UTILITY INTERACTIVE FUEL CELL INVERTER FOR DISTRIBUTED GENERATION: DESIGN CONSIDERATIONS AND EXPERIMENTAL RESULTS

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Abstract

Distributed Generation (DG) systems are potential solutions for efficient and economic integration of many non-conventional energy sources into the existing power grid. Among various alternative power sources, fuel cells are strong candidates for DG applications. Suitable interfacing of such resources into the DG network critically depends on design and performance of the power conversion stage.

In this work, the design and experimental results of a utility interactive fuel cell inverter system for DG application are discussed. A series resonant DC-DC converter coupled with a Sinusoidal Pulse Width Modulated (SPWM) inverter is considered as the power stage. While connected to the grid, the inverter works in the current controlled mode. Stand-alone mode of operation is maintained through a voltage-controlled scheme. A DSP (TMS320F2812) based feedback control architecture and aspects of utilizing Controller Area Network (CAN) Fieldbus within the DG network are discussed. Compatibility with the existing DG standards, cost issues, and performance indices are analyzed with reference to experimental results. Control, communication, and challenges of integrating fuel cell systems into the distribution grid are also highlighted.

***Keywords**: Power Electronics, Fuel Cells, Distributed Generation*

1. Introduction

With the advent of a deregulated energy industry, the concept of distributed electricity production is gradually taking shape. Distributed Generation (DG) could be defined as small-scale power generation plants diffused into the distribution side of the power grid that is either interconnected to the utility grid, or directly supplying consumer load or both. Unlike conventional centrally controlled power systems, this concept allows integration of a wide array of technologies (Diesel/Gas internal combustion engines, Stirling engines, Microturbines, Gas turbines, and Fuel cells) and could be placed conveniently near the consumer site. Many remotely located renewable sources such as, wind turbines, solar energy modules, biomass plants etc. could also be allowed to contribute power to the grid. However, enabling technologies that would create a low-cost, efficient and reliable interface between such sources and the utility (paralleled to the load) has only started to emerge [1].

Fuel cells are electrochemical devices that convert chemical energy contained in a fuel directly into electrical energy (with heat and water as exhausts). Among various non-renewable technologies, fuel cells are the cleanest and the most efficient. Modularity, scalability and dispatchability are also several favorable features [1]. However, high cost, technology immaturity and operational transients are obstacles that need to be removed. From power electronic point of view, conversion of a widely varying DC output of a fuel cell into grid compatible AC power is an aspect that needs to be addressed. The latter issue of grid integration is probably the more intriguing one, which equally applies to other distributed resources within the DG network.

In this work, various requirements of a fuel cell based distributed generation node are analyzed from the power electronics and controls perspective. A Polymer Electrolyte Membrane (PEM) fuel cell system has been considered as the DC source for the inverter. Design of a prototype system along with some experimental results is given with regard to technical discussions. The long-term objective of this work is to develop a fuel cell-power electronic interface that would meet certain performance and cost criteria to be commercially successful. Instead of focusing on the inverter alone, investigation of the broader concept for placing a fuel cell inverter system into the DG network through a suitable control and communication mechanism is attempted.

2. Control and Power Electronic Requirements

The interface between a fuel cell system and the utility grid (coupled with a consumer load) has two broad and interrelated fields where certain requirements need to be met, namely, power electronics and controls. These issues could be directed towards four areas (Fig. 1) [2]:

(a) Fuel Cell – Power Stage Interface
(b) Storage – Power Stage Interface
(c) The Power Stage
(d) Power Stage-Grid/Load Interface

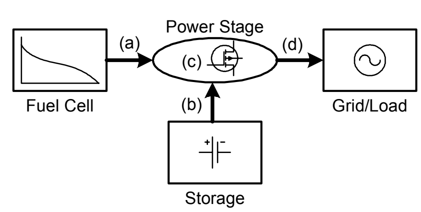

Figure 1: Breakdown of system requirements

(a) Fuel Cell – Power Stage Interface:

When a fuel cell is connected to the power stage, low frequency ripple and backward current injection may reduce the operational lifetime of the system. Therefore, adequate protection against such adversities needs to be provided. A galvanic isolation between the load and the fuel cell is also desired. The output of a fuel cell may vary widely (30-60V DC). Such variation needs to be processed within the power stage. The fuel cell system cannot deliver power during the start-up (in the range of hours) and operating transient (seconds to minutes) conditions. Therefore, an energy storage medium is essential for continuous dispatchability. A fuel cell has soft voltage characteristics and is more responsive to current changes. Therefore, a current mode control of the fuel cell is generally desired.

(b) Storage – Power Stage Interface

Additional auxiliary energy storage device (Battery, Ultracapacitor etc.) is almost vital for a fuel cell system. The placement of this unit (Low voltage side, or High voltage side) and subsequent topology selection (Parallel connection, or Bi-directional DC/DC converter, respectively) are also important considerations from performance and cost point of view.

(c) The Power Stage

The design of a power stage is more of an issue related to proper optimization between efficiency, cost, size and weight than of a technological innovation. Performance, manufacturability, and modularity are also important for batch production of such systems. A high frequency link step-up converter is desired for achieving galvanic isolation, high step-up ratio, lower size and higher efficiency. This stage essentially provides a fixed voltage level (higher DC or AC) against the variable DC output of a fuel cell. Another power stage is required for converting this stiff voltage into grid/load compatible AC voltage [3,4].

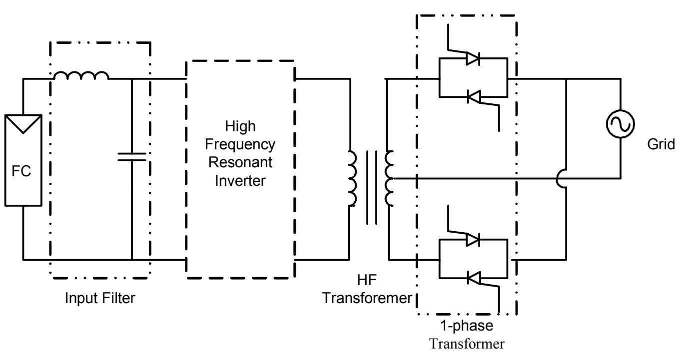

Figure 2: High frequency inverter with cycloconverter

Two topologies that have gained significant attention are given in Fig. 2 and Fig. 3. Each design has its own merits and demerits. However, the topology in Fig. 3 is probably more suited considering availability of off-the-shelf devices, control simplicity and richness of knowledge base.

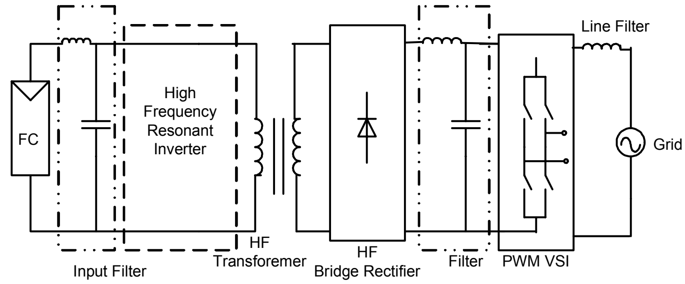

Figure 3: High frequency DC/DC stage with Inverter

(d) Power Stage-Grid/Load Interface

With regard to interfacing a power stage to the utility grid or stand-alone load, the control issues are more profound than the physical link itself. Performance, safety and power quality issues outlined by the IEEE-1547 standard are a set of benchmark guidelines for such application. Islanding protection, grid synchronization, seamless switching between grid connected and standby mode are some of the intriguing challenges that need to be solved in the controls and algorithm domain. Additionally, the control methodology is linked to the real-time (non-critical) communication mechanism between various DG elements (resources, loads and control centers).

3. Experimental Prototype

At Memorial University of Newfoundland a utility interactive fuel cell inverter system for application in DG network is being designed as part of the Atlantic Innovation Fund's "Beyond Kyoto: Atlantic Sustainable Power R&D Initiatives (ASPRI)" project. The long-term goal of this work is to develop a 2.5 kW fuel cell inverter system with greater range of features such as, cost-effective design, DG communication interface and compatibility with IEEE-1547 standard. Any development with such comprehensive detail is quite involved and time consuming. Therefore, an interim prototype with power, control and communication interfaces (without energy storage and split phase option) is being built at present.

The power stage consists of a high-frequency link DC/DC converter coupled with a Pulse Width Modulated (PWM) inverter (Fig. 4, Fig.5) in accordance with the topology outlined in Fig. 3. Additionally, three filter stages (Input, DC bus, and Line filter) are being considered. The fuel cell output voltage is taken to be 30-60V DC and peak power demand is considered as 5 kW.(presently a battery bank is being used as a DC source) The high frequency H-bridge inverter consists of IRFP2907 MOSFETs operated at 200kHz. A 5.6 kW planar transformer (Payton Planar Co., T1000AC-1-12) is being used for AC coupling and step up operation (Ratio = 1:11). Ultra-fast-recovery diodes (HFA50PA60C) are employed for rectification of the high-voltage high-frequency AC. The voltage source inverter unit consists of a H-bridge of IGBTs (IRG4PC30UD). Texas Instrument's TMS320F2812 based off-the-shelf kit eZdsp™ F2812 has been selected for control and communication purposes. Controller Area Network (CAN) interface between the inverter system and the DG network is also being investigated.

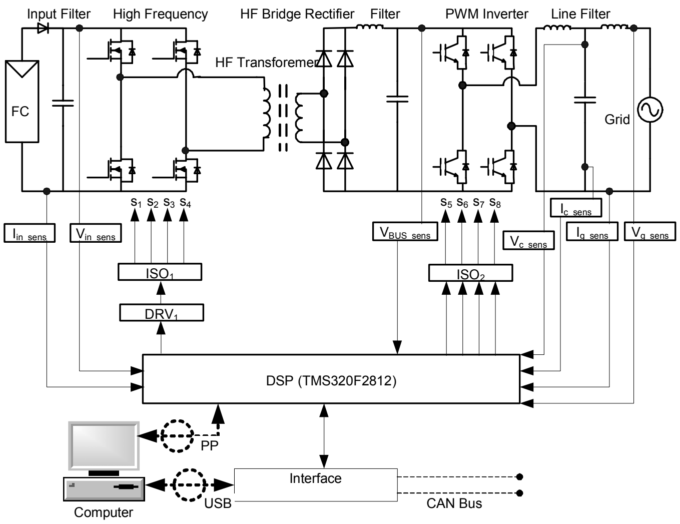

Figure 4: Single phase inverter prototype

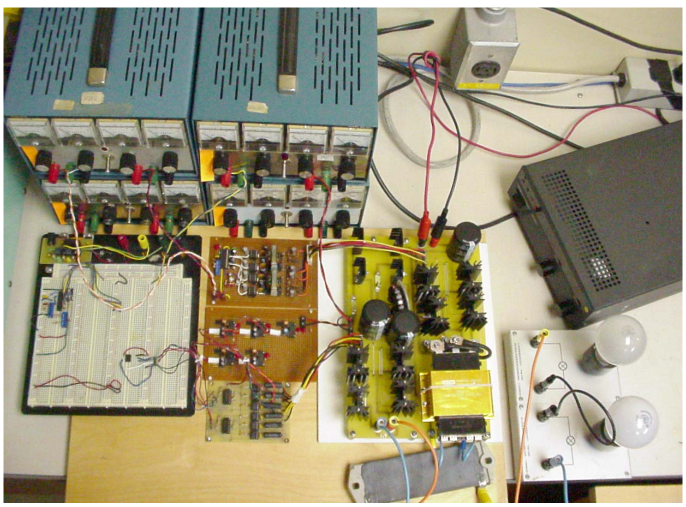

Figure 5: Prototype power and driver stage

For high frequency operation of the MOSFET H-bridge and control simplicity, Texas Instrument's UCC3895 IC with voltage/current controlled phase-shifted PWM capability has been found to be the most suitable option. Although the final design would contain resonant components for ZVS (zero voltage switching) at the high frequency inverter output, at present, only phase-shifted operation is being pursued at the cost of higher switching losses.

The proposed inverter system would operate in two distinct modes: Stand-Alone Mode and Utility Interactive Mode. In the former state, the inverter delivers power to a load with a fixed voltage and frequency under 'vo*ltage- controlled mode'*. When connected to the utility, the grid determines the output voltage and frequency. Therefore, for a demanded level of power injection, the inverter operates in the 'c*urrent controlled mode'* while connected to the grid [5]. For grid synchronization, the embedded phase locked loop (PLL) within the DSP could be utilized.

In Fig. 6 and Fig. 7, waveforms at the high-frequency inverter and PWM inverter are given for a particular observation.

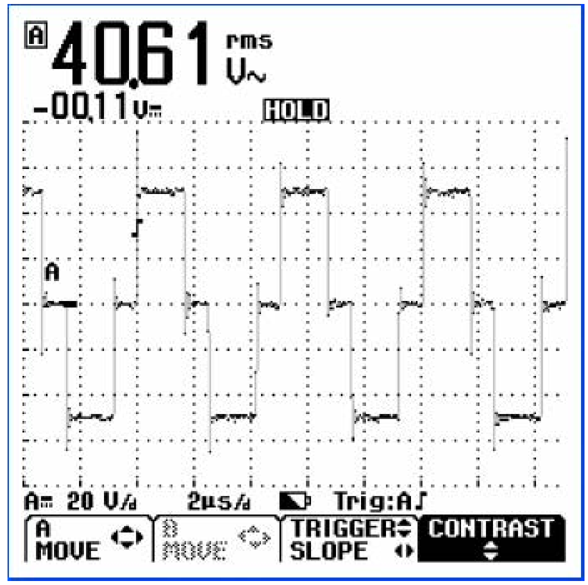

Figure 6: High frequency inverter output

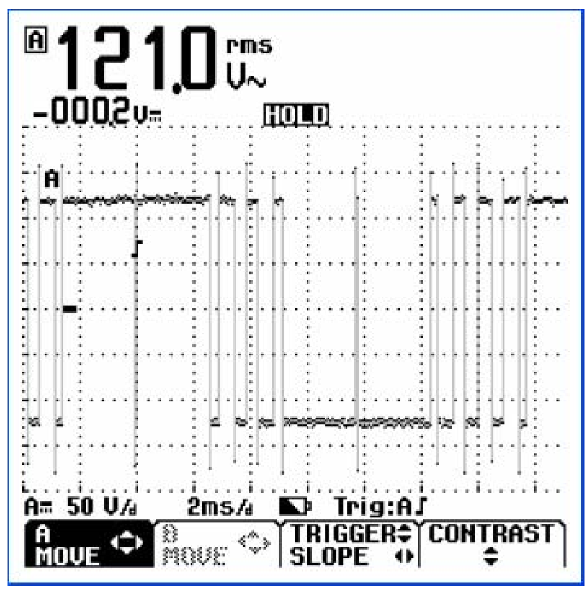

Figure 7: PWM voltage source inverter output

4. Further Work

The Development of a power electronic interface for a distributed resource with all desirable features is a monolithic task. As the market and infrastructural models of DG network with necessary dynamics and flexibility are only emerging, effective integration of an isolated resource to the utility grid appears to be even harder [1].

A DG network with control and communication interfaces could be envisioned with an architecture given in Fig. 8. Dispersed power generators and consumers loads are connected to the utility grid. These are controlled with distributed-intelligent controllers (DSP, Microcontroller etc.) with a CAN interface allowing real time communication with the rest of the system. Controller Area Network (CAN) has traditionally been used in the automotive industry. The simplicity, reliability and cost-efficiency is pushing this technology into diverse fields of application, especially in process and manufacturing industry [6]. A CAN network system with additional features such as repeaters and gateways could be an off-the-shelf solution for DG network communication. An aggregate of smaller DG units (at times called Microgrid, or Area Electric Power System) could be run by Independent System Operators (ISO). Several ISOs along with conventional utility operators would make up a complete system.

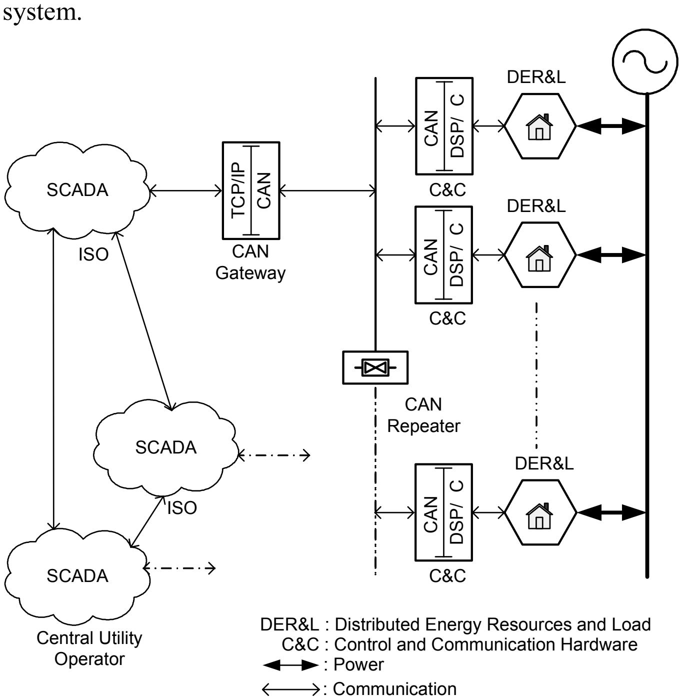

Figure 8: Communication and control system of a DG network

The control problem could be divided into three parts: Critical, Dispatch and Supervisory. Critical control is required within the power electronic, and protection circuitry with minimal need for communication. This is preferably implemented in the hardware level interface between the grid, generator and load. Some scheduling and load sharing capacity should also be embedded with the distributed controllers for economic operation (Dispatch control). Finally, supervisory control through SCADA systems would allow coordination between various DG elements.

5. Conclusions

With a brief look at the aptness of fuel cells in a Distributed Generation network, various critical requirements of a power electronic interface have been outlined in this work. Several design aspect of a prototype system along with some initial test results are also given. A broader overview of DG network communication and control architecture is given with a view to indicating the range and scope of further development. In conclusion it should be emphasized that contribution from many different research fields need to be combined for developing an effective system.

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