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Boost Inverter of fuel cell system with a single phase grid

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Abstract:

In this paper, the boost-inverter topology is used as a building block for a single-phase grid-connected fuel cell (FC) system offering low cost and compactness. In addition, the proposed system incorporates battery-based energy storage and a dc–dc bidirectional converter to support the slow dynamics of the FC. The single-phase boost inverter is voltage-mode controlled and the dc–dc bidirectional converter is current-mode controlled. The lowfrequency current ripple is supplied by the battery which minimizes the effects of such ripple being drawn directly from the FC itself.

Moreover, this system can operate either in a grid-connected or stand-alone mode. In the gridconnected mode, the boost inverter is able to control the active (P) and reactive (Q) powers using an algorithm based on a second-order generalized integrator which provides a fast signal conditioning for single-phase systems. Design guidelines, simulation, and experimental results taken from a laboratory prototype are presented to confirm the performance. Keywords: Boost inverter, fuel cell, grid-connected inverter, Power conditioning system (PCS), PQ control.

I. INTRODUCTION:

This One of RECENTLY, energy sources such as wind power systems, photovoltaic cells, and fuel cells have been extensively studied in response to global warming and environmental issues. The fuel cell is an important technology for new mobile applications and power grid distribution systems. For power distribution, fuel cell system requires a grid interconnection converter to supply power to the power grid. A grid interconnection converter using an isolation transformer is preferable for power grid distribution systems in terms of surge protection and noise reduction. In addition, size reduction and high efficiency are essential requirements. One of the problems in the fuel cell system is that the lifetime is decreased by the ripple current. Therefore, in order to extend the lifetime, the fuel cell ripple current must be reduced in the grid interconnection converter. However, when a single-phase pulse width-modulated (PWM) inverter is used for grid connection system, the power ripple is twice the frequency of the power grid. For Example, from the current–voltage characteristics of a 72-cell proton exchange membrane FC (PEMFC) power module, the voltage varies between 39 and 69 V. Moreover, the hydrogen and oxidant cannot respond the load current changes instantaneously due to the operation of components such as pumps, heat exchangers, and fuelprocessing unit [6]–[8]. Caisheng et al. [9] presented the cold-start which takes more than few seconds .

Thus, the slow dynamics of the FC must be taken into account when designing FC systems. This is crucial, especially when the power drawn from the FC exceeds the maximum permissible power, as in this case, the FC module may not only fail to supply the required power to the load but also cease to operate or be damaged [10]–[12]. Therefore, the power converter needs to ensure that the required power remains within the maximum limit [10], [12]. The objective of this paper is to propose and report full experimental results of a grid-connected single-phase FC system using a single energy conversion stage only.

n particular, the proposed system, based on the boost inverter with a backup energy storage unit, solves the previously mentioned issues (e.g., the low and variable output voltage of the FC, its slow dynamics, and current harmonics on the FC side). The single energy conversion stage includes both boosting and inversion functions and provides high power conversion efficiency, reduced converter size, and low cost [17]. The proposed singlephase grid-connected FC system can operate either in gridconnected or stand-alone mode. In the grid-connected mode, the boost inverter is able to control the active (P) and reactive (Q) powers through the grid by the proposed PQ control algorithm using fast signal conditioning for single-phase systems [20].

II. PROPOSED FC ENERGY SYSTEM:

A fuel cell is an electrochemical cell that converts a source fuel into an electrical current. It generates electricity inside a cell through reactions between a fuel and an oxidant, triggered in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate continuously as long as the necessary reactant and oxidant flows are maintained. Fuel cells are different from conventional electrochemical cell batteries in that they consume reactant from an external source, which must be replenished[1] – a thermodynamically open system. Bycontrast, batteries store electrical energy chemically and hence represent a thermodynamically closed system. Many combinations of fuels and oxidants are possible.

A hydrogen fuel cell uses hydrogen as its fuel and oxygen (usually from air) as its oxidant. Other fuels include hydrocarbons and alcohols. Other oxidants include chlorine and chlorine dioxide Fuel cells come in many varieties; however, they all work in the same general manner. They are made up of three segments which are sandwiched together: the anode, the electrolyte, and the cathode. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electrical current is created, which can be used to power electrical devices, normally referred to as the load.

At the anode a catalyst oxidizes the fuel, usually hydrogen, turning the fuel into a positively charged ion and a negatively charged electron. The electrolyte is a substance specifically designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire creating the electrical current. The ions travel through the electrolyte to the cathode. Once reaching the cathode, the ions are reunited with the electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide.

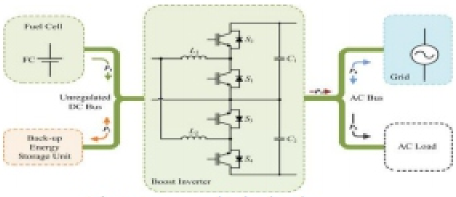

Fig 1. Proposed Block Diagram.

In this block diagram the models backup unit and the FC power module are connected in the unregulated dc bus and the boost-inverter output is connected to the local load and the grid. The representation of the power are mentioned as follows,

P1: FC output power

P2: backup unit input/output power,

P3: inverter output power

P4: power between the inverter and the grid and

P5: power to the ac loads.

A. Fuel cells :

Fuel cells are also well used for distributed generation applications, and can essentially be described as batteries which never become discharged as long as hydrogen and oxygen are continuously provided. The hydrogen can be supplied directly, or indirectly produced by reformer from fuels such as natural gas, alcohols, or gasoline. Each unit ranges in size from 1-250 kW or larger MW size. Even if they offer high efficiency and low emissions, today's costs are high. Phosphoric acid fuel cell is commercially available in the range of the 200 kW, while solid oxide and molten carbonate fuel cells are in a pre-commercial stage of development.

The possibility of using gasoline as a fuel for cells has resulted in a majordevelopment effort by the automotive companies. The recent research work about the fuel cells is focused towards the polymer electrolyte membrane (PEM) fuel cells. Fuel cells in sizes greater than 200 kW, hold promise beyond 2005, but residential size fuel cells are unlikely to have any significant market impact any time soon. Fig.1 shows a block diagram of fuel cell system which consists of a reformer, fuel cell s

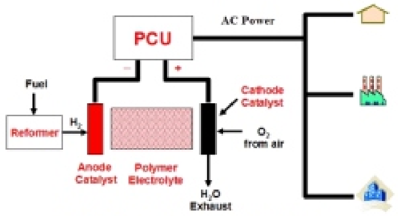

Fig 2. Basic Layout of FC System

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Moreover, the scalability of fuel cells has allowed for applications in almost every field. Fuel cell systems can be easily placed at any site in a power system for grid reinforcement, thereby deferring or eliminating the need for system upgrades and improving system integrity, reliability, and efficiency. Therefore, proper controllers need to be designed for a fuel cell system to make its performance characteristics as desired. Development of a standalone, reduced-order, dynamic model of fuel cell power plant connected to a distribution grid via dc/ac converter.

The proposed model includes the electrochemical and thermal aspects of chemical reactions inside the fuel-cell stack but the dynamics model of DC/DC and DC/AC Converters are not considered. A novel hierarchical control architecture for a hybrid distributed generation system that consists of dynamic models of a battery bank, a solid oxide fuel cell and power electronic converter has been presented. The fuel cell power plant is interfaced with the utility grid and a three phase pulse width modulation (PWM) inverter. A validated SOFC dynamic model used in this project.

III. BOOST INVERTER :

Boost dc–ac inverter naturally generates in a single stage an ac voltage whose peak value can be lower or greater than the dc input voltage. The main drawback of this structure deals with its control. Boost inverter consists of Boost dc–dc converters that have to be controlled in a variable-operation point condition. The sliding mode control has been proposed as an option. However, it does not directly control the inductance averaged-current. This paper proposes a control strategy for the Boost inverter in which each Boost is controlled by means of a double-loop regulation scheme that consists of a new inductor current control inner loop and an also new output voltage control outer loop.

These loops include compensations in order to cope with the Boost variable operation point condition and to achieve a high robustness to both input voltage and output current disturbances. As shown by simulation and prototype experimental results, the proposed control strategy achieves a very high reliable performance, even indifficult transient situations such as nonlinear loads, abrupt load changes, short circuits, etc., which sliding mode control cannot cope with.

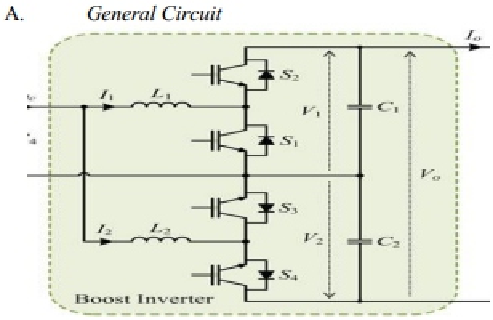

Fig3. Circuit diagram for boost inverter

B. Control Scheme:

A double-loop control scheme is chosen for the boost-inverter control being the most appropriate method to control the individual boost converters covering the wide range of operating points. This control method is based on the averaged continuous-time model of the boost topology and has several advantages with special conditions that may not be provided by the sliding mode control, such as nonlinear loads, abrupt load variations, and transient shortcircuit situations. Using this control method, the inverter maintains a stable operating condition by means of limiting the inductor current. Because of this ability to keep the system under control even in these situations, the inverter achieves a very reliable operation [16].

The reference voltage of the boost inverter is provided from the PQ control algorithm being able to control the active and reactive power. The voltages across C1 and C2 are controlled to track the voltage references using proportional-resonant (PR) controllers. Compared with the conventional proportional integral (PI) controller, the PR controller has the ability to minimize the drawbacks of the PI one such as lack of tracking a sinusoidal reference with zero steady-state error and poor disturbance.

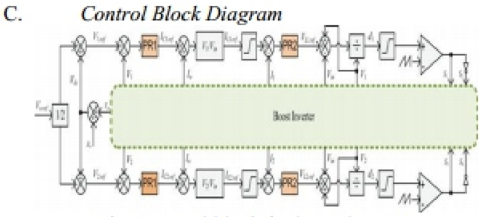

Fig 4.control block for boost inverter

D. IGBT :

IGBT is a three-terminal power semiconductor device, noted for high efficiency and fast switching.

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It switches electric power in many modern appliances: electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers. Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters.

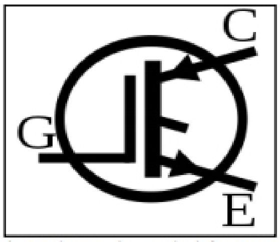

Fig.5.Electronic symbol for IGBT

The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low–saturation-voltage capability of bipolar transistors by combining an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device. The IGBT is used in medium- to high-power applications such as switched-mode power supply, traction motor control and induction heating. Large IGBT modules typically consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of amperes with blocking voltages of 6000 V, equating to hundreds of kilowatts. The IGBT is a fairly recent invention.

The first-generation devices of the 1980s and early 1990s were relatively slow in switching, and prone to failure through such modes as latch up (in which the device won't turn off as long as current is flowing) and secondary breakdown (in which a localized hotspot in the device goes into thermal runaway and burns the device out at high currents). Second-generation devices were much improved, and the current third-generation ones are even better, with speed rivalling MOSFETs, and excellent ruggedness and tolerance of overloads. The extremely high pulse ratings of second- and thirdgeneration devices also make them useful for generating large power pulses in areas like particle and plasma physics, where they are starting to supersede older devices like thyratrons and triggered spark gaps. Their high pulse ratings, and low prices on the surplus market, also make them attractive to the high-voltage hobbyist for controlling large amounts of power to drive devices such as solid-state Tesla coils and coilguns. Availability of affordable, reliable IGBTs is an important enabler for electric vehicles and hybrid cars.

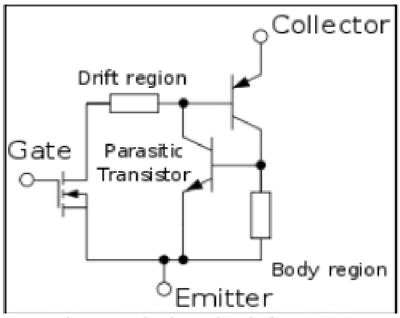

Fig 6. Equivalent circuit for IGBT

The IGBT is a semiconductor device with four alternating layers (P-N-P-N) that are controlled by a metal-oxide-semiconductor (MOS) gate structure without regenerative action IV. SIMULATION OF SOFC AND PQ CONTROL A. Simulation of SOFC The ac real power injection into the utility grid is considered to be the reference power for the fuel cell. The stack voltage and the reference power are used to determine the reference current which in turn is used to determine the fuel cell stack current. The fuel flow is proportional to the stack current. The partial pressure of hydrogen, oxygen and water are determined using the flow rates of hydrogen and oxygen. The stack voltage is based on the Nernst Equation which depends on the stack current and the partial pressures of the gas. Observation of the H_2, H_2O and O_2 pressures shows that the fuel cell does not reach a new equilibrium for the simulation of duration 1 second. Extended simulation periods are required to observe the dynamics of the chemical reaction.

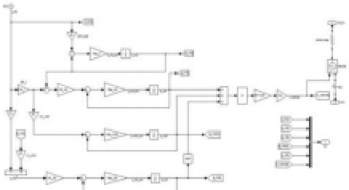

Fig7. SOFC inner block

B. PQ Control:

The control scheme proposed in this thesis is the decoupled PQ control. This controller controls the phase angle and amplitude of the voltage across the transformer. The difference in the phase angle between the voltage across the transformer and the utility side voltage determines the direction of the real and reactive power flow. Since the phase angle on the utility side is zero, phase angle of the voltage across the transformer determines the direction of the power flow. This control is basically a real power control since the reactive power is assumed to be zero.

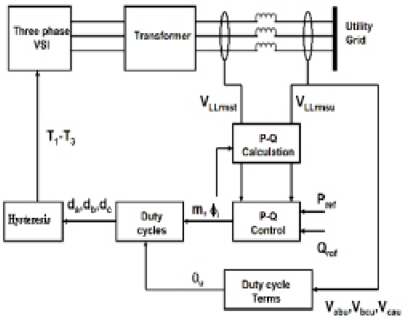

Fig 8. Block diagram of the overall control system of the inverter

The figure consists of various sub blocks to be dealt with, apart from the P-Q controller. The line-line voltage across the transformer and the utility side are measured from the system to calculate the real and reactive power flow. The P-Q controller compares the actual values with the reference real and reactive powers to obtain the phase angle of the transformer voltage and the modulation index, respectively. These control variables are used to determine the duty cycle control signals which when compared with the triangular wave, produce the switching signals for the inverter. This subsection consists of the real and reactive power calculation and the decoupled P and Q controller. The line-line voltage on the utility side (VLL rmsu) and the transformer (VLL rmst) are measured from the system. The real and reactive power flows are given by Equations.

$$P = \frac{V_{LLrmst} V_{LLrmsu} \sin(\phi_i)}{\omega L_t}$$

$$Q = V_{LLrmst} \left(\frac{V_{LLrmst} - V_{LLrmsu} \cos(\phi_i)}{\omega L_t} \right)$$

Where φi is the phase angle of the voltage on the inverter side and Lt is the leakage inductance of the transformer. For calculation purposes, the transformer is considered to be ideal; hence the angle lag due to Y-Y connection is neglected. The P-Q controller basically consists of PI controllers to control the phase angle and the modulation index.

The main requirement for the inverter switching signals is the phase angle and amplitude of the inverter voltage. Figure 3 shows the real and reactive power control system. The real power flow is given by Equation (8). The voltages and the reactance terms are more or less constant. The real power is directly proportional to the phase angle if the angle is small. Hence the real power flow can be used to control the phase angle of the inverter. Reactive power flow controls the amplitude of the transformer voltage. The error between the reference and the measured real power is fed into a PI controller to control the phase angle of the inverter as shown in the figure below. The inverter voltage, in turn, depends on the reactive power. The error between the reference and the measured reactive power is fed into the PI controller. The control of the transformer voltage is proportional to the control of the inverter voltage.ge is used to determine the amplitude of the modulation signals.

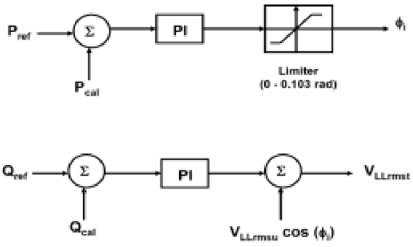

Fig 9. Control Diagram for Real and Reactive Power

C. Control Block For PQ Control:

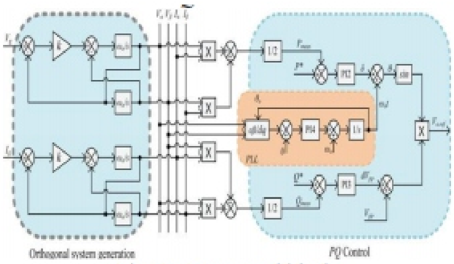

Fig 10. PQ control block

V. SIMULATION CIRCUIT AND RESULTS

A. Main block simulation Diagram for Grid – connected FC system.

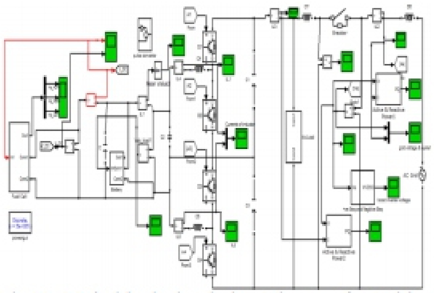

Fig 11. Main block simulation Diagram for Grid – connected FC system

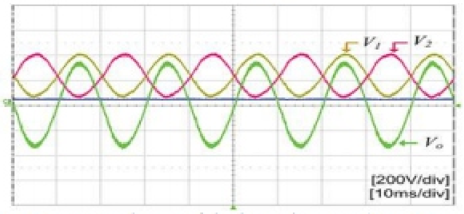

Fig 12.Output voltages of the boost inverter ($V1$, $V2$, and Vo) and dc input voltage, Vin

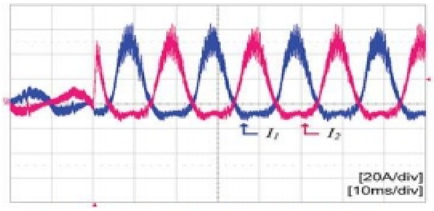

Fig 13. Current waveforms of $L1$ and $L2$.

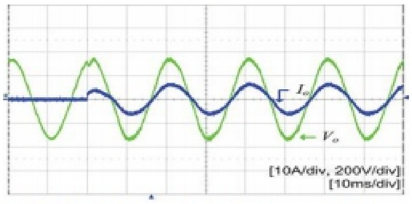

Fig 14.Simulation results for Voltage and Current

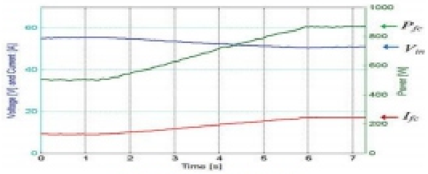

Fig 15. Load Curves.

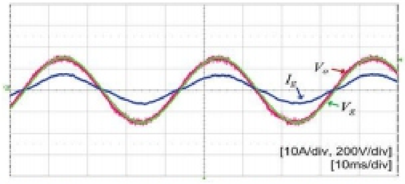

Fig 16.Inverter output voltage Vo, grid voltage Vg, and current through the inductor Lf.

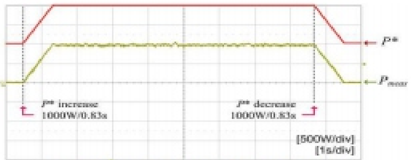

Fig 17. Active and Reactive Powers.

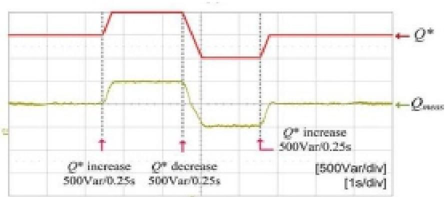

Fig 18. Measured Active and Reactive Powers.

VI. CONCLUSION AND FUTURE SCOPE Conclusion:

A dynamic model of the solid oxide fuel cell (SOFC) was developed in MATLAB. A three phase inverter has been modelled and connected between the SOFC-DC-AC system on the one side and the utility grid on the other side through an ideal transformer. A control strategy for the inverter switching signals has been discussed and modelled successfully. The inverter control scheme uses a decoupled PQ control strategy to control the phase angle of the inverter and the voltage across the transformer. The characteristics for the system have been obtained.

The transformer and inverter voltage waveforms have been plotted In an industrial power generation, fuel cell is one of most important sources of distributed energy in the future. Modelling and simulation study of a SOFC power system is investigated in this project. A validated SOFC dynamic model is used to model the fuel cell system.

A three phase inverter has been modelled and connected between the SOFC power system on one side and the utility grid on the other side through an ideal transformer. A control strategyfor the inverter switching signals has been discussed. In addition, the models for the three phase inverter are simulated and verified will be controllable to be 1 p.u.

FUTURE WORK:

The fuel cell system developed in this thesis can be modified for improving the applicability of the system. In this thesis, the thermodynamic effect of the fuel cell has not been considered. Future work can involve inclusion of thermodynamic equations. The performance of the stack voltage with and without the temperature effect can be obtained and its overall effect on the load.

In this thesis, an infinite bus has been modelled for utility grid. The work can be further extended to a higher order bus system. Different placements of the fuel cell unit can be studied and analysed. The performance of multiple units at multiple locations can also be studied. The performance of the fuel cell can also be tested by carrying out short circuit studies.

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