch, Halifax, NS) the only data available at that time for the Baie Verte peninsula area was the climatic data collected at Baie Verte. South West Brook only had four complete years of stream flow records in 1984. The Snook's Arm hydro plant production information was not used to create the MAR map.

The value of MAR used for Nippers Harbour in this report is the value calculated using the Snook's Arm production records (725 mm). A MAR of 842 mm, based on the available WSC stream flow records, is the value used for South West Brook.

B.4 MAR from the Snook's Arm Production Data

The Snook's Arm production records, along with plant specifications, were used to calculate the annual mean flow at Snook's Arm. The resultant MAR for the site was used as the MAR for Nipper's Harbour.

The Snook's Arm (560 kW) and Venam's Bight (360 kW) mini-hydro plants were built in 1957 to supply electric power to the Tilt Cove Mine. The plants were isolated from the island grid at the time of construction and were designed with significant storage capacity. The mine was closed down on June 20th, 1967 and the plants sold to Nfld. Hydro.

The plant specifications, when built, show a gross head of 284 ft., net head of 243 ft, rated turbine flow of 0.946 m^3/sec, full load turbine efficiency of 85%, penstock length of 3075 ft, a woodstave penstock diameter of 30 inches, drainage area of 30.1 km^2, and a storage volume of $7.6x10^6$ m^3. No modifications to dams or equipment have been made since the plant was built. It is assumed the generator efficiency is 96%, transformer efficiency is 99%, plant efficiency is 99%, producing an overall efficiency of 80%.

The available production records at the Snook's Arm mini-hydro plant indicate that the average annual energy production is 3,491,000 kWhr. Based on the energy produced and the installed capacity of 560 kW, the capacity factor is 71% and the average annual power production is 398.4 kW. The flow producing the average annual power of 398.4 kW is the useful flow. It is only slightly less than the mean flow, mainly because of the storage capacity created by damming four ponds within the Snook's Arm catchment area. The useful flow calculated for Snook's Arm is 0.655 m^3/sec.

The useful flow and mean flow have been derived from the production records and the original quoted plant specifications. Less flow was required to produce the rated power when the equipment was new. The combination of recent production records, original equipment specifications, an optimistic estimate of the overall efficiency (80%) and net head (77 m), and maximum plant operating time (365 days x 24 hrs), will result in a conservative estimate of the useful flow.

The average flow (Q_{mean}) will be higher than the useful flow. How much higher depends on the storage capacity of the site. If there is no spillage throughout the year then Q_{mean} equals the useful flow. There is a small amount of spillage at Snook's Arm during the spring run-off. Snook's Arm has a storage volume of 7.6×10^6 m^3, which translates to a storage factor of 0.37 and a useful flow ratio of 0.95. With the storage capacity given, the average flow (Q_{mean}) at Snook's Arm is 0.69 m^3/sec. Based on the average flow and the Snook's Arm drainage area, the mean annual run-off is 725 mm.

B.5 Flood Flow Estimates

Estimates of flood flows must be determined for the safe design of the dam and to reduce the risk of damage caused by flooding. The design flood and diversion flood return period are selected based on the perceived risk.

The Nipper's Harbour site is classified as low risk, since there is no risk of damage to downstream property or loss of life, the timber-crib dam can be safely overtopped, and reconstruction costs would not be excessive. Thus, the recommended design flood return period is 100 years, and the recommended diversion flood return period is 10 years.

The design flood and diversion flood for Nipper's Harbour were estimated using the procedures and software outlined in the report "*Regional Flood Frequency Analysis for the island of Newfoundland (1990)*" [64]. The report recommends using regional flood frequency analysis at unguaged sites and single station flood frequency analysis at sites near a hydrometric station on the same stream. Since Nipper's Harbour is not on a gauged stream, regional flood frequency analysis was used.

Nipper's Harbour is located in the Central Newfoundland Hydrologic Region (Region B) [64]. The regression equations in Region B used to estimate peak flows are only dependant on two physiographic characteristics, watershed area (DA) and drainage density (DRD). DRD is determined by dividing the total length of all streams in the watershed by the drainage area. Region B has the lowest standard error of all four regions identified on the island of Newfoundland. Nipper's Harbour has a drainage area (DA) of 33.8 km and a drainage density (DRD) of 1.07 1/km.

The results of the spreadsheet analysis (software being provided with Reference 64), indicated the 100-year design flood for Nipper's Harbour is 25 m^3/sec, and the 10-year diversion flood is 19 m^3/sec. The results of the software run produced a cautionary message questioning the reliability of the estimated flood flows. The drainage area at Nippers Harbour (33.8 km) was below the minimum acceptable drainage area for the Central Region (36.7 km). The author of the report, A.K. Beersing, was contacted. According to Mr. Beersing the results are valid if the drainage area is close to the lower limit and a large portion of the drainage area is controlled by lakes and swamps. The Nipper's Harbour drainage area has 95% of the watershed controlled by lakes and swamps. The results are considered as valid as any derived from prorating from the closest gauged stream, South West Brook (No. 02YM003).

B.6 Low Flow Estimates

An estimate of the low flows expected at the site is important in determining the firm capacity of a run-of-river mini-hydro installation. The estimated 2-year 7-day low flows, and the estimated 10-year 7-day low flows, are needed for the Water Use Authorization application[60], required by the Water Resources Division of the Department of Environment and Lands.

Unless the site of interest is on a gauged stream, it is difficult to estimate the low flows. Sometimes the initial estimate of the low flow is taken as the 95% exceedence flow shown on the flow duration curve. A better estimate of the low flows is found using the procedures and software outlined in the report "Estimation of Low Flows in Newfoundland (1991)" by A. K. Beersing [67]. The report presents a series of regional regression equations which were derived from the analysis of thirty-nine gauging stations on the island of Newfoundland. A spreadsheet uses the equations to estimate the low flows of several duration and return periods at unguaged streams.

The regression equations in the Central Newfoundland Region used to estimate low flows are dependant on one physiographic characteristic, the watershed area of Nipper's Harbour (33.8 km^2). For the Nipper's Harbour location, the software produced an estimated 2-year 7-day low flow of 0.066 m^3/s and an estimated 10-year 7-day low flow of 0.005 m^3/s.

B.7 Forebay Pondage

The natural head-pond at the Nipper's Harbour site will be enlarged slightly when the timber-crib dam is built. The low supply level (LSL) elevation is 88.7 m and the full supply level (FSL) is 89.7 m. The calculated maximum ice thickness of 1.0 m, and intake submergence of 1.2 m, means there will be negligible storage (less than one day) available during the winter. Regardless of the available storage, water levels in the forebay should be kept constant during the winter to prevent operational problems caused by a shifting ice cover.

The surface area of the forebay is determined by planimetry from the 1:1000 scale, 2 meter contour map produced for the area. The surface area at the FSL elevation of 89.7 m is 39,500 m^2, and at the LSL elevation of 88.7 m it is 38,100 m^2. The storage volume is 38,700 m^3. Given an installed capacity of 650 kW, a rated flow of 0.911 m^3/s, and minimum inflow conditions, the plant could run for 12 hours on the storage available.

Appendix C

Energy Calculation Spreadsheet - Nipper's Harbour

NIPPER'S HARBOUR MINI-HYDRO

SITE DATA

Instal. Capacity	650	kw
Cal. Capacity	650	kw
Mean Flow	0.772	m3/s

PENSTOCK INFORMATION

	Upper Section		Lower	Overall
Penstock Length	165	m	346	490
Penstock Dia.	0.711	m	0.813	n/a

HEAD INFORMATION

Dam Height	4	m
Headpond Elev.	90.2	m
Tailwater Elev.	1	m
Gross Head	89.2	m
Net Head	86.3	m

PRODUCTION DATA

	RUN-OF-RIVER		STORAGE	
Maximum Possible	4,887,995	kwh	4,887,995	kwh (85% eff.)
Energy Available	4,668,061	kwh	4,668,061	kwh
Spillage Loss	2,342,765	kwh	233,403	kwh
Production	2,325,295	kwh	4,434,658	kwh
C.F.	41%		78%	
Cents per kwh	$0.063		$0.063	
Revenue	$146,494		$279,383	

TURBINE FLOWS

Rated Tur.Flow	0.906	m3/s
Min. Tur. Flow	0%	
Max. Tur. Flow	110%	

TURBINE EFFICENCY

Full Load	90%
75% Load	79%
50% Load	70%
30% Load	50%

EFFICENCY RATINGS

Gen. Eff.	96%
Plant Eff.	99%
Trans. Eff.	99%

FRICTION RATINGS

	Upper Section		Lower	Overall
Velocity	2.28	m/sec	1.75	n/a
Reynolds No.	1.4E+06		1.3E+06	n/a
Abs. Roughness	0.03	mm stl	0.03	n/a
Rel. Roughness	0.00004		0.00004	n/a
Friction Factor	0.012		0.0116	n/a

Flow Duration Curve Data
South West Brook
(near Baie Verte)

Exceedance (%)	Flow (m3/s)	Volume (m3)
0	72.800	22958208
1	24.000	15263424
2	18.200	5739552
3	14.600	4604256
4	12.000	3784320
5	10.700	3374352
6	9.560	3014842
7	8.520	2686867
8	7.600	2396736
9	6.850	2160216
10	6.200	1955232
11	5.580	1759709
12	5.120	1614643
13	4.720	1488499
14	4.350	1371816
15	4.040	1274054
16	3.760	1185754
17	3.460	1091146
18	3.200	1009152
19	2.990	942926
20	2.800	883008
21	2.640	832550
22	2.510	791554
23	2.390	753710
24	2.270	715867
25	2.150	678024
26	2.060	649642
27	1.970	621259
28	1.890	596030
29	1.820	573955
30	1.740	548726
31	1.650	520344
32	1.580	498269
33	1.510	476194
34	1.460	460426
35	1.410	444658
36	1.360	428890
37	1.310	413122
38	1.270	400507
39	1.230	387893
40	1.190	375278
41	1.150	362664
42	1.110	350050
43	1.080	340589
44	1.040	327974
45	1.010	318514
46	0.985	310630
47	0.957	301800
48	0.929	292969
49	0.902	284455

Flow Duration Curve Data
Nipper's Harbour

Exceedance (%)	Flow (m3/s)	Volume (m3)
0	22.733	7169101
1	7.494	4766270
2	5.683	1792275
3	4.559	1437759
4	3.747	1181720
5	3.341	1053700
6	2.985	941437
7	2.661	839021
8	2.373	748423
9	2.139	674565
10	1.936	610555
11	1.742	549500
12	1.599	504200
13	1.474	464810
14	1.358	428373
15	1.262	397846
16	1.174	370272
17	1.080	340729
18	0.999	315125
19	0.934	294445
20	0.874	275735
21	0.824	259978
22	0.784	247176
23	0.746	235359
24	0.709	223542
25	0.671	211725
26	0.643	202862
27	0.615	193999
28	0.590	186121
29	0.568	179228
30	0.543	171349
31	0.515	162486
32	0.493	155593
33	0.472	148700
34	0.456	143776
35	0.440	138852
36	0.425	133928
37	0.409	129004
38	0.397	125065
39	0.384	121126
40	0.372	117187
41	0.359	113248
42	0.347	109309
43	0.337	106355
44	0.325	102416
45	0.315	99461
46	0.308	97000
47	0.299	94242
48	0.290	91485
49	0.282	88826

50	0.874	275625
51	0.846	266795
52	0.817	257649
53	0.790	249134
54	0.764	240935
55	0.741	233682
56	0.720	227059
57	0.699	220437
58	0.675	212868
59	0.649	204669
60	0.624	196785
61	0.600	189216
62	0.579	182593
63	0.560	176602
64	0.542	170925
65	0.524	165249
66	0.507	159888
67	0.489	154211
68	0.469	147904
69	0.451	142227
70	0.434	136866
71	0.419	132136
72	0.403	127090
73	0.387	122044
74	0.371	116999
75	0.356	112268
76	0.341	107538
77	0.327	103123
78	0.313	98708
79	0.300	94608
80	0.285	89878
81	0.271	85463
82	0.257	81048
83	0.244	76948
84	0.233	73479
85	0.223	70325
86	0.213	67172
87	0.202	63703
88	0.191	60234
89	0.179	56449
90	0.167	52665
91	0.153	48250
92	0.140	44150
93	0.127	40051
94	0.107	33744
95	0.092	29013
96	0.082	25860
97	0.062	19552
98	0.042	13245
99	0.025	7884
100	0.002	631

Anual Mean	2.471	m3/sec
MAR	836	mm

50	0.273	86069
51	0.264	83311
52	0.255	80455
53	0.247	77797
54	0.239	75236
55	0.231	72971
56	0.225	70903
57	0.218	68835
58	0.211	66472
59	0.203	63911
60	0.195	61449
61	0.187	59086
62	0.181	57018
63	0.175	55147
64	0.169	53374
65	0.164	51602
66	0.158	49928
67	0.153	48155
68	0.146	46186
69	0.141	44413
70	0.136	42739
71	0.131	41262
72	0.126	39686
73	0.121	38110
74	0.116	36535
75	0.111	35058
76	0.106	33581
77	0.102	32202
78	0.098	30823
79	0.094	29543
80	0.089	28066
81	0.085	26687
82	0.080	25309
83	0.076	24028
84	0.073	22945
85	0.070	21960
86	0.067	20976
87	0.063	19892
88	0.060	18809
89	0.056	17627
90	0.052	16446
91	0.048	15067
92	0.044	13787
93	0.040	12507
94	0.033	10537
95	0.029	9060
96	0.026	8075
97	0.019	6106
98	0.013	4136
99	0.008	2462
100	0.001	197

Anual Mean	**0.772**	**m3/sec**
MAR	**720**	**mm**

Turbine Flow (m3/s)	Upper Penstock Losses (m)	Lower Penstock Losses (m)	Head Losses (m)	Head Losses (%)	Net Head (m)	Turbine Eff. (%)	Overall Eff. (%)	Power (Kw)	Energy Produced (kwh)	Energy Lost (kwh)	Maximum Possible (kwh)
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	1,365,778	1,433,799
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	887,024	953,240
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	294,469	358,450
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	223,833	287,548
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	172,818	236,340
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	147,311	210,737
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	124,943	188,285
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	104,537	167,802
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	86,486	149,682
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	71,770	134,911
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	59,016	122,109
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	46,851	109,898
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	37,826	100,839
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	29,977	92,961
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	22,718	85,673
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	16,635	79,568
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	11,141	74,053
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	5,255	68,145
0.997	1.9	1.0	2.9	3.2%	86.3	90.0%	84.7%	715	62,634	153	63,024
0.934	1.8	0.8	2.6	2.9%	86.6	90.0%	84.7%	671	58,821	0	59,043
0.874	1.7	0.7	2.4	2.7%	86.8	90.0%	84.7%	630	55,211	0	55,419
0.824	1.6	0.7	2.3	2.5%	86.9	90.0%	84.7%	595	52,151	0	52,348
0.784	1.6	0.6	2.1	2.4%	87.1	90.0%	84.7%	567	49,653	0	49,840
0.746	1.5	0.5	2.0	2.3%	87.2	90.0%	84.7%	540	47,337	0	47,515
0.709	1.5	0.5	1.9	2.2%	87.3	70.0%	65.9%	400	35,010	0	45,182
0.671	1.4	0.4	1.8	2.1%	87.4	70.0%	65.9%	379	33,196	0	42,841
0.643	1.4	0.4	1.8	2.0%	87.4	70.0%	65.9%	363	31,831	0	41,080
0.615	1.3	0.4	1.7	1.9%	87.5	70.0%	65.9%	348	30,464	0	39,315
0.590	1.3	0.3	1.7	1.9%	87.5	70.0%	65.9%	334	29,245	0	37,743
0.568	1.3	0.3	1.6	1.8%	87.6	70.0%	65.9%	322	28,177	0	36,365
0.543	1.3	0.3	1.6	1.7%	87.6	70.0%	65.9%	308	26,955	0	34,787
0.515	1.2	0.3	1.5	1.7%	87.7	70.0%	65.9%	292	25,577	0	33,008
0.493	1.2	0.2	1.5	1.6%	87.7	70.0%	65.9%	280	24,503	0	31,623
0.472	1.2	0.2	1.4	1.6%	87.8	70.0%	65.9%	267	23,428	0	30,235
0.456	1.2	0.2	1.4	1.6%	87.8	70.0%	65.9%	259	22,659	0	29,243
0.440	1.2	0.2	1.4	1.5%	87.8	70.0%	65.9%	250	21,890	0	28,250
0.425	1.2	0.2	1.3	1.5%	87.9	70.0%	65.9%	241	21,120	0	27,256
0.409	1.2	0.2	1.3	1.5%	87.9	70.0%	65.9%	232	20,349	0	26,261
0.397	1.1	0.2	1.3	1.5%	87.9	77.0%	72.4%	248	21,705	0	25,465
0.384	1.1	0.1	1.3	1.4%	87.9	77.0%	72.4%	240	21,026	0	24,668
0.372	1.1	0.1	1.3	1.4%	87.9	77.0%	72.4%	232	20,346	0	23,871
0.359	1.1	0.1	1.2	1.4%	88.0	77.0%	72.4%	224	19,666	0	23,073
0.347	1.1	0.1	1.2	1.4%	88.0	77.0%	72.4%	217	18,985	0	22,274
0.337	1.1	0.1	1.2	1.4%	88.0	77.0%	72.4%	211	18,475	0	21,675
0.325	1.1	0.1	1.2	1.3%	88.0	77.0%	72.4%	203	17,794	0	20,876
0.315	1.1	0.1	1.2	1.3%	88.0	77.0%	72.4%	197	17,283	0	20,277
0.308	1.1	0.1	1.2	1.3%	88.0	77.0%	72.4%	192	16,856	0	19,777
0.299	1.1	0.1	1.2	1.3%	88.0	77.0%	72.4%	187	16,379	0	19,217
0.290	1.1	0.1	1.2	1.3%	88.0	77.0%	72.4%	182	15,902	0	18,656
0.282	1.1	0.1	1.1	1.3%	88.1	77.0%	72.4%	176	15,441	0	18,116
0.273	1.1	0.1	1.1	1.3%	88.1	77.0%	72.4%	171	14,963	0	17,556
0.264	1.1	0.1	1.1	1.3%	88.1	77.0%	72.4%	165	14,485	0	16,995
0.255	1.1	0.1	1.1	1.3%	88.1	77.0%	72.4%	160	13,990	0	16,414
0.247	1.1	0.1	1.1	1.2%	88.1	77.0%	72.4%	154	13,529	0	15,873
0.239	1.1	0.1	1.1	1.2%	88.1	77.0%	72.4%	149	13,085	0	15,352
0.231	1.0	0.1	1.1	1.2%	88.1	77.0%	72.4%	145	12,692	0	14,891
0.225	1.0	0.0	1.1	1.2%	88.1	77.0%	72.4%	141	12,333	0	14,470
0.218	1.0	0.0	1.1	1.2%	88.1	77.0%	72.4%	137	11,974	0	14,048
0.211	1.0	0.0	1.1	1.2%	88.1	77.0%	72.4%	132	11,564	0	13,567
0.203	1.0	0.0	1.1	1.2%	88.1	77.0%	72.4%	127	11,119	0	13,045
0.195	1.0	0.0	1.1	1.2%	88.1	77.0%	72.4%	122	10,691	0	12,544
0.187	1.0	0.0	1.1	1.2%	88.1	77.0%	72.4%	117	10,281	0	12,062
0.181	1.0	0.0	1.1	1.2%	88.1	77.0%	72.4%	113	9,922	0	11,640
0.175	1.0	0.0	1.1	1.2%	88.1	77.0%	72.4%	110	9,596	0	11,259
0.169	1.0	0.0	1.1	1.2%	88.1	77.0%	72.4%	106	9,288	0	10,897
0.164	1.0	0.0	1.0	1.2%	88.2	77.0%	72.4%	103	8,980	0	10,536
0.158	1.0	0.0	1.0	1.2%	88.2	77.0%	72.4%	99	8,689	0	10,194
0.153	1.0	0.0	1.0	1.2%	88.2	77.0%	72.4%	96	8,381	0	9,833
0.146	1.0	0.0	1.0	1.2%	88.2	77.0%	72.4%	92	8,039	0	9,431
0.141	1.0	0.0	1.0	1.2%	88.2	77.0%	72.4%	88	7,730	0	9,069
0.136	1.0	0.0	1.0	1.2%	88.2	77.0%	72.4%	85	7,439	0	8,728
0.131	1.0	0.0	1.0	1.2%	88.2	77.0%	72.4%	82	7,182	0	8,426
0.126	1.0	0.0	1.0	1.2%	88.2	77.0%	72.4%	79	6,908	0	8,105
0.121	1.0	0.0	1.0	1.2%	88.2	77.0%	72.4%	76	6,634	0	7,783
0.116	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	73	6,360	0	7,462
0.111	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	70	6,103	0	7,160
0.106	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	67	5,846	0	6,859
0.102	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	64	5,606	0	6,577
0.098	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	61	5,366	0	6,296
0.094	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	59	5,143	0	6,034
0.089	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	56	4,886	0	5,733
0.085	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	53	4,646	0	5,451
0.080	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	50	4,406	0	5,170
0.076	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	48	4,183	0	4,908
0.073	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	46	3,995	0	4,687
0.070	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	44	3,823	0	4,486
0.067	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	42	3,652	0	4,285
0.063	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	40	3,464	0	4,064
0.060	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	37	3,275	0	3,842
0.056	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	35	3,069	0	3,601
0.052	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	33	2,863	0	3,360
0.048	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	30	2,623	0	3,078
0.044	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	27	2,401	0	2,816
0.040	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	25	2,178	0	2,555

0.033	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	21	1,835	0	2,153
0.029	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	18	1,578	0	1,851
0.026	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	16	1,406	0	1,650
0.019	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	12	1,063	0	1,247
0.013	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	8	720	0	845
0.008	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	5	429	0	503
0.001	1.0	0.0	1.0	1.1%	88.2	77.0%	72.4%	0	34	0	40

Appendix D

Capital Cost Estimate - Nipper's Harbour

ITEM DESCRIPTION	UNIT	QUANTITY	PRICE	TOTAL	SECTION TOTAL
POWER HOUSE					
Building (8x10)	m2	80	$ 320	$ 25,600	
Excavation					
Foundation wall	m3	40	$ 35	$ 1,400	
Turbine	m3	15	$ 35	$ 525	
Foundation Concrete					
Building	m3	16	$ 450	$ 7,200	
Turbine	m3	7	$ 600	$ 4,200	
Mech./ Elect. Services				$ 10,000	
Station Service				$ 5,000	
				$ 53,925	$ 53,925
Turbine					
Generator & Frame					
Inlet valve & coupling					
Hydraulic Unit					
Head Level Controller					
Governor & Controller					
Switchgear & Controls					
	Sub-total			$ 423,150	
Shipping				$ 5,000	
Spare parts				$ 10,000	
				$ 438,150	$ 438,150
PENSTOCK					
Polyethlyene 600 mm ID	m	165	365	$ 60,225	
Old Steel Pipe 34 " diameter	m	346	400	$ 138,400	
				$ 198,625	$ 198,625
FOREBAY DAM / INTAKE					
Timber Crib				$ 55,000	$ 55,000
ACCESS ROADS					
to dam site				$ 40,000	$ 40,000
SWITCHYARD					
Transformer				$ 25,000	
Recloser				$ 12,000	
Concrete Pad				$ 1,000	
Grounding				$ 2,000	
Grading & Fencing				$ 3,000	
600 V Cables				$ 12,000	
Primary Line (25 kV)				$ 10,000	
				$ 65,000	$ 65,000
CONNECTING TO HYDRO GRID					
Interconnection				$ 5,000	
Metering				$ 35,000	
				$ 40,000	$ 40,000
MISCELLANEOUS					
Upgrading HV line (0.7 km)				$ 17,500	
Telephone Line				$ 3,000	
Stream Gauge				$ 15,000	
Installation/ commissioning				$ 38,000	
Telemetering				$ 15,000	
				$ 88,500	$ 88,500
	Total Direct Construction Costs				$ 979,200
	Engineering		15%		$ 146,880
	Sub - Total				$ 1,126,080
	Contingency		15%		$ 168,912
	GRAND TOTAL				**$ 1,294,992**
Annual Operating & Maintenanc	(2% of Grand Total)				$ 25,900

Appendix E

Economic Evaluation Spreadsheet - Nipper's Harbour

NIPPER'S HARBOUR MINI HYDRO
PROJECT VALUATION — Page 1

TECHNICAL SPECIFICATIONS

Installed Capacity	638 Kw
Internal Demand (Winter)	5 kW
Internal Demand (Summer)	2 kW

ANNUAL COSTS

Operations	$30,000 @ Mw
Maintenance	$15,000 @ Mw
Insurance	
Public Liability	$13,000 @ Mw
Replacement Value	$10,000 @ Mw
Business Interuption	$10,000 @ Mw
Provincial Water Rentals	$0.50 per HP-Year
Telephone	$2,500 @ Year
Municipal Taxes	$5,000 @ Mw

AFTER-TAX INCOME

Personal Tax Rate	40.0%
IRR Estimate	40.0%
IRR Actual	#DIV/0!

VALUATION OF THE PROJECT

Discount Rate	10.0%
PV (1997)	($257,551)
Equity (1997)	($275,914)
Net PV (1997)	($533,465)
Waiting PV Rate	8.0%
PV (1993)	($189,308)
Equity (1993)	($202,805)
Net PV (1993)	($392,113)
Owner's Share	100.0%
PV of Shares	($189,308)
PV of Shares (minus equity)	($392,113)

NIPPER'S HARBOUR MINI HYDRO PROJECT VALUATION Page 2

CCA BENEFIT TO LARGE COMPANY

Total Corporate Income Tax Rate	59.0%
PV of Maximum CCA Usage (1997)	$674,212
PV of Actual CCA Usage (1997)	($131,284)
Net CCA Benefit (1997)	$805,496
Net CCA Benefit (1993)	$592,064

REVENUE / PRICE

Hydro Interruption	1%
Plant Maintenance	2%
Capacity Factor	41%
Winter C.F.	41%
Summer C.F.	41%
Variable Flow Factor	0.8

	Maximum	Actual	Combined
Winter Energy Price	$0.0358	$0.0352	$0.0772
Winter Demand Price	$0.0450	$0.0420	
Summer Energy Price	$0.0358	$0.0358	$0.0568
Summer Demand Price	$0.0211	$0.0210	
Annual Blended Rate			$0.0652

Winter Hours	3624 hrs.
Summer Hours	5136 hrs.
Total Hours @ Year	8760 hrs.

Escalation Index	Demand	Energy
1993	2.00%	2.00%
1994	2.00%	2.00%
1995	2.00%	2.00%
1996	2.00%	2.00%
Total	8.24%	8.24%

DEBT FINANCING

PROJECT CAPITAL COST (1993)	$1,300,000
PROJECT CAPITAL COST (1996)	$1,379,570
PERCENT OWNERSHIP	100%
OWNER RESPONSIBILITY	$1,379,570
PERCENT EQUITY REQ'D	20%
EQUITY	$275,914
LOAN AMOUNT	$1,103,656
INTEREST RATE	10.0%
YEARS PAYOUT	20
ANNUAL LOAN PAYMENT	$129,635

CCA and IRR Calculation

						($275,914)	
($22,252)	($22,252)	$0	$1,401,823	$344,893	$0	($41,522)	-15.0%
($18,760)	($18,760)	$0	$1,420,582	$689,785	$0	($39,956)	-14.5%
($38,359)	($38,359)	$0	$1,458,941	$344,893	$0	($38,359)	-13.9%
($36,730)	($36,730)	$0	$1,495,671	$0	$0	($36,730)	-13.3%
($35,068)	($35,068)	$0	$1,530,739	$0	$0	($35,068)	-12.7%
($33,373)	($33,373)	$0	$1,564,112	$0	$0	($33,373)	-12.1%
($31,644)	($31,644)	$0	$1,595,756	$0	$0	($31,644)	-11.5%
($29,881)	($29,881)	$0	$1,625,636	$0	$0	($29,881)	-10.8%
($28,082)	($28,082)	$0	$1,653,718	$0	$0	($28,082)	-10.2%
($26,247)	($26,247)	$0	$1,679,966	$0	$0	($26,247)	-9.5%
($24,376)	($24,376)	$0	$1,704,341	$0	$0	($24,376)	-8.8%
($22,467)	($22,467)	$0	$1,726,809	$0	$0	($22,467)	-8.1%
($20,520)	($20,520)	$0	$1,747,329	$0	$0	($20,520)	-7.4%
($18,534)	($18,534)	$0	$1,765,863	$0	$0	($18,534)	-6.7%
($16,509)	($16,509)	$0	$1,782,371	$0	$0	($16,509)	-6.0%
($14,442)	($14,442)	$0	$1,796,814	$0	$0	($14,442)	-5.2%
($12,335)	($12,335)	$0	$1,809,149	$0	$0	($12,335)	-4.5%
($10,185)	($10,185)	$0	$1,819,334	$0	$0	($10,185)	-3.7%
($7,993)	($7,993)	$0	$1,827,326	$0	$0	($7,993)	-2.9%
($5,756)	($5,756)	$0	$1,833,083	$0	$0	($5,756)	-2.1%

DEBT SERVICING

Income Before Int. & Tax Deducted	P & I Payments	Net Cash (before tax)	Loan - Beginning Balance	Interest Expense on Loan	Applied to Principal	Loan - Ending Balance
$88,113	$129,635	($41,522)	$1,103,656	$110,366	$19,269	$1,084,387
$89,679	$129,635	($39,956)	$1,084,387	$108,439	$21,196	$1,063,191
$91,276	$129,635	($38,359)	$1,063,191	$106,319	$23,316	$1,039,875
$92,905	$129,635	($36,730)	$1,039,875	$103,987	$25,648	$1,014,227
$94,567	$129,635	($35,068)	$1,014,227	$101,423	$28,212	$986,015
$96,262	$129,635	($33,373)	$986,015	$98,601	$31,034	$954,981
$97,991	$129,635	($31,644)	$954,981	$95,498	$34,137	$920,844
$99,754	$129,635	($29,881)	$920,844	$92,084	$37,551	$883,293
$101,553	$129,635	($28,082)	$883,293	$88,329	$41,306	$841,988
$103,388	$129,635	($26,247)	$841,988	$84,199	$45,436	$796,551
$105,259	$129,635	($24,376)	$796,551	$79,655	$49,980	$746,571
$107,168	$129,635	($22,467)	$746,571	$74,657	$54,978	$691,593
$109,115	$129,635	($20,520)	$691,593	$69,159	$60,476	$631,118
$111,101	$129,635	($18,534)	$631,118	$63,112	$66,523	$564,594
$113,127	$129,635	($16,509)	$564,594	$56,459	$73,176	$491,419
$115,193	$129,635	($14,442)	$491,419	$49,142	$80,493	$410,926
$117,300	$129,635	($12,335)	$410,926	$41,093	$88,542	$322,383
$119,450	$129,635	($10,185)	$322,383	$32,238	$97,397	$224,986
$121,642	$129,635	($7,993)	$224,986	$22,499	$107,136	$117,850
$123,879	$129,635	($5,756)	$117,850	$11,785	$117,850	$0

EXPENSES

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698
$19,523	$9,761	$8,460	$6,508	$6,508	$135	$2,550	$3,254	$56,698

REVENUE - Generated over 20 year life of the project

End of Year	Winter kWh Production	Energy Escalation Index	Winter Energy Price	Winter Energy Earnings	Winter Demand Earnings	Total Winter Earnings	Summer kWh Production	Summer Energy Price	Summer Energy Earnings	Summer Demand Earnings	Total Summer Earnings	Annual kWh Production	Annual Gross Income
1	929,846	2.00%	$0.0389	$36,137	$42,273	$78,410	1,333,203	$0.0395	$52,696	$30,305	$83,001	2,263,049	$144,811
2	929,846	2.00%	$0.0396	$36,860	$42,273	$79,133	1,333,203	$0.0403	$53,750	$30,305	$84,055	2,263,049	$146,377
3	929,846	2.00%	$0.0404	$37,597	$42,273	$79,870	1,333,203	$0.0411	$54,825	$30,305	$85,130	2,263,049	$147,974
4	929,846	2.00%	$0.0412	$38,349	$42,273	$80,622	1,333,203	$0.0419	$55,922	$30,305	$86,227	2,263,049	$149,603
5	929,846	2.00%	$0.0421	$39,116	$42,273	$81,389	1,333,203	$0.0428	$57,040	$30,305	$87,345	2,263,049	$151,265
6	929,846	2.00%	$0.0429	$39,898	$42,273	$82,171	1,333,203	$0.0436	$58,181	$30,305	$88,486	2,263,049	$152,960
7	929,846	2.00%	$0.0438	$40,696	$42,273	$82,969	1,333,203	$0.0445	$59,345	$30,305	$89,650	2,263,049	$154,689
8	929,846	2.00%	$0.0446	$41,510	$42,273	$83,783	1,333,203	$0.0454	$60,531	$30,305	$90,837	2,263,049	$156,452
9	929,846	2.00%	$0.0455	$42,340	$42,273	$84,613	1,333,203	$0.0463	$61,742	$30,305	$92,047	2,263,049	$158,251
10	929,846	2.00%	$0.0464	$43,187	$42,273	$85,460	1,333,203	$0.0472	$62,977	$30,305	$93,282	2,263,049	$160,086
11	929,846	2.00%	$0.0474	$44,051	$42,273	$86,324	1,333,203	$0.0482	$64,236	$30,305	$94,542	2,263,049	$161,957
12	929,846	2.00%	$0.0483	$44,932	$42,273	$87,205	1,333,203	$0.0491	$65,521	$30,305	$95,826	2,263,049	$163,866
13	929,846	2.00%	$0.0493	$45,831	$42,273	$88,104	1,333,203	$0.0501	$66,832	$30,305	$97,137	2,263,049	$165,813
14	929,846	2.00%	$0.0503	$46,747	$42,273	$89,020	1,333,203	$0.0511	$68,168	$30,305	$98,473	2,263,049	$167,799
15	929,846	2.00%	$0.0513	$47,682	$42,273	$89,955	1,333,203	$0.0522	$69,532	$30,305	$99,837	2,263,049	$169,824
16	929,846	2.00%	$0.0523	$48,636	$42,273	$90,909	1,333,203	$0.0532	$70,922	$30,305	$101,227	2,263,049	$171,891
17	929,846	2.00%	$0.0534	$49,609	$42,273	$91,881	1,333,203	$0.0543	$72,341	$30,305	$102,646	2,263,049	$173,998
18	929,846	2.00%	$0.0544	$50,601	$42,273	$92,874	1,333,203	$0.0553	$73,788	$30,305	$104,093	2,263,049	$176,148
19	929,846	2.00%	$0.0555	$51,613	$42,273	$93,886	1,333,203	$0.0565	$75,263	$30,305	$105,568	2,263,049	$178,340
20	929,846	2.00%	$0.0566	$52,645	$42,273	$94,918	1,333,203	$0.0576	$76,769	$30,305	$107,074	2,263,049	$180,577

Appendix F

Summary of Project Features - Nipper's Harbour

F.1 Location

The proposed mini hydro project will develop the potential of the stream flowing into Nipper's Harbour on the Baie Verte Peninsula, which includes the drainage system fed by Pine Pond, Buskam Pond, Gull Pond, Greenwood Pond, Saddler Pond, Nippers Harbour Pond, and Noble Pond. The site is located on the 1:50,000 scale topographical map titled "Nippers Harbour" (2E/13) at Latitude 49°48', Longitude 55°52'.

F.2 Description

The project is a "run-of-river" development, having a maximum installed capacity of approximately 650 kilowatts and an annual energy production of 2300 MWhr. The Francis turbine will operate using a gross head of 89 metres and an average annual flow of 0.77 m^3/s. The penstock will have a length of 490 metres. The development requires an intake structure, but not a reservoir.

F.3 Hydrology

The Nipper's Harbour development is located on an ungauged stream. A synthesized time series of daily flows was generated using stream flow data from the nearest gauged stream, South West Brook (No. 02YM003). The production records of the Snook's Arm plant, owned by Nfld. Hydro, were used to calculate the mean annual run-off (MAR). The MAR for Nipper's Harbour was assumed to be the same as the Snook's Arm MAR (725 mm). The Snook's Arm drainage area is located 13 kilometres from Nipper's Harbour and has similar site characteristics and physiographic features. The flow duration curve values, along with site specifications, are listed on the attached spreadsheet hard copy.

The 100-year design flood for Nipper's Harbour is 25 m^3/sec. The 10-year diversion flood is 19 m^3/sec. The estimated 2-year 7-day low flows 0.066 m^3/sec and the estimated 10-year 7-day low flow is 0.005 m^3/sec.

F.4 Interconnection Point & Transmission Line

The interconnection point to the Hydro system will be on the 25 kV side of the Nipper's Harbour substation. A 0.7 km 25 kV transmission line will connect the substation to the 25 kV / 600 V, 750 kVA, outdoor transformer located at the powerhouse. The transmission line will be a single wood pole line, paralleling the north side of the fish storage facility access road. The estimated cost of interconnection, including metering and tie-in, to be paid by the developer, is approximately $40,000.

F.5 Dam/Spillway

The dam will be located at the outlet of the natural head-pond at elevation 86.2 m AMSL. It will be a small 4 m high timber crib structure with a crest length of 20 m, and approximately 12 m at the base. The intake and spillway are incorporated in the dam structure, with the intake located on the east side of the dam. There is exposed bedrock in the vicinity of the proposed location of the dam abutments and foundation.

F.6 Storage

The natural head-pond is enlarged slightly with the addition of the timber-crib dam. The reservoir area is limited to the storage provided by this head-pond. The storage capacity is 42,300 m^3, which corresponds to approximately 15 hours of storage at rated load, assuming minimum inflow.

F.7 Penstock

The total penstock length is 490 m.. A 165 m long, 24" diameter polyethylene penstock will run above ground from the intake to the top of a 6 m high cliff (EL 60 m AMSL). The remaining section of penstock will be steel, 325 m long and 28" in diameter. The penstock will parallel the east bank of the stream.

F.8 Turbine

A Francis turbine was selected because of the high efficiency at rated load. The 15 hours of storage will permit the turbine to run in the "on/off" mode at rated load during low flow periods, maximizing the kWh production.

F.9 Generator

The induction generator will be used.

F.10 Access

The powerhouse is accessible via the fish storage facility access road. Approximately 200 m^3 of rock must be blasted and removed near the powerhouse to gain access to the lower penstock route. A 1.6 km Class D access road will be built to the intake location. Dam materials and sections of the polyethylene penstock will be transported to the site using this road. The route is covers level barrens with one stream crossing.

F.11 Environmental Assessment

The project meets the requirements of the Environmental Assessment Guide, and is not considered to be an undertaking subject to registration. The plant capacity is less than 1 megawatt, the area to be flooded is less than 500 hectares, no flooding will occur within a Special Area, no development is located within a Special Area (although a portion of the drainage area is located within a Waste Disposal Site Special Area), and no transmission line will be located at a distance greater than 500 metres from an existing right-of-way.

There are no residential, commercial, or recreational facilities located near the stream. The water diverted for hydroelectric use will be returned to the stream bed 490 metres down-stream of the intake.

Salmon and sea trout do not use the stream because of the natural falls located below the proposed intake.

The National Sea Products facility, which uses water from the same stream, is only operational during the summer fishing season, and uses a small (4" diameter) polyethylene hose running above ground to service its building. The Water Resources Division of the Department of Environment and Lands established that the facility needed only a incidental amount of the stream flow.

Appendix G

Detailed Steady State Analysis of the Induction Machine

Steady State Analysis of the Induction Machine

The steady state performance of the induction machine, in both motor and generator mode, is predicted using the equivalent circuit for the induction machine, along with nameplate data and manufacturer's impedance data.

. Mathcad is used to solve the network equations derived from the equivalent circuit. The resultant current values are used to calculate I^2R losses and iron losses. A table of current values are generated for varying values of slip. The calculated full load current is identified and the corresponding slip compared to the nameplate slip. The corresponding calculated full load power factor(pf) is noted. The calculated pf is increased by 0.6% to compensate for friction and windage losses (not accounted for in the equivalent circuit).

The calculated pf, nameplate full-load current, and nominal terminal voltage are used to calculate the motoring input power (kW). The output power, in hp, is converted to kW and used with the input power to calculate the efficiency at full load. This data, along with the calculated currents at full load, is used to find the total stray/friction/windage loss. The stray loss is isolated by assuming the friction & windage loss is approximately 0.6% of the total. Stray losses and friction and windage are assumed to be constant for all values of slip

All losses (primary I^2R, secondary I^2R, iron (core) loss, friction and windage, and stray have now been identified. Now it is possible to calculate the efficiency and power output for all values of slip, both in motoring mode and generator mode. The power factor and torque are calculated and graphed over the full range of slip. The maximum breakdown torque and associated speed, for both motoring and generating, are identified from the graph.

Units and Constants

$\Omega := \frac{volt}{amp}$ $\qquad$ $A := amp$ $\qquad$ $V := volt$

$KV := \frac{volt}{1000}$ $\qquad$ $KVA := volt \cdot amp \cdot 1000$

Motor Nameplate Data

Rated Horsepower:	$HP := 670$
Full-Load Current:	$I_{FL} := 639$
Terminal Voltage:	$V_{LL} := 575$
Synchronous Speed:	$RPM_{syn} := 600$
RPM at Rated Load:	$RPM_{FL} := 592$
Slip at Rated Load:	$S_{FL} := 0.0133$
PF at Rated Load:	$pf_{FL} := 0.843$

Manufacturer's Data

Stator Resistance: $R_1 := .0132$ Stator Reactance: $X_1 := 0.048$

Rotor Resistance: $R_2 := .0061$ Rotor Reactance: $X_2 := 0.049$

Magnetizing Resistance: $R_{fe} := 25$ $R_m := 0.0381$ Magnetizing Reactance $X_m := 1.092$

$$Z_{m10} := \frac{1}{\left(\frac{1}{R_{fe}} - 0.9158 \cdot j\right)}$$

$$Z_{m10} = 0.0476 + 1.0899j$$

$R_{m10} := |Z_{m10}| \cdot \cos(\arg(Z_{m10}))$ $R_{m10} = 0.0476$ $R_m := R_{m10}$ $R_m = 0.0476$

Locked Rotor Current @ Full Voltage $I_{LRv} := 3800$

Locked Rotor Current PF: $PF_{LR} := 0.29$

Per Unit (P.U.) Base Values

Base Voltage (3ϕ): $V_{3\phi} := V_{LL}$ $V_{3\phi} = 575$

Base Voltage (1ϕ): $V_{1\phi} := \frac{V_{LL}}{\sqrt{3}}$ $V_{1\phi} = 332$

Base KVA (3ϕ): $KVA_{base} := \frac{\sqrt{3} \cdot I_{FL} \cdot V_{LL}}{1000}$ $KVA_{base} = 636.4$

Base Current: $I_{base} := \frac{KVA_{base}}{3 \cdot V_{1\phi}} \cdot 1000$ $I_{base} = 639$

Base Impedance: $Z_{base} := \frac{V_{LL}^2}{KVA_{base} \cdot 1000}$ $Z_{base} = 0.5195$

Terminal Voltage (P.U.): $V_t := \frac{V_{LL}}{\sqrt{3}} \cdot \frac{1}{V_{1\phi}}$ $V_t = 1$

Manufacturer's Data - Per Unit (P.U.) Impedance's

Stator Resistance: $R_{1pu} := \frac{R_1}{Z_{base}}$ $\quad R_{1pu} = 0.0254$

Rotor Resistance: $R_{2pu} := \frac{R_2}{Z_{base}}$ $\quad R_{2pu} = 0.0117$

Magnetizing Resistance: $R_{mpu} := \frac{R_m}{Z_{base}}$ $\quad R_{mpu} = 0.0916$

Stator Reactance: $X_{1pu} := \frac{X_1}{Z_{base}}$ $\quad X_{1pu} = 0.0924j$

Rotor Reactance: $X_{2pu} := \frac{X_2}{Z_{base}}$ $\quad X_{2pu} = 0.0943j$

Magnetizing Reactance: $X_{mpu} := \frac{X_m}{Z_{base}}$ $\quad X_{mpu} = 2.1019j$

Range of Slip Values

Start Slip: $S_{start} := -0.5$

Run Slip: $S_{end} := 0.5$

Number of points: $N := 4000$

Range for the Plot: $i := 1..N$

Step Size: $Step := \frac{S_{start} - S_{end}}{N+1}$

Slip Value: $S_i := S_{start} - Step \cdot i$

Generator mode: maximum negative slip when i = 1

Motor mode: maximum positive slip when i = N

Equivalent Circuit Impedance Calculations

The equivalent circuit representation for motor mode and generation mode is identical. The difference between modes lies in the direction of the current flow for the primary, secondary, and magnetizing branch. The source supplying the power losses will also change from motoring to generation. Because of these factors the equations used to calculate current, power, and efficiency will differ between modes

Stator Impedance: $Z_1 := R_{1pu} + X_{1pu}$

Magnetizing Impedance: $Z_m := R_{mpu} + X_{mpu}$

Calculate the Effect of the Starting Resistance:

The induction motor has a rotor design allowing for high starting current on startup and an associated high starting torque. This value of current decreases as the rotor picks up speed (slip becomes less), thus the effective rotor resistance is different at each value of slip. It is assumed the change in resistance is linear. When the slip reaches zero only the effect of the run resistance remains. The varying nature of the rotor resistance changes the reflected rotor impedance, total impedance of the equivalent machine circuit, line current and torque values.

To calculate the changing value of rotor reflected impedance (Zi), first the starting resistance is derived from the manufacturer's specified locked rotor current, then the rotor reflected impedance is calculated for each increment in slip.

Calculate the complex form of the Locked Rotor Current:

Locked Rotor Current Angle:

$$\alpha := -\operatorname{acos}(PF_{LR}) \qquad PF_{LR} = 0.29$$

$$I_{LRreal} := I_{LRv} \cdot \cos(\alpha)$$

$$I_{LRimaj} := I_{LRv} \cdot \sin(\alpha)$$

$$I_{LR} := I_{LRreal} + (I_{LRimaj}) \cdot j$$

Locked Rotor Current Value:

$$I_{LR} = 1102 - 3636.7i$$

$$|I_{LR}| = 3800$$

$$\arg\left(I_{LR}\right) = -73.1 \cdot deg$$

P.U. Locked Rotor Current:

$$I_{LRpu} := \frac{I_{LR}}{I_{base}}$$

$$I_{LRpu} = 1.7246 - 5.6912j$$

Calculate Rotor Starting Resistance:

$$Z_{LR} := \frac{V_t}{I_{LRpu}}$$

$$Z_{2st} := \frac{Z_{LR} - Z_1}{Z_m - Z_{LR} + Z_1} \cdot Z_m$$

$$R_{2start} := \left|Z_{2st}\right| \cdot \cos\left(\arg\left(Z_{2st}\right)\right)$$

Starting Resistance: $R_{2start} = 0.0249$

Run Resistance: $R_{2pu} = 0.0117$

Thus the rotor resistance (R_{2adji}) will change with slip, ranging between 0.0213 Ω p.u. at startup to 0.0115 Ω p.u. near synchronous speed. As slip approaches zero, wither from generator mode or motor mode, the machine approaches synchronous speed. At this operating point only the run resistance (R_{2pu}) has any effect.

Calculate Increment: $$R_{2inc} := \frac{R_{2start} - R_{2pu}}{\frac{N}{2} + 1}$$

Adjusted Rotor Resistance:

$$R_{2adj_i} := \begin{cases} R_{2pu} - R_{2inc} \cdot \left(\frac{N}{2} - i\right) & \text{if } S_i > 0 \quad \text{(motor mode)} \\ R_{2pu} + R_{2inc} \cdot \left(\frac{N}{2} - i\right) & \text{otherwise} \quad \text{(generator mode)} \end{cases}$$

Rotor Reflected Impedance:

$$Z_i := \frac{R_{2adj_i} + 0.0008}{S_i} + X_{2pu}$$

Total Impedance of the Equivalent Motor Circuit:

$$Z_{total_i} := Z_1 + \frac{Z_i \cdot Z_m}{Z_i + Z_m}$$

Calculate Motor and Generator Mode Currents

Line (Stator) Current (P.U.):

$$I_{1_i} := \begin{cases} \dfrac{V_t}{Z_{total_i}} & \text{if } (S_i > 0) \\ \left(\dfrac{V_t}{Z_{total_i}}\right) & \text{otherwise} \end{cases}$$

(motor mode)

(generator mode)

Air Gap Voltage (P.U.): $E_{a_i} := \begin{cases} \left(V_t - I_{1_i} \cdot Z_1\right) & \text{if } S_i > 0 \\ \left(V_t + I_{1_i} \cdot Z_1\right) & \text{otherwise} \end{cases}$ (motor mode) (generator mode)

Rotor Reflected Current (P.U.):

$$I_{2_i} := \begin{cases} \left(I_{1_i} \cdot \dfrac{Z_m}{Z_m + Z_i}\right) & \text{if } S_i > 0 \\ \dfrac{\left(E_{a_i}\right)}{Z_i} & \text{otherwise} \end{cases}$$

(motor mode)

(generator mode)

Magnetizing Current (P.U.): $I_{m2_i} := \dfrac{E_{a_i}}{Z_m}$

The calculated per unit currents are in complex form. They must be converted to polar form and take on actual values. The magnitudes of the actual currents are used to calculate losses and power levels. The phase angle of the stator current represents the power factor angle.

Motoring

Actual Stator Current: $I_{1actual_i} := \left|I_{1_i}\right| \cdot I_{base}$ $I_{1actual_{2047}} = 636$

$S_{2047} = 0.0116$

Actual Reflected Rotor Current: $I_{2actual_i} := \left|I_{2_i}\right| \cdot I_{base}$

$I_{2actual_{2047}} = 535$

Actual Magnetizing Current: $I_{mactual_i} := \left|I_{m2_i}\right| \cdot I_{base}$

Generating

Power Factor (motoring): $pf_i := \cos\left(\arg\left(I_{1_i}\right)\right)$

$\theta_{I_i} := \arg\left(I_{1_i}\right)$

$I_{1actual_{1954}} = 641$

$S_{1954} = -0.0116$

$I_{2actual_{1954}} = 599$

$pf_{2047} = 0.822$

$pf_{1954} = -0.794$

Calculate Friction, Windage, and Stray Losses:

(these losses are assumed to be constant at all loads)

Rotor Losses at Full Load: $P_{R2FL} := \dfrac{3 \cdot \left(I_{2actual_{2047}}\right)^2 \cdot R_2}{1000}$

Stator Losses at Full Load: $P_{statorFL} := \dfrac{3 \cdot \left(I_{1actual_{2047}}\right)^2 \cdot R_1}{1000}$

Core Losses at Full Load: $P_{mFL} := \dfrac{3 \cdot \left(I_{mactual_{2047}}\right)^2 \cdot R_m}{1000}$

Output Power at Full Load: $P_{OFL} := 670 \cdot 0.746$

Input Power at Full Load: $P_{inFL} := \dfrac{\sqrt{3} \cdot I_{FL} \cdot V_{LL} \cdot pf_{FL}}{1000}$

Friction, Windage & Stray Losses (P_{fws}) :

$$P_{fws} := P_{inFL} - P_{R2FL} - P_{statorFL} - P_{mFL} - P_{OFL}$$

$$P_{fws} = 4$$

Rotor Losses at all loads: $P_{R2_i} := \dfrac{3 \cdot \left(I_{2actual_i}\right)^2 \cdot R_2}{1000}$

Stator Losses at all loads: $P_{stator_i} := \dfrac{3\cdot\left(I_{1actual_i}\right)^2\cdot R_1}{1000}$

Core Losses at all loads: $P_{m_i} := \dfrac{3\cdot\left(I_{mactual_i}\right)^2\cdot R_m}{1000}$

Motor mode Input Power: $P_{in_i} := \dfrac{\sqrt{3}\cdot I_{1actual_i}\cdot V_{LL}\cdot pf_i}{1000}$

Induction Machine Output Power Calculations

(both motor mode and generator mode)

$$P_{O1_i} := \begin{cases} \left(P_{in_i} - P_{stator_i} - P_{m_i} - P_{R2_i} - P_{fws}\right) & \text{if } S_i>0 \quad \text{(motor mode)} \\ \dfrac{\sqrt{3}\cdot I_{1actual_i}\cdot V_{LL}\cdot pf_i}{1000} & \text{otherwise} \quad \text{(generator mode)} \end{cases}$$

Induction Machine Input Power Calculations

(both motor mode and generator mode)

$$P_{in1_i} := \begin{cases} \left(\left|P_{O1_i}\right| + P_{stator_i} + P_{m_i} + P_{R2_i} + P_{fws}\right) & \text{if } S_i<0 \quad \text{(generator mode)} \\ P_{in_i} & \text{otherwise} \quad \text{(motor mode)} \end{cases}$$

$RPM_i := 600\cdot\left(1 - S_i\right)$

$P_{O1_{2047}} = 484$

$\dfrac{P_{O1_{2047}}}{.746} = 648$ hp

$\max\left(P_{O1}\right) = 1312.42$

$P_{O1_{1954}} = -507$ kw

$\dfrac{\max\left(P_{O1}\right)}{0.746} = 1759$ hp

$P_{in1_{2047}} = 520$ kw

$\left|\min\left(P_{O1}\right)\right| = 1547$

$P_{in1_{1954}} = 548$ kw

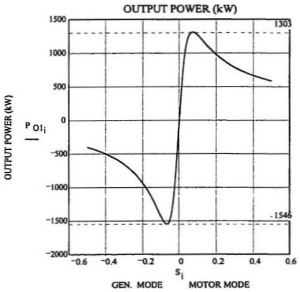
$RPM_{2047} = 593.0$

$RPM_{1954} = 607.0$

<u>Note:</u> The magnetizing branch power loss is larger during generation mo
than motor mode. This is to be expected since the air gap voltage will be
in generator mode in order to maintain the terminal voltage, which is fixed
grid. The higher air gap voltage translated into higher real magnetizing cu
component and a subsequent higher magnetizing losses. Remember, the
voltage is dropped across the stator impedance in generator mode such tl
the stator voltage and terminal voltage must add to give the air gap voltag

Also note that the generator supplies the losses thus one would expect th
reflected rotor current to be larger in generator mode than in motor mode.
The larger current means greater rotor losses in generator mode and less

Since friction, windage and core losses are assumed to be constant at bo
full load motor and generator speed, the differences in losses and efficien
between modes stems from the differences in core losses and rotor losses



Torque:
(motor mode and generator mode)

$$T_i := \begin{cases} \left(\dfrac{P\,O1_i}{0.746} \cdot \dfrac{33000}{2 \cdot \pi \cdot RPM_i} \right) & \text{if } S_i > 0 \\ \left(\dfrac{P\,in1_i}{0.746} \cdot \dfrac{-33000}{2 \cdot \pi \cdot RPM_i} \right) & \text{otherwise} \end{cases}$$

$T_{2047} = 5743$ $\quad T_{2326} = 16694$

$T_{1954} = -6359$ $\quad T_{1526} = -23648$

Note: While the output power graph has more distinct max/min points (a compared to the torque graph), it cannot be used to find the pullout torque speeds. The torque applied in generator mode is equal to the input power while in motor mode the torque developed is equal to the motor output pov

The maximum pullout torque for the Generator occurs at a speed of approximately 670 rpm.

The maximum pullout torque for the Motor occurs at a speed of approxima 550 rpm.

$S_{2326} = 0.0814$ $\quad RPM_{2326} = 551$

$S_{1523} = -0.1193$ $\quad RPM_{1526} = 671$

$\max(T) = 16696$ ft-lb

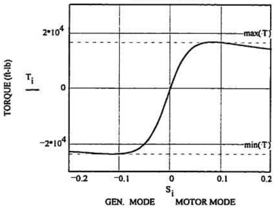
$\min(T) = -23652$ ft-lb

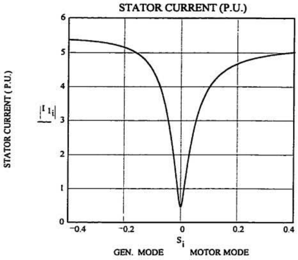
$T_{1526} = -23648$

Ratio of pullout torque as a generator to pullout torque as a motor:

$$\frac{|\min(T)|}{\max(T)} = 1.42$$

TORQUE vs SLIP

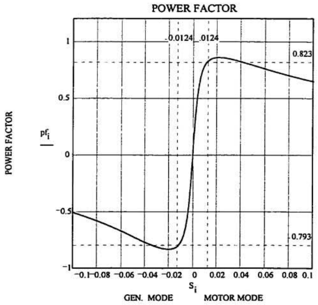




$\max(pf) = 0.8592$
$\min(pf) = -0.8329$

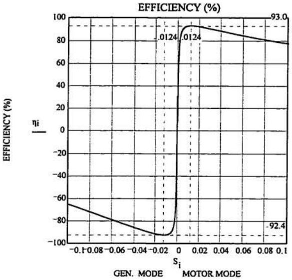
$pf_{Mfl} := pf_{2047}$ $\quad pf_{Mfl} = 0.8216$ $\quad S_{2047} = 0.0116$

$pf_{Gfl} := pf_{1954}$ $\quad pf_{Gfl} = -0.7941$ $\quad S_{1954} = -0.0116$



Efficiency: $\eta_i := \frac{P_{O1_i}}{P_{in1_i}} \cdot 100$ $\quad \eta_{Mfl} := \eta_{2047}$ $\quad \eta_{Mfl} = 93.0$

$\eta_{Gfl} := |\eta_{1954}|$ $\quad \eta_{Gfl} = 92.5$



Appendix H

Expert System Documentation

H.1 Hydro-Plant Equipment

A. *Mechanical*

1. Generator
   a. Front bearing
   b. Back bearing
   c. Rotor balance
   d. Brushes & rigging

2. Turbine
   a. Front Bearing
   b. Back Bearing
   c. Runner
   d. Wicket gates
   e. Scroll Case
   f. Governor

3. Auxiliary equipment
   a. Speed Increaser
   b. Governor Hydraulic Unit
      (1) solenoid pump
   c. Bearing Coolant system

B. *Electrical Equipment*

1. Utility
   a. Three(3) single-phase Transformers
   b. Station service transformer
   c. Control transformer
   d. Current transformer
   e. Lightening Arrestor
   f. Main Disconnect
   g. Main Breaker
   h. Kwh meter

2. Generator
   a. Rotor
   b. Stator
   c. Voltage regulator
   d. Speed switch

3. Auxiliary Equipment
   a. Battery charger
   b. Building Supply

C. *Civil*

1. Main Valve
2. Pressure transmitter (Water level)

H.2 Problems and Symptoms

Mechanical Problems

A. Bad Bearings

1. Cause:
    a. Loss of bearing coolant
    b. Worn bearings
    c. Unbalanced rotor/runner
2. Symptoms:
    a. Bearing coolant low-flow switch
    b. High Bearing temperature
    c. High vibration

B. Rotor Unbalance

1. Cause:
    a. Faulty rotor
    b. Sustained over-speed
2. Symptoms:
    a. High Vibration

C. Unbalanced runner

1. Cause:
    a. Bent blades
    b. Debris between Blades
    c. Ice between Blades
2. Symptoms
    a. High Vibration

D. Stuck gates

1. Cause:
    a. Governor problems
    b. Seized bearings
    c. Debris
    d. Ice

2. Symptoms:
    a. Over/under frequency trip
    b. over-speed switch

Governor Problems

A. Linkage Broken

1. Cause:
    a. Stuck gate-to much strain on arm
    b. Faulty connection point
2. Symptom:
    a. Over/under-frequency trip
    b. over-speed switch

B. Solenoid Pump seized

1. Cause:
    a. Dirty hydraulic fluid...check filter
    b. Bad bearings
2. Symptoms:
    a. Pump motor tripped
    b. Low-Flow switch tripped
    c. Over/under frequency trip

C. Solenoid Pump motor Tripped

1. Cause:
    a. Motor winding burnt
    b. Solenoid pump seized
    c. Motor bearings bad
2. Symptoms:
    a. Circuit breaker tripped
    b. Low-flow switch tripped

D. Hydraulic line blocked

1. Cause:
    a. Dirty Hydraulic fluid...check filter
2. Symptom:
    a. Low-flow switch tripped

Electrical Problems

A. Generator windings faults

1. Cause:
    a. Winding Temperature above rating

(1) High room temperature
(2) Overload
(3) Unbalanced load

b. Over-voltage
(1) Voltage regulator damaged
(2) Sustained Over-speed
(3) Lightning Strike

2. Symptom:
a. Instantaneous Over-current trip
b. Ground Fault trip

B. Generator Overload

Utility Problems

A. Utility Substation Trip

1. Cause:
a. Faulty Hydro-plant relaying
b. Fault on Tx-line to Hydro-plant
c. Substation Problem
d. System problem

2. Symptom:
a. Under-voltage trip
b. Under-frequency trip

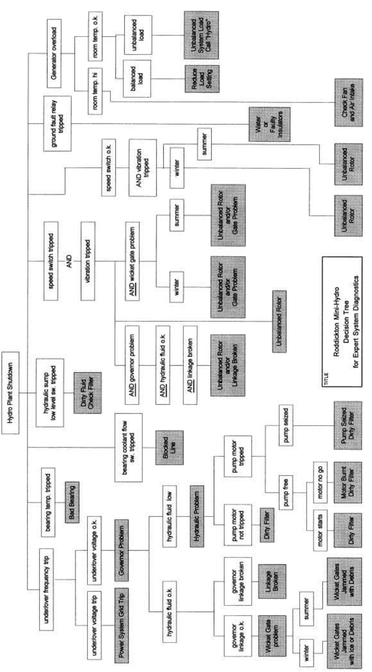
B. Unbalanced System Loads

1. Cause:
a. large single-phase loads

2. Symptom:
a. unbalanced meter readings

C. Lightning strike

H.3 Decision Tree



H.4 Qualifiers, Variables, & Choices

Subject:
Mini-Hydro Plant Diagnostics

Author: Norris Eaton

Starting text:

The expert system software, "EXSYS Professional", is used to diagnose the cause of a plant shutdown. The shutdown may have occurred because of a mechanical, electrical, or utility problem. The plant programmable logic controller (PLC) continually monitors the sensors and relays. Given sets of conditions are interpreted by the PLC to initiate a plant shutdown. After the shutdown, the status of the sensors and relays is transferred to the expert system. These data, along with the rules and prompted operator response, are sufficient to immediately diagnose the cause of the problem. Specific remedial action is then recommended.

Ending text:

A list of the sensors tripped during this particular shutdown were shown on the previous screen. Hit <P> on the next screen to see them again. The most likely causes of the plant shutdown are listed in order of priority. While the causes listed may not appear to be related, all recommendations should be followed.

Uses all applicable rules in data derivations.

Calls the external program c:\exsys\xs\hydro2.exe /m

Probability System: 0 - 10

DISPLAY THRESHOLD: 1

QUALIFIERS:

1 The vibration switch is

tripped
o.k.

Name: Vibration
Maximum acceptable = 1

2 The bearing temperature is

hot

o.k.

Name: Bearing Temp.
Maximum acceptable = 1

3 The speed switch is

tripped
o.k.

Name: Over-speed
Maximum acceptable = 1

4 The bearing coolant flow is

low
o.k.

Name: Bearing coolant
Maximum acceptable = 1

5 The governor hydraulic fluid flow is

low
o.k.

Name: Hydraulic flow
Maximum acceptable = 1

6 The hydraulic fluid sump level is

low
o.k.

Name: Sump level
Maximum acceptable = 1

7 The headpond water level is

low
o.k.

Name: Headpond level
Maximum acceptable = 1

8 The problem is the

unbalanced runner
unbalanced rotor
unknown

governor
wicket gates
hydraulic system
generator overload
blocked flow

Name: Problem
Default value = 3
Maximum acceptable = 1

9 The season of the year is

summer
fall
winter
spring

Name: Season
Maximum acceptable = 3

10 The under-frequency relay is

tripped
o.k.

Name: Under-freq.
Maximum acceptable = 1

11 The over-frequency relay is

tripped
o.k.

Name: Over-freq.
Maximum acceptable = 1

12 The over-voltage relay is

tripped
o.k.

Name: Over-voltage
Maximum acceptable = 1

13 The under-voltage relay is

tripped
o.k.

Name: Under-voltage

Maximum acceptable = 1

14 The reverse power relay is

tripped
o.k.

Name: Reverse power
Maximum acceptable = 1

15 The governor linkage is

o.k.
broken
jammed/seized

Name: Gov. linkage
Maximum acceptable = 2

16 The hydraulic pump motor is

tripped (Check breaker)
not tripped

Name: Hydraulic motor
Maximum acceptable = 1

17 The hydraulic pump is

free when turned over by hand
siezed

Name: Hydraulic pump
Maximum acceptable = 1

18 After the breaker is reset, the motor will

start
will not start

Name: Hyd. motor start
Maximum acceptable = 1

19 The instantaneous overcurrent relay is

tripped
o.k.

Name: Ins overcurrent
Maximum acceptable = 1

20 The overload device is

tripped
o.k.

Name: Overload relay
Maximum acceptable = 1

21 The ground-fault relay is

tripped
o.k.

Name: Gnd.fault relay
Maximum acceptable = 1

22 Water pooled on the floor or excessive dampness is

evident
not evident

Name: Signs of water
Maximum acceptable = 1

23 The power house temperature is

high
o.k.

Name: Powerhouse temp
Maximum acceptable = 1

24 After restarting the plant, the current meter readings are

balanced
unbalanced

Name: Unbalanced load
Maximum acceptable = 1

25 The local EMERGENCY STOP button is

activated (depressed)
normal

Name: Emergency stop
Maximum acceptable = 1

CHOICES:

1 Loss of bearing coolant

2 Worn bearings...check.

3 Unbalanced runner caused by debris stuck between blades.

4 Bearings probablly o.k.–check.

5 Unbalanced runner caused by debris bending blades.

6 Unbalanced rotor caused by sustained overspeed.

7 Blocked coolant line..open bypass.

8 Faulty sensor...check.

9 Unbalanced runner caused by ice collecting between blades.

10 unbalanced runner

11 Wicket gates are jammed with ice or debris.

12 Wicked gates are jammed with debris

13 Dirty hydraulic fluid...check filter.

14 Hydraulic pump motor has tripped, but motor is o.k.

15 Hydraulic pump motor is burnt...replace.

16 Hydraulic pump is seized...replace.

17 Low sump level...hydraulic fluid leak.

18 Short circuit on generator winding or power cable...perform thorough electrical and visual checks.

19 Ground fault trip caused by dampness...find leak...dry out electrical gear... check-out generator.

20 Check insulated connection points...check-out generator.

21 The generator load is to high...reduce the kW setting.

22 There is an unbalanced load on the system...call Nfld. Hydro.

23 Check the cooling fan and air intake.

24 Water level at the intake is to low...do not attempt to start plant until levels rise.

25 Low flow...ice or debris blocking intake.

26 Penstock frozen at main valve.

27 Low flow...debris blocking intake.

28 Plant shutdown caused by local EMERGENCY STOP.

29 "Hydro" system trip due to line fault or substation breaker opening...restart plant.

30 Lightning strike...check lightning arrestors...restart plant.

31 The governor linkage is jammed or broken...fix.

32 Main control valve jammed open.

VARIABLES:

1 FILTER
"filter" variable description
Displayed at the end of a run as text only

2 PUMP MOTOR
"Pump motor" variable description
Displayed at the end of a run as text only

3 PUMP SEIZED
"Pump seized" variable description
Displayed at the end of a run as text only

4 BLOCKED VALVE
"Blocked valve" variable description
Displayed at the end of a run as text only

5 BLOCKED VALVE LINK
"Blocked Valve & faulty Linkage" variable description
Displayed at the end of a run as text only

6 HIGH kW
"High kW" variable description
Displayed at the end of a run as text only

7 POWERHOUSE TEMP
"Power house temperature" variable description
Displayed at the end of a run as text only

8 UNBALANCED LOAD
"Unbalanced load" variable description
Displayed at the end of a run as text only

9 INST OVERCURRENT
"Instantaneous over-current" variable description
Displayed at the end of a run as text only

10 MONTH
Month of the year
Numeric variable

H.5 Expert System Rules

RULE NUMBER: 1
IF:
The vibration switch is tripped
and The speed switch is tripped

THEN:
Unbalanced rotor caused by sustained overspeed. - Confidence=7/10
and Worn bearings...check. - Confidence=3/10

RULE NUMBER: 2
IF:
The vibration switch is tripped
and The speed switch is o.k.

THEN:
The problem is the unbalanced runner

RULE NUMBER: 3
IF:
The bearing temperature is hot

THEN:
Worn bearings...check. - Confidence=10/10

RULE NUMBER: 4
IF:
The bearing coolant flow is low

THEN:
Blocked coolant line..open bypass. - Confidence=8/10
and Faulty sensor...check. - Confidence=5/10
and Worn bearings...check. - Confidence=2/10

RULE NUMBER: 5
IF:
The problem is the unbalanced runner
and The season of the year is summer OR fall OR spring

THEN:
Unbalanced runner caused by debris stuck between blades. - Confidence=8/10
and Unbalanced runner caused by debris bending blades. - Confidence=4/10
and Worn bearings...check. - Confidence=3/10

RULE NUMBER: 6
IF:
The problem is the unbalanced runner
and The season of the year is winter

THEN:
Unbalanced runner caused by ice collecting between blades. - Confidence=7/10
and Worn bearings...check. - Confidence=3/10

RULE NUMBER: 7
IF:
The under-frequency relay is tripped
and The under-voltage relay is o.k.

THEN:
The problem is the governor

RULE NUMBER: 8
IF:
The over-frequency relay is tripped
and The over-voltage relay is o.k.

THEN:
The problem is the governor

RULE NUMBER: 9
IF:
The problem is the governor
and The governor hydraulic fluid flow is o.k.
and The governor linkage is o.k.

THEN:
The problem is the wicket gates

RULE NUMBER: 10
IF:
The problem is the governor
and The governor hydraulic fluid flow is o.k.
and The governor linkage is broken OR jammed/seized

THEN:
The governor linkage is jammed or broken...fix. - Confidence=10/10

RULE NUMBER: 11
IF:
The governor hydraulic fluid flow is low

THEN:
The problem is the hydraulic system

RULE NUMBER: 12
IF:
The problem is the hydraulic system
and The hydraulic pump motor is not tripped

THEN:
Dirty hydraulic fluid...check filter. - Confidence=8/10
and "filter" variable description

RULE NUMBER: 13
IF:
The problem is the hydraulic system
and The hydraulic pump motor is tripped (Check breaker)
and The hydraulic pump is free when turned over by hand
and After the breaker is reset, the motor will start

THEN:
Hydraulic pump motor has tripped, but motor is o.k. - Confidence=9/10
and Dirty hydraulic fluid...check filter. - Confidence=8/10
and "filter" variable description

RULE NUMBER: 14
IF:
The problem is the hydraulic system
and The hydraulic pump motor is tripped (Check breaker)
and The hydraulic pump is free when turned over by hand
and After the breaker is reset, the motor will will not start

THEN:
Hydraulic pump motor is burnt...replace. - Confidence=9/10
and Dirty hydraulic fluid...check filter. - Confidence=6/10
and "Pump motor" variable description

RULE NUMBER: 15
IF:
The problem is the hydraulic system
and The hydraulic pump motor is tripped (Check breaker)
and The hydraulic pump is siezed

THEN:
Hydraulic pump is seized...replace. - Confidence=9/10
and Dirty hydraulic fluid...check filter. - Confidence=3/10
and "Pump seized" variable description

RULE NUMBER: 16
IF:
The problem is the wicket gates
and The season of the year is winter

THEN:
Wicket gates are jammed with ice or debris. - Confidence=8/10

RULE NUMBER: 17
IF:
The problem is the wicket gates
and The season of the year is summer OR fall OR spring

THEN:
Wicked gates are jammed with debris - Confidence=8/10

RULE NUMBER: 18
IF:
The hydraulic fluid sump level is low

THEN:
Low sump level...hydraulic fluid leak. - Confidence=9/10
and Dirty hydraulic fluid...check filter. - Confidence=5/10
and Faulty sensor...check. - Confidence=3/10

RULE NUMBER: 19
IF:
The instantaneous overcurrent relay is tripped

THEN:
Short circuit on generator winding or power cable...perform thorough electrical and visual checks. - Confidence=9/10
and Faulty sensor...check. - Confidence=2/10
and "Instantenous overcurrent" variable description

RULE NUMBER: 20
IF:
The ground-fault relay is tripped
and Water pooled on the floor or excessive dampness is evident

THEN:
Ground fault trip caused by dampness...find leak...dry out electrical gear... check-out generator. - Confidence=8/10

RULE NUMBER: 21
IF:
The ground-fault relay is tripped
and Water pooled on the floor or excessive dampness is not evident

THEN:
Check insulated connection points...check-out generator. - Confidence=7/10

RULE NUMBER: 22
IF:
The overload device is tripped
and The power house temperature is o.k.

THEN:
The problem is the generator overload

RULE NUMBER: 23
IF:
The overload device is tripped
and The power house temperature is high

THEN:
Check the cooling fan and air intake. - Confidence=8/10
and "Power house temperature" variable description

RULE NUMBER: 24
IF:
The problem is the generator overload
and After restarting the plant, the current meter readings are balanced

THEN:
The generator load is too high...reduce the Kw setting. - Confidence=8/10
and "High Kw" variable description

RULE NUMBER: 25
IF:
The problem is the generator overload
and After restarting the plant, the current meter readings are unbalanced

THEN:
There is an unbalanced load on the system...call Nfld. Hydro. - Confidence=8/10
and "Unbalanced load" variable description

RULE NUMBER: 26
IF:
The reverse power relay is tripped
and The season of the year is summer OR fall OR spring

THEN:
Low flow...debris blocking intake. - Confidence=9/10

RULE NUMBER: 27
IF:
The reverse power relay is tripped
and The season of the year is winter

THEN:
Low flow...ice or debris blocking intake. - Confidence=8/10
and Penstock frozen at main valve. - Confidence=4/10

RULE NUMBER: 28
IF:
The under-frequency relay is tripped
and The under-voltage relay is tripped

THEN:
"Hydro" system trip due to line fault or substation breaker opening...restart plant. - Confidence=9/10

RULE NUMBER: 29
IF:
The over-frequency relay is tripped
and The over-voltage relay is tripped

THEN:
"Hydro" system trip due to line fault or substation breaker opening...restart plant. - Confidence=9/10

RULE NUMBER: 30
IF:
The over-voltage relay is tripped
and The speed switch is o.k.

THEN:
Lightning strike...check lightning arrestors...restart plant. -

Confidence=8/10

RULE NUMBER: 31
IF:
The headpond water level is low

THEN:
Water level at the intake is too low...do not attempt to start plant until levels rise. - Confidence=8/10
and Faulty sensor...check. - Confidence=4/10

RULE NUMBER: 32
IF:
The vibration switch is tripped
and The speed switch is tripped
and The problem is the wicket gates
and The season of the year is winter

THEN: Unbalanced rotor caused by sustained overspeed. - Confidence=7/10
and Worn bearings...check. - Confidence=3/10
and Wicket gates are jammed with ice or debris. - Confidence=8/10
and Main control valve jammed open. - Confidence=8/10
and "Blocked valve" variable description

RULE NUMBER: 33
IF:
The vibration switch is tripped
and The speed switch is tripped
and The problem is the wicket gates
and The season of the year is summer OR fall OR spring

THEN: Unbalanced rotor caused by sustained overspeed. - Confidence=7/10
and Worn bearings...check. - Confidence=3/10
and Wicked gates are jammed with debris - Confidence=8/10
and "Blocked valve" variable description
and Main control valve jammed open. - Confidence=8/10

RULE NUMBER: 34
IF:
The vibration switch is tripped
and The speed switch is tripped
and The problem is the governor

and The governor hydraulic fluid flow is o.k.
and The governor linkage is broken OR jammed/seized

THEN: Unbalanced rotor caused by sustained overspeed. - Confidence=7/10
and Worn bearings...check. - Confidence=3/10
and The governor linkage is jammed or broken...fix. - Confidence=10/10
and Wicked gates are jammed with debris - Confidence=8/10
and Main control valve jammed open. - Confidence=8/10
and "Blocked Valve & faulty Linkage" variable description

RULE NUMBER: 35
IF:
[MONTH]=12
THEN: The season of the year is winter

RULE NUMBER: 36
IF:
[MONTH]>=1
and [MONTH]<=11
THEN: The season of the year is winter

RULE NUMBER: 37
IF:
[MONTH]=5
THEN: The season of the year is spring

RULE NUMBER: 38
IF:
[MONTH]>=6
and [MONTH]<=8
THEN: The season of the year is summer

RULE NUMBER: 39
IF:
[MONTH]>=9
and [MONTH]<=11
THEN: The season of the year is fall

H.6 HYDRO2.EXE Source Code

```
{ HYDRO PLANT DIAGNOSTICS &
  PROGRAMMABLE LOGIC CONTROLLER (PLC) DATA TABLE

        Norris Eaton
        Written in Turbo Pascal 4.0

  A number of test files have been created to simulate the status of various sensors, as recorded by the PLC.

The data table is a reserved area of the PLC controller memory which stores the current status of all of the input sensors and
output relays. Sixteen bit words, with each bit being a "1" or "0", are dumped to a file on disk when a plant          shutdown
occurs. An example of the arrangment is shown;

        0000 1000 0101 1001

  The sixteen bit format is converted to the form required by EXSYSP, using this external program, "HYDRO2.PAS". The
        results of that conversion are stored in the file "RETURN.DAT". The "RETURN.DAT" file is automatically deleted
        after it has been read by EXSYSP.

  Each "bit" of the 16-bit "word" represents the status of each sensor. Starting from the left, they are;

  Mechanical Sensors

   * Vibration
   * Bearing Temp.
   * Bearing coolant
   * Over-speed

   * Hydraulic flow
   * Sump level
   * Powerhouse temp
   * Headpond level

  Electrical Relays

   * Overload
   * Inst. over current
   * Ground fault
   * reverse power

   * Over voltage
   * Under voltage
   * Over frequency
   * Under frequency

}
{*******************************************************************}

uses Crt, Dos;

var
 Dummy     : integer;
 Selection : char;

 Year,
 Month,
 Day,
 DayOfWeek : word;
```

```
const
  Indent ='          ';

{***************************************************************}

procedure Wait;

var
  Temporary : char;

begin
  GotoXY  (28,24); ClrEol;
  TextColor(LightCyan);
  Write   ('< HIT ANY KEY TO CONTINUE >');

  Temporary := Readkey;
end; { of procedure Wait }

{***************************************************************}

procedure Introduction;

begin

  ClrScr;
  GotoXY ( 25,2);
  TextColor(LightRed);
  Writeln (' HYDRO-PLANT SHUTDOWN SIMULATION');
  GotoXY  (18,5);
  TextColor(LightCyan);
  Writeln ('The programmable logic controller (PLC) monitors');
  Writeln (Indent,'the status of the sensors.  When a plant shutdown');
  Writeln (Indent,'occurs, the expert system calls an external program.');
  Writeln (Indent,'This program ( HYDRO2.EXE ) converts the sensor data');
  Writeln (Indent,'into the correct format and loads the information');
  Writeln (Indent,'into the expert system.');
  Writeln;
  Writeln;
  Writeln (Indent,'To simulate the Expert System Diagnostics, select');
  Writeln (Indent,'one of the sample data sets that may occur when a');
  Writeln (Indent,'plant shutdown occurs.  The Expert System will find');
  Writeln (Indent,'the cause of the shutdown, based on the sensor data');
  Writeln (Indent,'from the PLC and the operator response to questions.');
  Writeln;
  Textcolor(LightRed);
  Writeln (Indent,'Note:  This screen and accompanying menu would not');
  Writeln (Indent,'       appear in the actual expert system.');
  GotoXY  (16, WhereY + 4);

  Wait;
end; { of procedure Introduction }

{***************************************************************}

procedure Menu ( var Selection : char);

begin
  ClrScr;
  GotoXY ( 25,5);
  TextColor(LightRed);
  Writeln (' HYDRO-PLANT SHUTDOWN SIMULATION');
  GotoXY ( 25,8);
  TextColor(LightCyan);
```

```
  Writeln ('Please Select One of the Following:');
  Writeln;  GotoXY (25, WhereY);

  TextColor(LightBlue);
  Writeln ( '1.');  GotoXY (25, WhereY);
  Writeln ( '2.');  GotoXY (25, WhereY);
  Writeln ( '3.');  GotoXY (25, WhereY);
  Writeln ( '4.');  GotoXY (29, 10);

  TextColor(LightCyan);
  Writeln ('Problem 1');   GotoXY (29, WhereY);
  Writeln ('Problem 2');  GotoXY (29, WhereY);
  Writeln ('Problem 3');   GotoXY (29, WhereY);
  Write   ('Problem 4');

  Selection := ReadKey;
end;  { of Menu procedure }

{*************************************************************}

procedure Process (Shutdown: string);

var
  Infile,
  Outfile  : text;
  Status   : char;
  Count    : integer;

begin
  Count := 0;
  assign (Infile, Shutdown);
  reset  (Infile);
  assign (Outfile,'Return.dat');
  rewrite(Outfile);

  GetDate(Year, Month, Day, DayOfWeek);  {month for season}
  write  (Outfile,'V10 ');
  writeln(Outfile, Month);


  while not eof(Infile) do

  begin
    read(Infile,Status);
    Count:= Count+1;

    case Count of
      1: begin
          write (Outfile,'Q1 ');      {vibration sw.}
          if Status = chr(49)
            then writeln(Outfile,'1')
            else writeln(Outfile,'2')
        end;


      2: begin
          write (Outfile,'Q2 ');      { bearing temp.}
          if Status = chr(49)
            then writeln(Outfile,'1')
            else writeln(Outfile,'2')
        end;


      3: begin
```

```
    write (Outfile,'Q4 ');     {Bearing coolant}
    if Status = chr(49)
      then writeln(Outfile,'1')
      else writeln(Outfile,'2')
  end;


 4: begin
    write (Outfile,'Q3 ');     { Over-speed }
    if Status = chr(49)
      then writeln(Outfile,'1')
      else writeln(Outfile,'2')
  end;


 5: begin
    write (Outfile,'Q5 ');     { hydraulic flow }
    if Status = chr(49)
      then writeln(Outfile,'1')
      else writeln(Outfile,'2')
  end;


 6: begin
    write (Outfile,'Q6 ');     { sump level }
    if Status = chr(49)
      then writeln(Outfile,'1')
      else writeln(Outfile,'2')
  end;


 7: begin
    write (Outfile,'Q23 ');    {powerhouse temp}
    if Status = chr(49)
      then writeln(Outfile,'1')
      else writeln(Outfile,'2')
  end;


 8: begin
    write (Outfile,'Q7 ');     {Headpond level}
    if Status = chr(49)
      then writeln(Outfile,'1')
      else writeln(Outfile,'2')
  end;


 9: begin
    write (Outfile,'Q20 ');    {Overload relay}
    if Status = chr(49)
      then writeln(Outfile,'1')
      else writeln(Outfile,'2')
  end;


 10: begin
    write (Outfile,'Q19 ');    {Ins overcurrent}
    if Status = chr(49)
      then writeln(Outfile,'1')
      else writeln(Outfile,'2')
  end;


 11: begin
```

```
        write (Outfile,'Q21 ');    {Gnd.fault relay}
        if Status = chr(49)
          then writeln(Outfile,'1')
          else writeln(Outfile,'2')
      end;


     12: begin
        write (Outfile,'Q14 ');    {Reverse power}
        if Status = chr(49)
          then writeln(Outfile,'1')
          else writeln(Outfile,'2')
      end;


     13: begin
        write (Outfile,'Q12 ');    {Over-voltage}
        if Status = chr(49)
          then writeln(Outfile,'1')
          else writeln(Outfile,'2')
      end;


     14: begin
        write (Outfile,'Q13 ');    {Under-voltage}
        if Status = chr(49)
          then writeln(Outfile,'1')
          else writeln(Outfile,'2')
      end;


     15: begin
        write (Outfile,'Q11 ');    {Over-freq. }
        if Status = chr(49)
          then writeln(Outfile,'1')
          else writeln(Outfile,'2')
      end;


     16: begin
        write (Outfile,'Q10 ');    {Under-freq. }
        if Status = chr(49)
          then writeln(Outfile,'1')
          else writeln(Outfile,'2')
      end;

   end;  {of case Count}
  end;  {while not eof}
  close (Infile);
  close (Outfile);
end;  {Process}

{*************************************************************************}

begin   {main program}

 Introduction;
 repeat
  Menu  ( Selection );
  case Selection of
   '1' : Process( 'Test1.plc');
   '2' : Process( 'Test2.plc');
   '3' : Process( 'Test3.plc');
```

```
    '4' : Process( 'Test4.plc');
   else
    begin
     Writeln;
     Writeln;
     GotoXY  (25, WhereY);
     Writeln ( 'Please Enter <1>, <2>, <3>, or <4>');
     Wait;
    end;  { of else statement }
   end;  { of case statement }
  until Selection in ['1' .. '4'];
end.  {of main program}
```

H.7 External Interface

Files used:	HYDRO2.EXE	HYDRO2.PAS	RETURN.DAT
	TEST1.PLC	TEST2.PLC	TEST3.PLC
	TEST4.PLC		

The status of all sensors and relays when a shutdown occurs is recorded by the programmable controller (PLC). The status is transferred to the expert system via the external program, "HYDRO2.EXE" and the file, "RETURN.DAT". The file "RETURN.DAT" is automatically erased after the information it contains is loaded into the expert system.

The external program, "HYDRO2.EXE", performs three functions:

a. It transforms the binary representation of the sensor status into a format that "Exsys Professional" understands. Once that is done, it writes the information to the file "RETURN.DAT".

b. It takes the computer system clock date, extracts the month, transforms it to the "Exsys Professional" format, and writes the information in the file "RETURN.DAT". The information on the month is used by the expert system to determine the season. This avoids having to ask the operator/technician for the season.

c. Since an actual hook-up to a programmable logic controller (PLC) was not possible, "HYDRO2.EXE" simulates four different shutdown conditions. Selecting any condition from the menu (displayed automatically) loads the binary representation of the sensor status from one of four test files, "TEST1.PLC", "TEST2.PLC", "TEST3.PLC", "TEST4.PLC".

The external program was written in "Turbo Pascal 4.0". The ASCII listing of the source code is contained in Appendix "H.6".

H.8 Report Generator

Files used: HYDRO2.OUT HYDRO2.RPT

The normal output screen can be cumbersome if information needed is different from what is contained in the "CHOICES". The report generator is used to output a list of all mechanical and electrical sensors that have tripped during the plant shutdown. In this way, the sensors can be displayed on a separate screen from the regular output screen. The operator may need the sensor information in a concise format. The report generator option makes this possible.

The report generator commands are stored in the file "HYDRO2.OUT". When you run the expert system, it automatically runs "HYDRO2.OUT". "HYDRO2.OUT" produces a file, "HYDRO2.RPT", which contains the ASCII representation of the user defined output screen. The same screen can also be sent to the printer.

Report Generator Command File HYDRO2.OUT

```
File a:hydro2.rpt
" "
"               MECHANICAL SENSORS"
" "
Q1 1 /"         HIGH VIBRATION                        TRIPPED"
Q2 1 /"         HIGH BEARING TEMPERATURE              TRIPPED"
Q4 1 /"         BEARING COOLANT–LOW FLOW              TRIPPED"
Q3 1 /"         GENERATOR OVERSPEED                   TRIPPED"
Q5 1 /"         HYDRAULIC FLUID–LOW FLOW              TRIPPED"
Q6 1 /"         HYDRAULIC FLUID–LOW SUMP              TRIPPED"
Q23 1 /"        HIGH POWERHOUSE TEMPERATURE           TRIPPED"
Q7 1 /"         LOW HEADPOND LEVEL                    TRIPPED"
" "
"               ELECTRICAL SENSORS"
" "
Q20 1 /"         OVERLOAD RELAY                       TRIPPED"
Q19 1 /"         INSTANTANEOUS OVERCURRENT            TRIPPED"
Q21 1 /"         GROUND FAULT RELAY                   TRIPPED"
Q14 1 /"         REVERSE POWER RELAY                  TRIPPED"
Q12 1 /"         OVER-VOLTAGE RELAY                   TRIPPED"
Q13 1 /"         UNDER-VOLTAGE RELAY                  TRIPPED"
Q11 1 /"         OVER-FREQUENCY RELAY                 TRIPPED"
Q10 1 /"         UNDER-FREQUENCY RELAY                TRIPPED"

close
display a:hydro2.rpt
```

H.9 Custom Screens

Files used: HYDRO2.SCR

Some of the rules need more information that what is available from the sensors and relays. The operator / technician has to answer a question posed by the expert system in order to get the information. Normally this is done by displaying the qualifier. This was not desirable in this case for two reasons:

a. When the qualifier is displayed, a number of options are available to the operator. The operator should be able to monitor the system, but NOT be able to change the system run (ie. "QUIT" & "CHANGE").

b. More information than just the qualifier has to be given to the operator. "Custom Screen" or "Custom Help" could have been used. The "Custom Screen" option was selected because it will always display the vital information to the operator. The "Custom Help" has to be invoked by the operator ("?" key).

Custom screens were also used to display the extra data that is not included in "CHOICES", such as symptoms of the problem and remedial action. Each "CHOICE" has an associated output screen, which is triggered by a "text variable", and displayed at the end of the run. The final "CHOICES" screen is still displayed at the end to provide an overview of the probable causes of the shutdown.

The source code for the custom qualifier screens and variable screens are contained in the file "HYDRO2.SCR". This file is automatically loaded when the expert system is run

Custom Screens HYDRO2.SCR

The custom screen file contains the commands and text for each qualifier and variable screen .

```
~Q "Gov. linkage"

~border 3,12,17,66,ltred
~color yellow

~curset 5,16
Sensors indicate that governor related problems
~curset 6,16
```

caused the plant shutdown. More information is
~curset 7,16
needed.

~color ltcyan

~curset 10,21
Check the governor linkage. It is

~curset 12,21
1) o.k.
~curset 13,21
2) broken
~curset 14,21
3) jammed/seized
~curset 16,21

~Q "Hydraulic motor"

~border 3,9,18,69,ltred
~color yellow

~curset 5,14
Sensors indicate that problems with the governor
~curset 6,14
hydraulic system caused the shutdown. More
~curset 7,14
information is needed about the hydraulic pump motor.

~color ltcyan

~curset 10,18
Check the hydraulic pump motor breaker. It is

~curset 12,18
1) tripped
~curset 13,18
2) not tripped
~COLOR WHITE
~curset 16,24
RESET THE PUMP MOTOR BREAKER
~curset 14,18

~Q "Hydraulic pump"

~border 3,9,17,67,ltred
~color yellow

~curset 5,14
There is a problem with the governor hydraulic
~curset 6,14
system. More information is needed about the
~curset 7,14
hydraulic pump.

~color ltcyan

~curset 10,14
Check to see if the hydraulic pump can be turned
~curset 11,14
over freely by hand. It is

~curset 13,14
1) turning freely
~curset 14,14
2) siezed

~curset 16,14

~Q "Hyd. motor start"

~border 3,11,14,65,ltred
~color yellow

~curset 5,18
After the hydraulic pump motor breaker
~curset 6,18
has been reset, try to restart the pump.

~color ltcyan

~curset 8,18
The hydraulic pump motor will

~curset 10,18
1) start
~curset 11,18
2) will not start

~curset 13,18

~Q "Signs of water"

~border 3,11,16,65,ltred
~color yellow

~curset 5,18
The ground fault relay has tripped. Water
~curset 6,18
or excessive dampness is a common cause of
~curset 7,18
ground faults. Check for water pooled on the
~curset 8,18
floor near breaker and/or control panel.
~color ltcyan

~curset 10,18
Water or excessive dampness is

~curset 12,18
1) evident
~curset 13,18
2) not evident

~curset 15,18

~Q "Unbalanced load"

~border 3,11,18,65,ltred
~color yellow

~curset 5,18
The overload relay has tripped. Usually

```
~curset 6,18
it will trip because of a high Kw setting
~curset 7,18
or an unbalanced system load.
~curset 9,18
Restart the plant. Check the current meter
~curset 10,18
reading on each phase.

~color ltcyan

~curset 12,18
The current meter readings are

~curset 14,18
1)  balanced
~curset 15,18
2)  unbalanced
~curset 17,18


~V 1

~border 3,11,15,65,yellow
~color ltcyan

~curset 5,27
CAUSE OF PLANT SHUTDOWN
~color ltred
~curset 7,18
The governor hydraulic flow is restricted.
~curset 8,18
The most likely cause is a dirty filter.
~curset 9,18
Check / change the filter and restart the
~curset 10,18
hydraulic pump.
~curset 12,18
~color ltcyan
1)  Continue
~curset 13,18


~V 2

~border 3,11,20,65,yellow
~color ltcyan

~curset 5,27
CAUSE OF PLANT SHUTDOWN
~color ltred
~curset 7,18
The hydraulic pump motor is probally burnt.
~curset 8,18
Disconnect the supply and check the motor.
~curset 9,18
Replace if necessary.
~curset 11,18
Restricted governor hydraulic flow caused
~curset 12,18
the motor problem. The most likely cause
~curset 13,18
of the restricted flow is a dirty filter.
~curset 14,18
```

Check / change the filter and restart the
~curset 15,18
hydraulic pump.
~curset 17,18
~color ltcyan
1) Continue
~curset 18,18

~V 3

~border 3,11,18,65,yellow
~color ltcyan

~curset 5,27
CAUSE OF PLANT SHUTDOWN
~color ltred
~curset 7,18
The hydraulic pump has seized because of
~curset 8,18
normal wear or misalignment. The pump
~curset 9,18
motor is o.k.. Replace pump.
~curset 11,18
Restricted governor hydraulic flow was NOT
~curset 12,18
the cause of the problem. Check the filter
~curset 13,18
anyway.
~curset 15,18
~color ltcyan
1) Continue
~curset 16,18

~V 4

~border 3,11,20,65,yellow
~color ltcyan

~curset 5,27
CAUSE OF PLANT SHUTDOWN
~color ltred
~curset 7,18
The generator rotor may be damaged due
~curset 8,18
to the sustained overspeed. Excessive
~curset 9,18
vibration is an indication of this problem.
~curset 11,18
The overspeed must have been caused by
~curset 12,18
both the wicket gates and the main valve
~curset 13,18
being jammed at the same time. The shut-
~curset 14,18
down procedure tries to close both. Check
~curset 15,18
for debris at both locations.
~curset 17,18
~color ltcyan
1) Continue
~curset 18,18

```
~V 5

~border 3,11,19,63,yellow
~color ltcyan

~curset 5,27
CAUSE OF PLANT SHUTDOWN
~color ltred
~curset 7,18
The broken or jammed linkage caused a loss
~curset 8,18
of governor control.  The resultant over/
~curset 9,18
under frequency trip shed the load.  The
~curset 10,18
wicket gates and main valve must be
~curset 11,18
jammed with debris, making it impossible
~curset 12,18
to stop the flow, causing the overspeed.
~curset 13,18
Check the gen. rotor & bearings for damage.
~curset 14,18
Clear the debris at valve & wicket gates.
~curset 16,18
~color ltcyan
1)  Continue
~curset 17,18


~V 6

~border 3,11,20,68,yellow
~color ltcyan

~curset 5,27
CAUSE OF PLANT SHUTDOWN
~color ltred
~curset 7,18
The overload relay had tripped.  This is
~curset 8,18
the result of high generator winding
~curset 9,18
temperatures.  Abnormally high powerhouse
~curset 10,18
temperatures, a high Kw setting, or an
~curset 11,18
unbalanced system load could cause the problem.
~curset 13,18
A high Kw load setting is the most likely
~curset 14,18
cause of the present problem.  Reduce the
~curset 15,18
setting.
~curset 17,18
~color ltcyan
1)  Continue
~curset 18,18


~V 8

~border 3,11,20,65,yellow
```

```
~color ltcyan

~curset 5,27
CAUSE OF PLANT SHUTDOWN
~color ltred
~curset 7,18
The overload relay had tripped.  This is
~curset 8,18
the result of high generator winding
~curset 9,18
temperatures.  Abnormally high powerhouse
~curset 10,18
temperatures, a high Kw setting, or unbalanced
~curset 11,18
system load could cause the problem.
~curset 13,18
An unbalanced system load is the most likely
~curset 14,18
cause of the present problem.  CALL "NFLD.
~curset 15,18
HYDRO" FOR ASSISTANCE.
~curset 17,18
~color ltcyan
1)  Continue
~curset 18,18


~V 7

~border 3,11,20,65,yellow
~color ltcyan

~curset 5,27
CAUSE OF PLANT SHUTDOWN
~color ltred
~curset 7,18
The overload relay had tripped.  This is
~curset 8,18
the result of high generator winding
~curset 9,18
temperatures.  Abnormally high powerhouse
~curset 10,18
temperatures, a high Kw setting, or unbalanced
~curset 11,18
system load could cause the problem.
~curset 13,18
High powerhouse room temperature is the most
~curset 14,18
likely cause of the present problem.  Check
~curset 15,18
the cooling fan and clear the air intake.
~curset 17,18
~color ltcyan
1)  Continue
~curset 18,18


~V 9

~border 3,11,18,65,yellow
~color ltcyan

~curset 5,27
```

CAUSE OF PLANT SHUTDOWN
~color ltred
~curset 7,18
The instantaneous overcurrent relay had
~curset 8,18
tripped. This is an indication of serious
~curset 9,18
damage to the generator windings.
~curset 11,18
Do a thorough electrical and visual check
~curset 12,18
of the stator and rotor windings. Also
~curset 13,18
check the main cable feeder.
~curset 15,18
~color ltcyan
1) Continue
~curset 16,18

H.10 System Configuration Options

File used: HYDRO.BAT

The "HYDRO.BAT" file is a short batch file which automatically executes the run-time version of Exsys Professional and the "Small Hydro-Plant Diagnostics" files (ie. HYDRO2.RUL, etc.).

Batch File Listing

```
ECHO OFF
CLS
EXSYSP HYDRO2
```

File used: HYDRO2.CFG

The custom configuration file, "HYDRO2.CFG", customizes the Diagnostics Expert System, and is automatically used when "HYDRO2.*" files are loaded.

Configuration File Listing

```
CHANGEOFF
NOQUESTIONS
ENDMSG=DIAGNOSTIC SYSTEM ERROR.
READHELP
LIMITOFF
HELPOFF
QUITOFF
REDISPOFF
```

a. **CHANGEOFF**

CHANGEOFF disables the change and rerun feature. The operator should be able to monitor the expert system, but not change the value of the qualifiers. The qualifier values are set by the PLC.

There is another command called LIMITOPTIONS, which can do the job of CHANGEOFF. It was not used because it also disabled PRINT on the output screen. PRINT is needed to ensure that the operator can, at any time, view the report generator screen which shows the sensors that are tripped.

b. **LIMITOFF**

Prevents the user from changing the threshold limit value for displaying choices.

c. **HELPOFF**

Disables the expert system shell "HELP", not the "custom HELP" feature.

d. **QUITOFF**

Prevents the user from quitting the expert system from a qualifier screen or the final conclusion screen. The user can still exit the program from the final screen via the "DONE" command.

f. **NOQUESTIONS**

Eliminates the questions asked of the user at the beginning of the run. A final application, such as the "Diagnostic Expert System", has to have good control over who has access to the program. "NOQUESTIONS" is one way of limiting access.

At the beginning of the run, the title screen will be displayed and then the rules will be executed. The user will not be given the option to display rules.

g. **ENDMESSAGE**

If none of the CHOICES available has a value greater than the threshold value, then there must be a problem with the hardware or software. A message is displayed providing information on who to call for help.