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Design Considerations of a Utility Interactive Fuel Cell Inverter

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***Abstract*—The concept of deregulated energy infrastructure is rapidly shaping the future of power generation and grid constitution. Control, communication and integration of various alternative energy resources within a Distributed Generation (DG) network have opened up areas of new challenges and opportunities. The power interface between a fuel cell system and the distribution grid is one such intriguing issue.**

With the advent of various grid-interactivity, safety, efficiency and power quality standards (such as, IEEE 1547), the design of a cost effective-high performance power electronic inverter for a fuel cell system is a challenge. In this paper, various design criteria, topologies and control aspects of a grid-tied fuel cell inverter are discussed. An overview of some fundamental design standards, and a systematic approach for topology selection is given. An outline of a possible DSP based hardware configuration, communication and control is also provided. Initial simulation of the proposed scheme along with considerations for practical implementations of fuel cell inverter are discussed.

***Index Terms*—Fuel cell, Distributed Generation, Single Phase Inverter, Controller, Modeling and Simulation**

I. INTRODUCTION

WITH increasing interest in alternative energy systems wind, solar, micro-hydro, biomass and fuel cell based power sources are being considered for domestic, commercial and industrial installations in various parts of the world. Solar and wind power based systems are forerunners in this category. Bulk energy production from renewable sources for commercialization through the main electricity grid has been regarded as a success in many countries. However, connecting smaller energy sources for injecting power into the grid is a relatively novel concept. This idea of tying small-scale alternate power sources to the distribution grid for commercial purposes is termed as Distributed Generation (DG) [1,2]. It is expected that, utilization of distributed energy resources would be economical and beneficial to the overall power scenario, in terms of power quality, reliability and energy efficiency.

Power from almost all of these alternative systems is either inherently variable or dependent on environmental conditions. A power-conditioning unit is therefore required to extract usable energy from these sources. There is a great research need to provide directions and solutions in designing low-cost, high-performance, efficient and reliable power converters for such systems [1,3].

Fuel cells are electrochemical devices that convert energy in the hydrogen fuel directly into electrical energy and water vapor. This technology is potentially suited for a diverse field of applications such as, automobile, residential houses, and consumer electronics. Flexibility of fuel usage, scalability, longevity and emission free operation make this a good alternative for future power generation.

This paper focuses on various issues regarding interconnection of fuel cells to the utility grid through a power-conditioning unit. Various policy and regulatory issues along with cost and performance conditions dominate the design of such a power converter. These non-technical aspects are discussed in Section II. A review of various available power electronic solutions and inverter topologies are discussed in Section III. Power electronic converter for fuel cell systems and their controller design procedures are discussed in Section IV. Based on these discussions, two inverter systems are approached for further analysis, followed by a computer-based modeling (using MATLAB-Simulink™ environment) in Section V. Simulation results and an outline of DSP based implementation method are discussed in Sections VI and VII, respectively.

II. SYSTEM REQUIREMENTS

Utility interactive inverter systems are defined as power conditioning units that maintain sufficient flexibility and robustness to interact with the power distribution grid. Variations in grid voltage, frequency, and outage are some of the aspects that an inverter should be capable of handling. Power quality, safety, electromagnetic interference (EMI), reliability, efficiency, cost, size, weight etc. are some of the deciding factors that determine the practical usability of such an inverter [3,5,6]. There exists a number of regulatory and policy directions for interconnecting distributed energy resources to the grid. IEEE standard 1547™ [6] is the most recent and well-researched document for such systems. Several issues outlined in this standard along with some practical considerations [5] are highlighted below:

A. *Grid Interactivity*

The inverter system should be able to detect the grid automatically and start delivering power upon a controlled

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request. Whenever a grid outage occurs, the inverter should disconnect itself immediately from the utility to avoid islanding. The unit can also be designed for standalone when needed. An agreed list of tolerance level in voltage and frequency is given in Table I [5,6].

TABLE I
VOLTAGE AND FREQUENCY VARIATIONS ACCEPTABLE LIMITS

Voltage	Tolerance
110V	Variation: +15% ~ -20%
240V	Variation: +15% ~ -20%
<50V	Clearance time: 0.16s
50<V<88	Clearance time: 2.0s
110<V<120	Clearance time: 1.00s
V>120V	Clearance time: 0.16s
Frequency	**Tolerance**
60 Hz	Variation: ± 2%
50 Hz	Variation: ± 2%
>60.5 Hz (<30 kW)	Clearance time: 0.16s
<59.3 Hz (<30 kW)	Clearance time: 0.16s
<59.8-57.0 Hz (>30 kW)	Clearance time: 0.16s ~ 300s

B. *Power Quality*

The power should have a low harmonic distortion (typically 5% or better) and good peak power capability (typically 5:1) (Table II).

TABLE II
HARMONIC ORDER AND ACCEPTABLE RANGES

Individual Harmonic Order,h (odd Harmonics)	H < 11	11 ≤ H < 17	17 ≤ H < 23	23 ≤ H < 35	35 ≤ H	Total Distortion
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

C. *Performance*

The fuel cell based inverter system should have an overall efficiency of 90% or above, with power level varying from 5% to 100%. The input could be a variable DC source with wide range of variation (for 1 kW system, DC input voltage may vary from 30V to 60V). A modular design scheme run by simple control mechanism should be followed to increase reliability.

D. *Safety and Other Issues*

Galvanic isolation, lifetime, environmental conditions, noise, EMI, protection, auxiliary storage device are also significant factors in designing inverter systems. Therefore, available industry standards need to be followed in the design level.

III. SURVEY OF INVERTER TOPOLOGIES

Fuel cell output voltage is a variable DC, usually much lower than the r.m.s. value of the grid voltage. Therefore a boost stage is generally used in the converter. To protect the power source, a galvanic isolation is required. Two fundamental converter topologies are shown in Fig 1.

The topology in Fig .1(a) requires a low frequency transformer at the second stage, which makes the system heavy and costly. In most cases the second topology is chosen. It gives a range of options in designing DC-DC converters and using different switching and control schemes. This topology could be further classified in two major categories: Voltage-fed and current-fed (Fig 2) inverters.

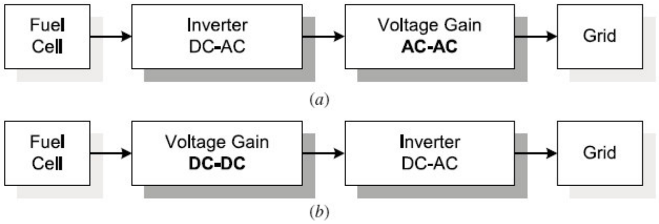

Fig. 1. (a) Inverter with AC boost stage (b) DC boost stage with inverter

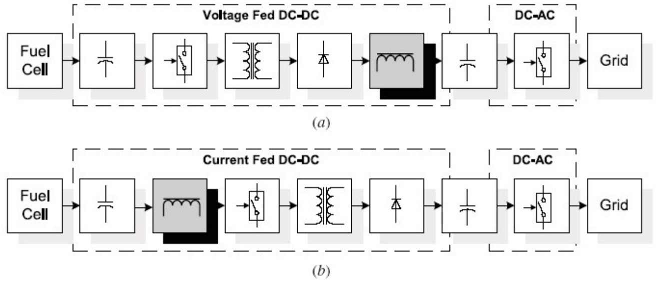

Fig. 2: (a) Voltage fed converter (b) Current fed converter

The DC-DC boost stage in the voltage fed converter may use a conventional-boost, forward, fly-back, or High-frequency link converter. On the other hand the current fed scheme may utilize a push-pull or full-bridge converter at the DC-DC stage [7]. A further classification of these topologies are given below:

A. *PWM Inverter with Low Frequency Transformer*

In this scheme, the low-level DC voltage of the fuel cell is inverted by a Pulse Width Modulated (PWM) inverter and fed to the grid through a line-frequency transformer (Fig. 3). This structure is also robust, simple and provides proper boost and isolation with minimum number of components.

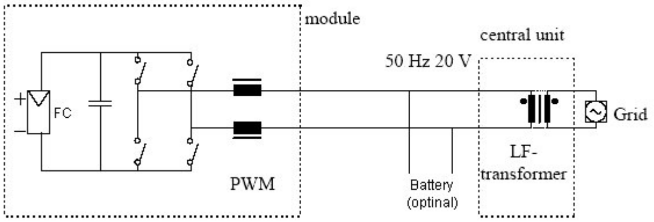

Fig. 3. PWM Inverter with Low Frequency Transformer

On the contrary, the transformer size is comparatively large in order to deliver sufficient power to the grid. The only control available for the inverter is the PWM modulation of the power switches. These limitations make the topology practically unsuitable for most applications.

B. *Boost Converter, PWM Inverter with Low-Frequency Transformer*

The switch mode boost converter increases the DC input voltage to a higher level. For many cases, the amplification cannot be done with only one boost stage. Therefore, the inverted output of the PWM inverter is further stepped up with the low-frequency transformer (Fig. 4).

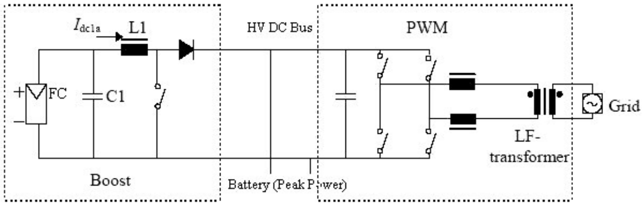

Fig. 4. Boost Converter, PWM Inverter and Low-Frequency Transformer

Even though higher degree of control is available in this configuration, the need for transformer is still an obstacle. The hard switching of the boost converter makes it less efficient and requires higher heat dissipation mechanisms.

C. *Forward Converter with PWM Inverter*

The limitations of the previous topology could be overcome by a forward converter acting as the only boost stage. The output of the PWM inverter could then be directly connected to the grid through filters (Fig. 5).

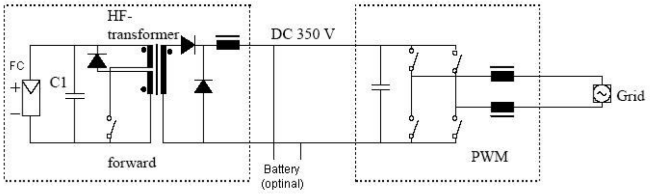

Fig. 5. Forward Converter and PWM Inverter

The disadvantage of this configuration is, a high ripple in the input current requires a large input capacitor. The DC bus contains high-voltage square wave signals, which creates electromagnetic interference (EMI) problems.

D. *Flyback Converter with PWM Inverter*

The flyback converter boosts the DC voltage and the PWM inverter generates an approximate sine wave. Even though simplicity and low cost are advantages of such topology, it is suitable for low power applications (Fig. 6).

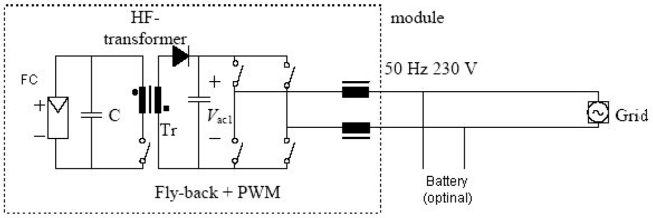

Fig. 6. Flyback Converter and PWM Inverter

High stress on the switch makes this circuit unsuitable for higher kW range applications.

E. *Square Wave Transformer Feeding a PWM Inverter*

The H-bridge inverter feeds a square wave current to the transformer, which boosts it up to a higher level after rectification on the secondary side. The second inverter converts this DC into AC for direct integration with the grid (Fig. 7).

Assuming the transfer inductance of the transformer to be high, the inductor in the high voltage DC bus could be eliminated. This topology is more dependent on solid-state switches than passive components and has gained more applicability than the previous configurations [8].

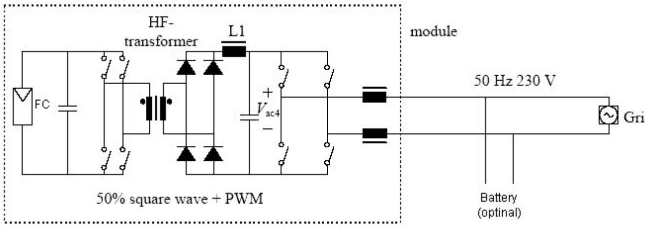

Fig. 7. Square Wave Transformer Feeding a PWM Inverter

F. *High Frequency Resonant Inverter-Cycloconverter*

The high-frequency-resonant-inverter (HFRI) converts the variable DC output of the fuel cell into a higher-level AC voltage. However, the frequency of the HFRI is much higher compared to the grid. Therefore, a cycloconverter could be could be used for adjusting the frequency (Fig. 8).

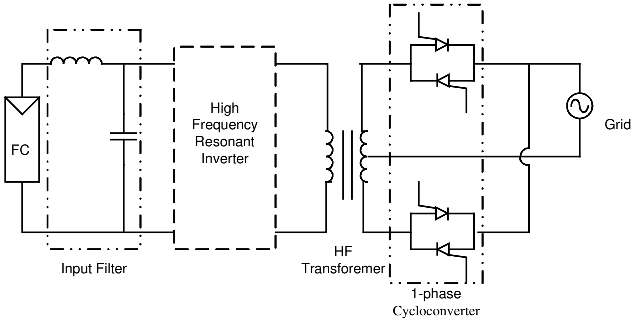

Fig. 8. High Frequency Resonant Inverter-Cycloconverter

The response of the system is fast, power factor is good, number of stages is limited to two, and line connectivity is simple. However, realization of a cycloconverter and its control circuitry is relatively complicated.

G. *High Frequency Resonant Inverter-Rectifier-PWM VSI*

The HFRI-rectifier-PWM Voltage Source Inverter (VSI) is one of the most suitable topologies in terms of cost, size, and efficiency. It has a fast response, good power factor, and favorable overall performance (Fig. 9).

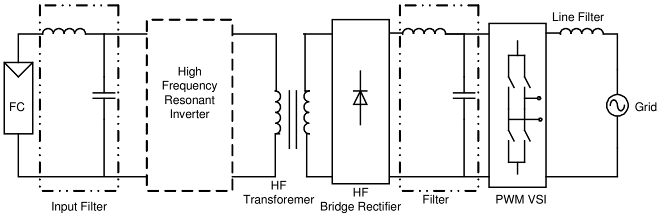

Fig. 9. High Frequency Resonant Inverter-Rectifier-WM VSI

It requires a line filter for grid connection and suitable control circuitry for driving the resonant inverter at the boost stage and the voltage source inverter at the final stage.

H. *High Frequency Resonant Inverter-Rectifier-LCI*

In this scheme a high-frequency inverter, rectifier and Line Commutated Inverter (LCI) are used. The inductor at the high voltage DC bus makes the previous assemblies appear as a current source to the PWM inverter.

The line-commutated inverter (LCI) operates at the maximum firing angle. The utility line current approximates square wave and hence proper harmonic filter is required. The control operation is conducted by adjusting the frequency of the HFRI inverter (Fig. 10).

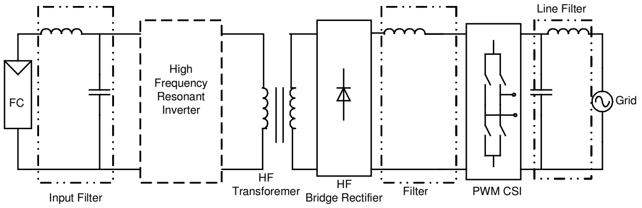

Fig. 10. High Frequency Resonant Inverter-Rectifier-LCI

IV. ANALYSIS OF GRID INTERACTIVE INVERTER

The grid-connected inverter is probably the most significant component in the utility interfaced fuel cell system. Initially, one inverter with a third order filter (LCL type) and its necessary control methods are investigated (Fig. 11). In the latter section, a simplification using a first order filter (L type) is employed to analyze a complete fuel cell based utility interactive system (Fig. 17).

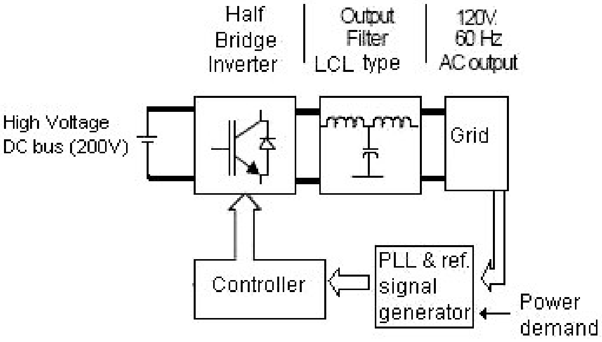

Fig. 11. Analysis of Grid Interactive Inverter

A single-phase half-bridge voltage source inverter connected to the grid through a third order (LCL type, Fig. 11) filter is discussed in reference [11]. Dynamic small-signal modeling, selection of control variables, and investigation of control methods are investigated in the sections to follow.

A. Selection of Controller Variables

It is required that the injected current to the grid should in phase with the grid voltage to have near-unity power factor. Variations of the grid voltage and frequency should also be encountered sufficiently. To reduce stress on the switches, the switching frequency should be optimum. On the other hand, switching frequency need to be high enough to allow use of smaller filter. Proper control variables should be chosen to maintain stability of operation. In a practical system, the grid voltage and frequency could be sensed by a Phase Locked Loop (PLL) device. The dynamics of a PLL should also be taken into account for designing the controller.

A single phase half bridge voltage sources inverter with LCL filter may have a number of parameters to be considered for feedback control. The inverter output voltage, V_{inv}, Inverter output current, I_{inv}, Capacitor voltage V_c, Capacitor current I_c and Grid current, I_{grid} are such parameters (Fig. 12). Since the grid voltage is determined by the utility, the injected grid current, I_{grid} need to be controlled. At the first look it may appear that, direct sensing and control of I_{grid} would be enough to achieve the control goal. However, a root locus plot for these parameters using the small-signal dynamic models [11] shows several significant deviations.

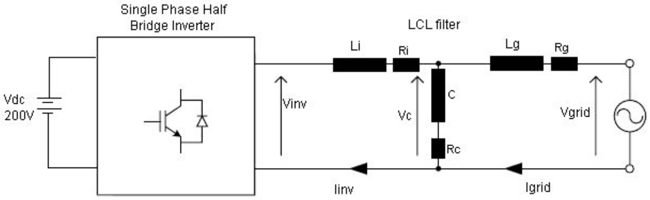

Fig. 12. Selection of control variables

A root-locus plot of these parameters using equation set (1) yields that; Grid current I_{grid} has two of its poles on the right-hand side of the S-plane, making it unsuitable for stable operation (Fig. 13).

$$\frac{\begin{bmatrix} \hat{i}_{grid} \\ \hat{v}_c \\ \hat{i}_c \\ \hat{i}_{inv} \end{bmatrix}}{\hat{d}} = \frac{\dfrac{2V_{dc}}{L_1}\begin{bmatrix} 1/L_g C \\ 1/C(s+R_g/L_g) \\ s(s+R_g/L_g) \\ s^2+R_g s/L_g+1/L_g C \end{bmatrix}}{s^3+a_2 s^2+a_1 s+a_o} \tag{1}$$

Where, a_o, a_1, a_2 depends on R_i, L_i, R_g, L_g and C [11].

On the contrary, capacitor current I_c, and Inverter current I_{inv} have their poles on the left-hand side of the S-plane for the closed loop root-locus analysis (Fig. 14, 15). Capacitor voltage V_c shows oscillating pattern along the imaginary axis (Fig. 16).

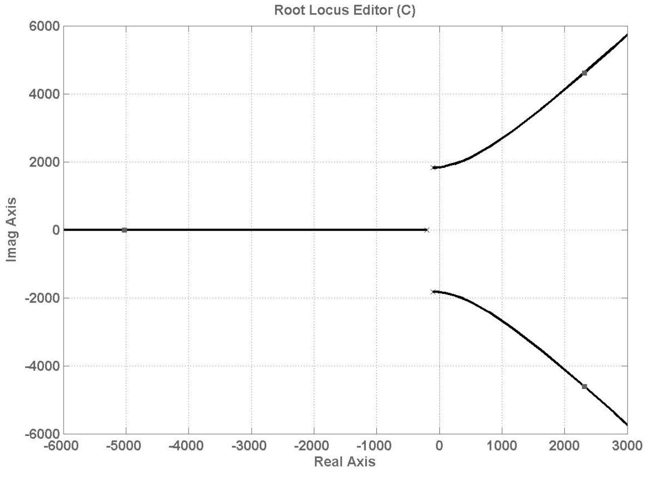

Fig. 13. Root-locus of Grid current, I_{grid}

A multiple feedback loop indirect control method for allowing the inverter to inject current to the grid at a specified power factor and harmonic distortion level is used [11]. The capacitor current, I_c is used as the inner-loop feedback variable whereas the capacitor voltage, V_c is used in the outer loop.

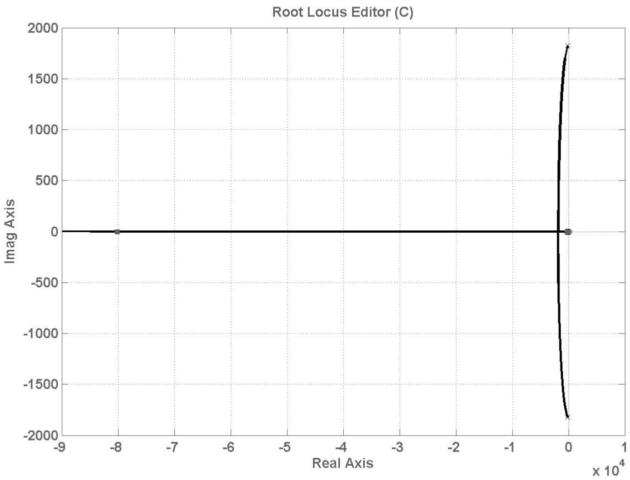

Fig. 14. Root-locus of Capacitor current, I_c

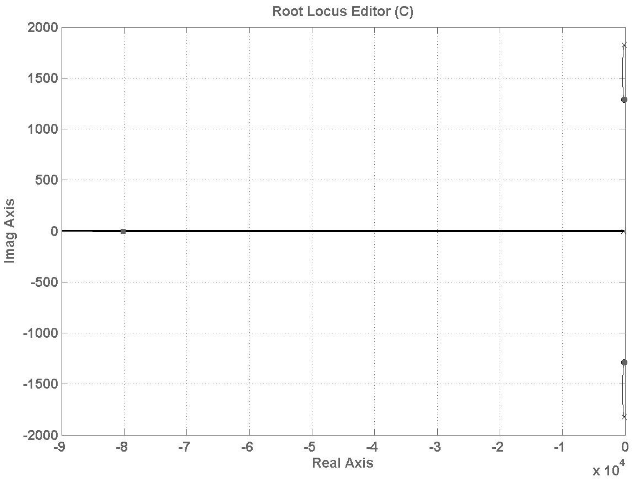

Fig. 15. Root-locus of Inverter current, I_{inv}

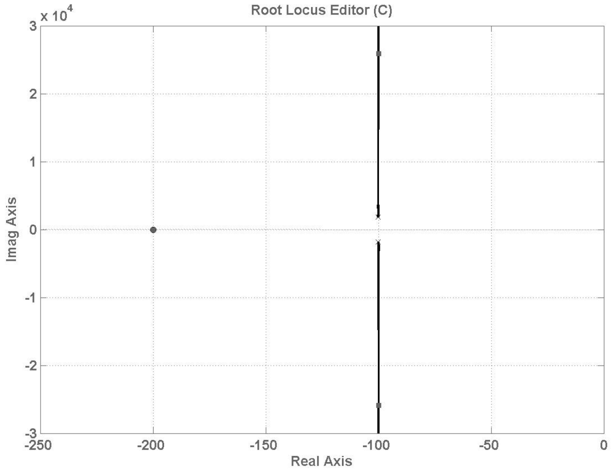

Fig. 16. Root locus of Capacitor voltage, V_c

For a demand grid current, I_{grid} (with a specific power factor), the reference capacitor voltage, V_{cref} could be found by back calculation using the LCL filter component values.

$$V_{cref} = I_{grid} X_{Lg} + V_{grid} \tag{2}$$

Where, X_{Lg}, is the inductive filter reactance at the grid side, which is composed of the inductor L_g and parasitic resistance R_g. For unity power factor operation,

$$\begin{aligned} V_{cref} &= V_{Lg} + V_{Rg} + V_{grid} \\ V_{cref} &= L_g \frac{dI_{grid}}{dt} + I_{grid} R_g + V_{grid} \end{aligned} \tag{3}$$

Similarly, the reference capacitor current, I_{cref} could be generated using the Capacitor voltage V_{cref} and values of the capacitive branch components.

$$V_{cref} = V_c + I_{cref} R_c \tag{4}$$

Modifying further and solving the following sets of equations, I_{cref} is determined.

$$\begin{aligned} V_{cref} &= V_c + R_c C \frac{dV_c}{dt} \\ I_{cref} &= C \frac{dV_c}{dt} \end{aligned} \tag{5}$$

Where, C and R_C are the capacitor and parasitic resistor in the capacitive branch. These reference signals are generated from the demand grid current, I_{grid} and could be used for controlling V_c and I_c towards fulfilling the control goal.

B. *Fuel Cell Inverter*

A complete system made up of a 1 kW fuel cell, a DC-DC high frequency link boost converter, a dual-half bridge inverter (for split phase supply, i.e., both 120V/60 Hz and 230V/50Hz) with line filter and control mechanism is analyzed in the following sections. Use of a LCL type filter is avoided in order to observe the performance of the complete system within a reasonable simulation time.

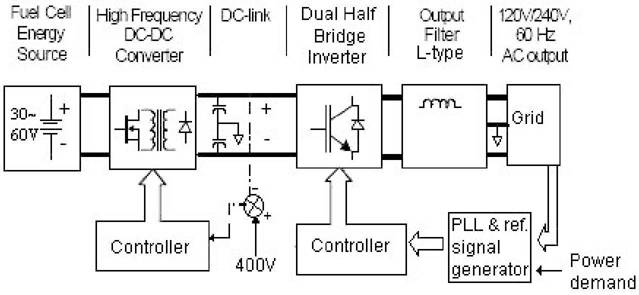

Fig. 17. Analysis of a 1 kW Fuel-Cell Based Grid Interactive Power Conditioner

The DC-DC boost stage uses a high frequency full-bridge inverter, high frequency transformer, bridge rectifier and a controller. Two half-bridge inverters were arranged with proper PWM technique to provide multiple phase supply. A set of simulation is done to indicate use of the dual phase grid connection system.

Among various types of fuel cells, Proton Exchange Membrane (PEM) fuel cells are the most suitable systems for the application being considered. A single fuel cell may deliver 933 mA/cm^2 at a rated voltage of 0.5V. Therefore, several cells need to be connected in series to form a stack that could deliver power to a required level.

A 1 kW fuel cell stack is modeled with dynamic approach as outlined in [12]. The stack consists of 72 cells (each with 30cm^2 area) in series and rated current and voltages are 28 A, 36 V respectively. A separate controller is required to operate the fuel cell system. However, investigation of a fuel cell controller is beyond the scope of this analysis.

C. *DC-DC Converter*

The DC-DC converter consists of a full-bridge inverter, high frequency transformer and a rectifier. To avoid the need for an inductor at the output of the rectifier, Sinusoidal Pulse Width Modulation (SPWM) technique is applied. This may impose high stress on the switches. Use of several switches in series – parallel combination may reduce this problem. MOSFETs are typically suitable for the high frequency operation. In this analysis, the switching frequency is taken as 50 kHz.

D. *Dual Half-Bridge Inverter*

Two single-phase half-bridge inverters operated at PWM signals with 180^o phase difference are employed to allow multiple output phases. The neutral terminal is realized with a capacitive branch having two equal high value capacitors with their connection node grounded (Fig. 17). The switching is done at 10 kHz and IGBTs are used. One L type filter is used to reduce the output harmonics.

The high voltage DC bus is maintained at a 400V level by using one PI controller. This controller senses the bus voltage, compares it with the reference 400V and modulates the sine wave that generates PWM switching signals for the high frequency inverter. A separate controller generates the split phase inverter switching signals. It senses the grid current, compares with the demand current and adjusts the PWM modulation index accordingly. A phase locked loop (PLL) senses the variations in grid frequency and adjusts the demand grid current frequency (Fig. 17).

V. MODELING AND SIMULATION

A. *Modeling of System 1 (Grid Interactive Inverter)*

The utility interactive inverter described in Section IV(A) is simulated to study the behavior of such a system (Fig. 18).

The half-bridge inverter is connected to a LCL type filter arrangement. Each of these filter components are kept separate to have access to capacitor voltage and current. The filter parameters are: L_i=5e-3, R_i=400e-3, L_g=0.650e-3, R_g=280e-3, C=45e-6, and R_c=5e-3.

The inverter is modeled with a simple comparator and logic arrangements in a subsystem named Subsys-HBI (Fig 18). The controller unit consists of two controllers. The current controller (inner loop) compares capacitor current with the reference signal. The output is then combined with the outer voltage loop that senses capacitor voltage and compares with the voltage reference signal.

The reference signal generator takes grid current as the command signal and also accommodates changes in grid voltage and frequency variations (Subsys-RFG, Fig 18). This produces reference signals for the capacitor current and voltage according to the equations outlined in Section 4(A).

The Phase Locked Loop (PLL) used in the reference signal generator block is modeled within the Subsys-RSG (fig. 18) according to [13].

B. *Modeling of System 2(Fuel-Cell Based Grid Interactive Power Conditioner)*

The complete fuel cell based inverter system is modeled and simulated with a view to indicating success of control methods and topology flexibility in Fig. 19.

Fig. 19 shows the MATLAB/Simulink^{TM} blocks where the output is connected to 120V/60Hz grid. The value of line filter parameters are Lg = 10mH, Rg = 0.5W.

It is required to protect the fuel cell from taking in electricity. Therefore a diode is placed between the fuel cell and the power converter. The fuel cell block is reported in [12] and the 'fuel-cell-current-estimator' block is a virtual model

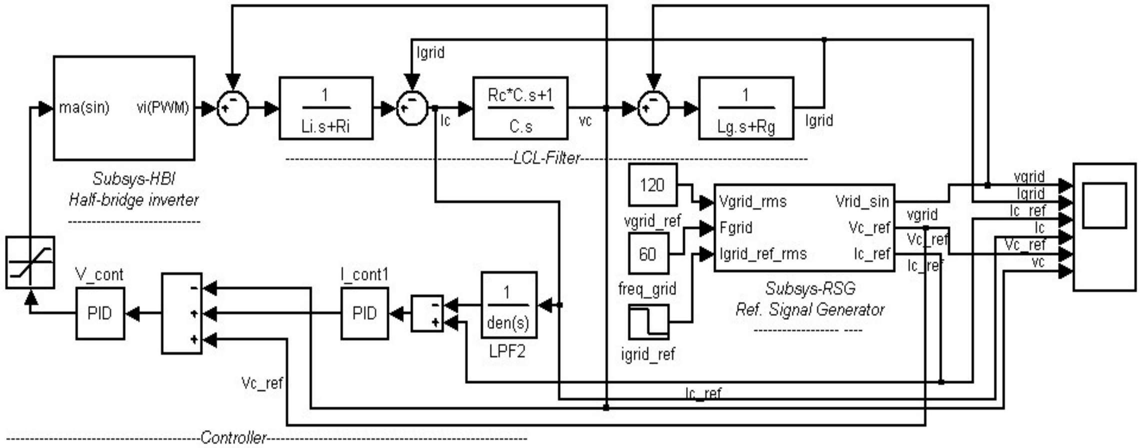

Fig. 18. Grid connected Half-bridge inverter with multiple feedback loop indirect current controller

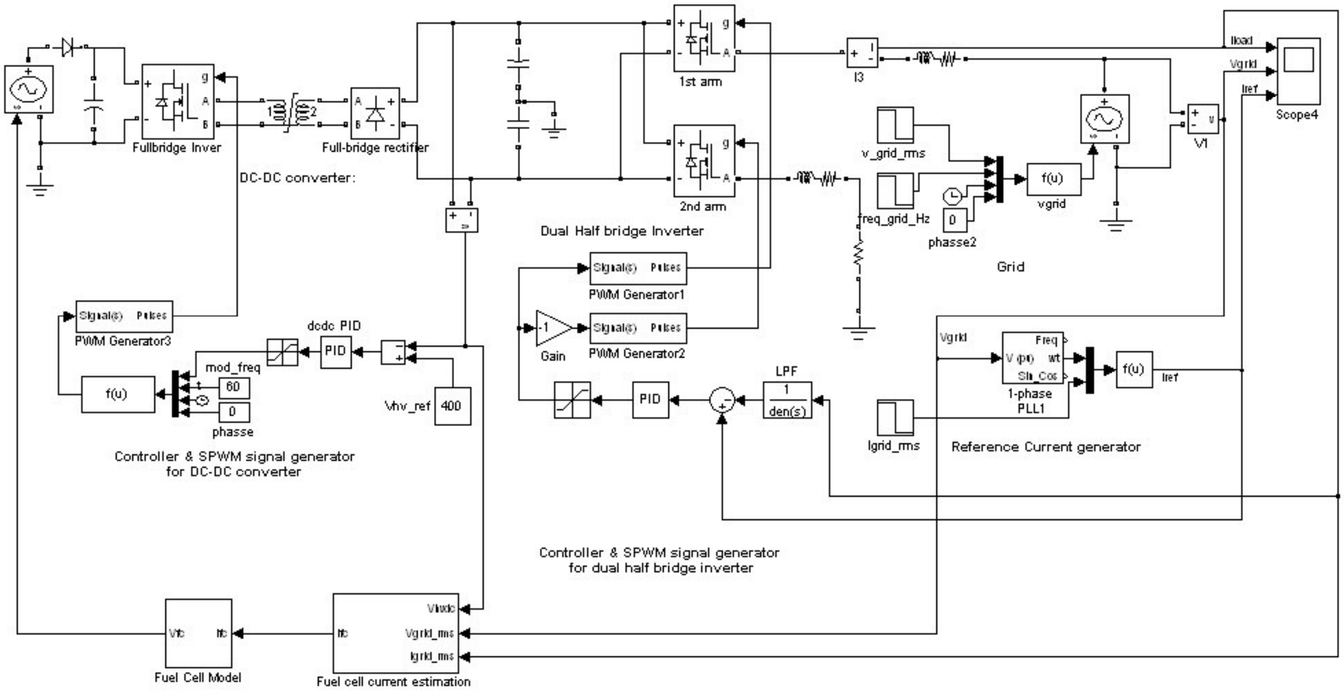

Fig 19: Grid (120V-60Hz) connected fuel cell inverter system with controller

that approximates the current drawn from it such that the stack output voltage could be determined.

VI. RESULTS

A. System 1

The half bridge inverter with 3rd order LCL type filter is designed and modeled such that several key goals of grid interfacing could be demonstrated. The scheme should be able to sense grid voltage and frequency variations, generate reference capacitor current and voltage from the demand current (or power) and control the inverter accordingly.

After several trial and error attempts the controller parameters are found as: Inner current controller $K_p = 1.75$, $K_I = 0.25$ and Outer voltage controller $K_p = 5.75$, $K_I = 1.75$.

As seen in Fig.20 (c, e), with a demand current of 8.33A (corresponding to 1 kW power injection) the reference signal generator creates Capacitor reference current, I_{c_ref} and voltage, V_{c_ref}, which are of sinusoidal shape. In Fig. 20 (d, f) it could be seen that the actual values of these parameters match closely with the reference. However, the capacitor current contains high amount of harmonics. The injected grid current is a sinusoidal ac with near unity power factor (0.98) as seen in fig. 20(a, b). A step change in demand current from 8.33 A to 6.5 A at 0.03 sec causes some adjustments in reference signals and the grid current reduces to the desired level (Fig. 20 (b)) within one cycle.

B. System 2

The second system is more comprehensive and maintains the ability of connecting in two different types of grids. The controller parameters were found to be: DC-DC boost

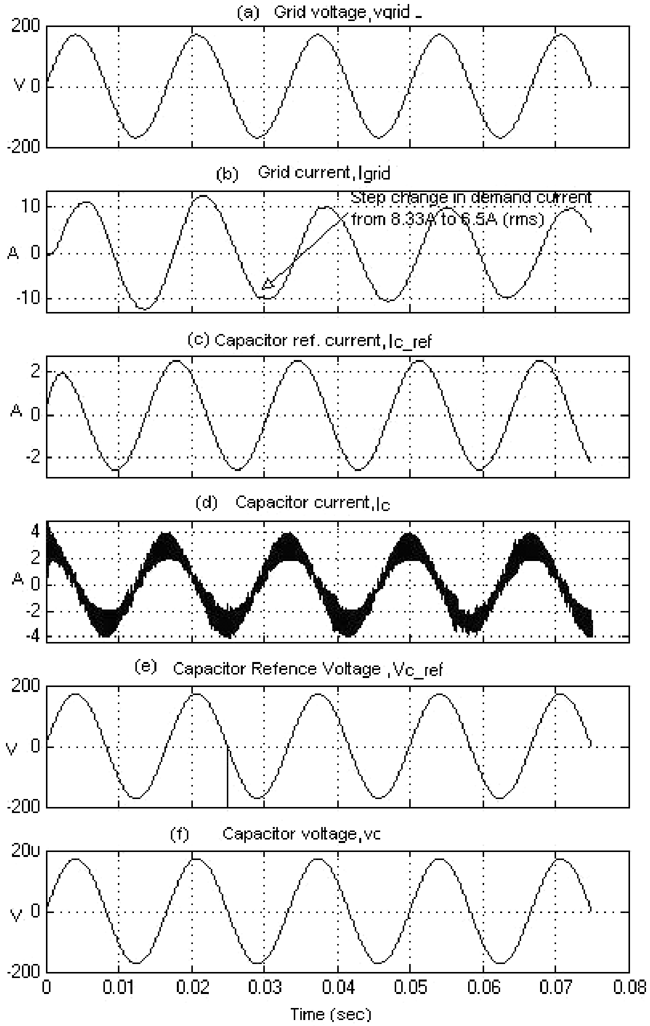

Fig. 20. Simulation results for the half-bridge grid interactive inverter

converter: $K_p = 0.025$, $K_I = 0.015$ and Inverter controller: $K_p = 1.15$, $K_I = 0.5$.

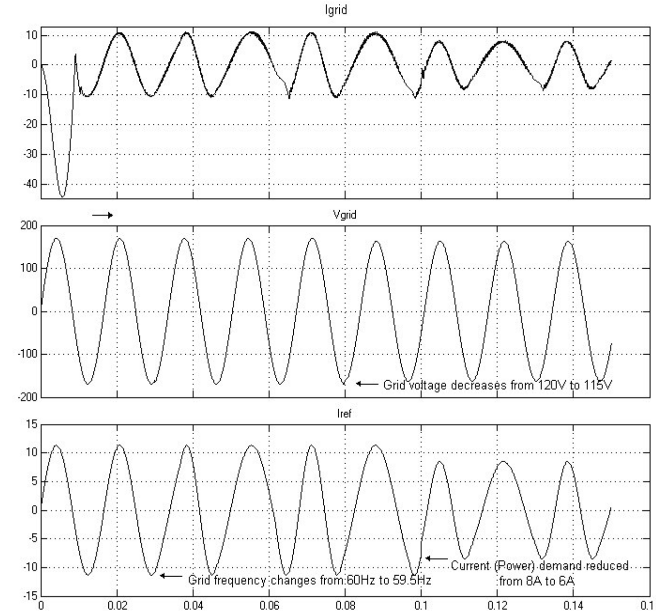

Fig. 21. Single-phase inverter, 120V/60Hz operation

As seen in Fig. 21(a, b), there is some start-up transients due to the computer simulation itself. Moreover, the reference signal, I_{ref} appeared to have suffered harmonic distortion due to the PLL's lack of controllability. Except for these limitations, overall performance of the system is acceptable. The PLL circuit encounters the changes in grid frequency at 0.04 second. The injected grid current was capable of following the reference signals after the initial transients. A change in demand current (i.e., power) at 0.1 second successfully reduces the actual injected current (Fig. 22). The changes in grid voltage at 0.08 second had little affect on the overall performance.

VII. DSP BASED IMPLEMENTATION IN A DG NETWORK

Various Digital Signal Processing (DSP) systems are becoming cheaper and user friendly, especially in the fields of data acquisition and control. Texas Instrument's TMS320LF2407TM chip based systems are being widely used for power electronic and drives applications [14]. This DSP chip is inherited from TI's 240X family, and bears good real time processing capability, which is optimized and suited for control applications being considered. In order to allow "real-time" communication, programming and debugging a custom-built parallel port interface between the DSP board and the PC could be developed.

The fuel cell inverter system works as a source node in the distributed generation network. The Controller Area Network (CAN) is a potential solution for communicating within various elements of the system [15]. In order to connect a personal computer for monitoring the data flow from the resource side, a USB interface with CAN compatibility could be designed. The design should include modular hardware and user-friendly software.

The methods and mediums of short/long distance communication and inverter paralleling are also issues of significant implications. A conceptual outline of a fuel cell system integrated in the DG network is shown in Fig. 22.

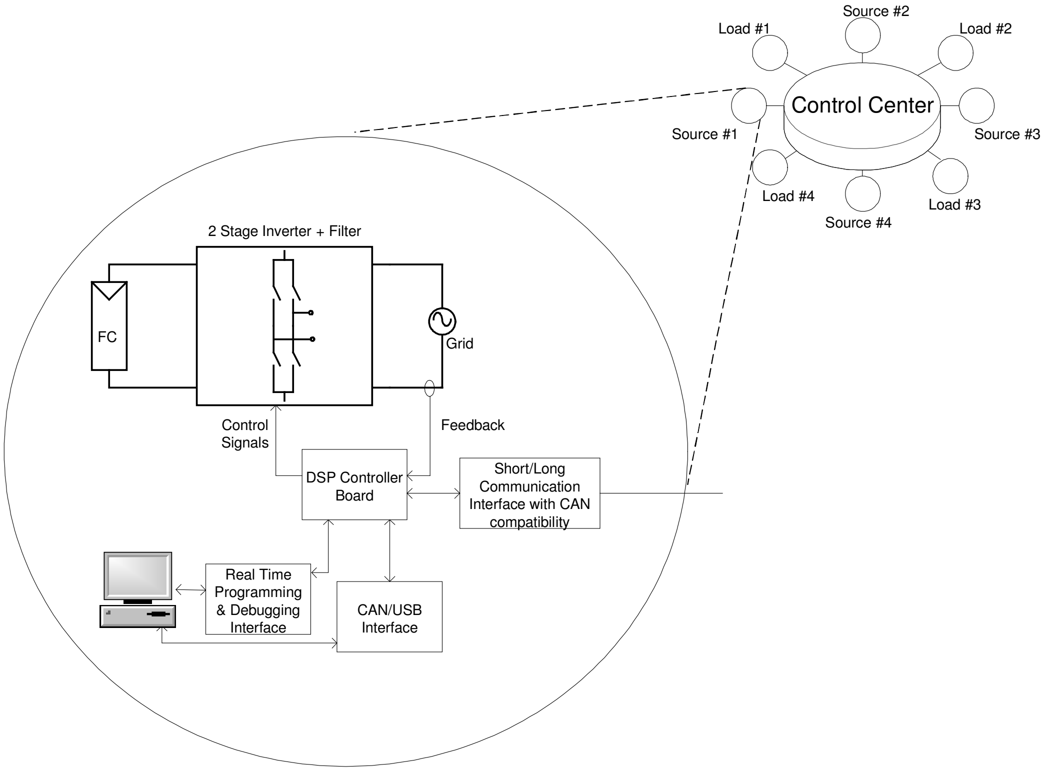

Fig. 22. Conceptual Outline of a fuel-cell inverter system within a DG network

VIII. CONCLUSION

A general discussion on utility interface system requirements followed by a literature review of available power electronic circuit topologies have been discussed. Key issues regarding an inverter's interaction with the utility grid were investigated with a half-bridge 3rd order filter based system. To demonstrate the overall performance of a fuel cell based grid tied power converter, a complete system has been modeled and simulated with some simplification against the initial scheme. Controllers were designed and their range of controllability has been shown. It has been found that, the LCL filter based system requires more rigorous analysis in designing the controller. However, the L filter based system showed good controllability but had drawbacks in the PLL model.

Further work may include integrating both of these systems into one, designing better controllers and grid sensing elements. Analysis of harmonic distortion, cost, efficiency, and regulatory issues are also expected. Design and testing of such inverter system along with operation within a Distributed Generation network are expected in the later works.

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