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Single-Phase Single-Stage FC System with BESS

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Abstract:
Integration of fuel-cell with single-phase grid, a boost converter is proposed in this paper. Battery Energy Storage System is proposed for storage of energy. Due to slow dynamics of fuel cell a bidirectional converter has been used. The single-phase boost inverter is voltage-mode controlled andthe dc–dc bidirectional converter is current-mode controlled. Thelow-frequency current ripple is supplied by the battery whichminimizesthe effects of such ripple being drawn directly from the FCitself. The proposed system is having two modes of operations, are grid-connected and stand-alone modes. The active and reactive powers controlled by boost inverter, in grid connected mode.

INTRODUCTION

In energy generation systems based on solar photovoltaic and fuel cells (FCs) need to be conditioned for both dc and ac loads. The overall system includes power electronics energy conversion technologies and may include energy storage based on the target application [1]-[2]. However, the FC systems must be supported through additional energy storage unit to achieve high-quality supply of power. When such systems are used to power ac loads or to be connected with the electricity grid, an inversion stage is also required.

The typical output voltage of low-power FC is low and variable with respect to the load current. For instance, based on the current–voltage characteristics of a 72-cell proton exchange membrane FC (PEMFC) power module, the voltage varies between 39 and 69 V depending upon the level of the output current [3-5]. Moreover, the hydrogen and oxidant cannot respond the load current changes instantaneously due to the operation of components such as pumps, heat ex changers, and fuel-processing unit. Caishengetal 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. Therefore, the power converter needs to ensure that the required power remains within the maximum limit. A two-stage FC power conditioning system to deliver ac power has been commonly considered. The two-stage FC power conditioning system encounters drawbacks such as being bulky, costly and relatively inefficient due to its cascaded power conversion stages [6].

To alleviate these drawbacks, a topology that is suitable for ac loads and ispowered from dc sources able to boost and invert the voltage at the same time has been proposed. The doubl4 loop control scheme of this topology has also been proposed for better performance even during transient conditions [7].

The proposed system, based on the boost inverter with a backup energystorage unit, solves the previously mentioned issues. The single energyconversion stage includes both boosting and inversion functionsand provides high power conversion efficiency, reducedconverter size, and low cost

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FUEL CELL ENERGY SYSTEM

Design of fuel cell

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The flow of power between the each section can be shown in fig 1. This system consists of two power converters: theboost inverter and the bidirectional backup unit.

The boost inverter is supplied by the FC and thebackup unit, which are both connected to the same unregulateddc bus, while the output side is connected to the load and gridthrough an inductor. The system incorporates a current-modecontrolled bidirectional converter with battery energy storage tosupport the FC power generation and a voltage-controlled boostinverter.

The FC system should dynamically adjust to varying inputvoltage while maintaining constant power operation. Voltageand current limits, which should be provided by the manufacturersof the FC stack, need to be imposed at the input of theconverter to protect the FC from damage due to excessive loadingand transients. Moreover, the power has to be ramped up anddown so that the FC can react appropriately, avoiding transientsand extending its lifetime [6]. The converter also has to meet themaximum ripple current requirements of the FC.

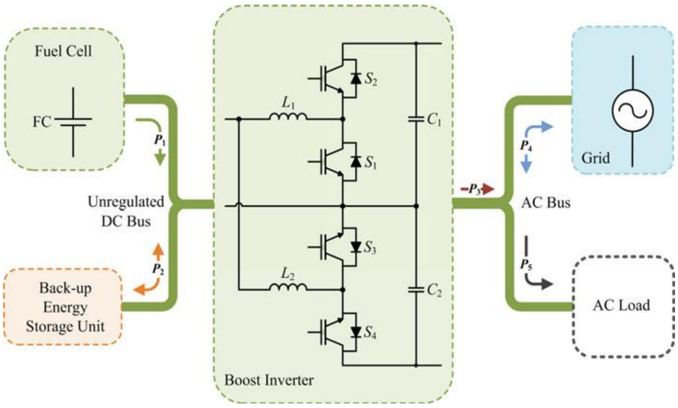

Fig 1: Block diagram for the proposed grid-connected FC system

The 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. (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).

PROPOSED GRID-CONNECTED FC SYSTEM

In the grid-connected mode, the system is also providingactive (P) and reactive (Q) power control. A key concept ofthe PQ control in the inductive coupled voltage sources is theuse of a grid compatible frequency and voltage droops [7].Therefore, the active and reactive powers are controlled by thesmall variations of the voltage phase and magnitude. The controlof the inverter requires a fast signal conditioning for single-phasesystems. In the proposed system, the second-order generalizedintegrator (SOGI) algorithm has been employed.

Boost Inverter

The boost inverter consists of two bidirectional boost convertersand their outputs are connected in series. Each boost converter generates a dc bias with deliberateac output voltage (a dc-biased sinusoidal waveform as an output),so that each converter generates a unipolar voltage greaterthan the FC voltage with a variable duty cycle.

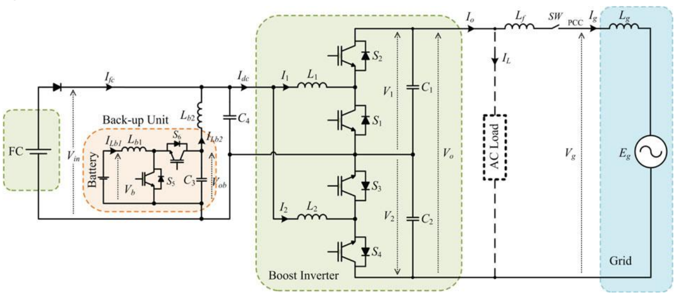

Fig 2: structure of the proposed grid-connected FC system.

A double-loop control scheme is chosen for the boost-inverter control being the most appropriate method to controlthe individual boost converters covering the wide range ofoperating points. This control method is based on the averagedcontinuous-time model of the boost topology and has severaladvantages with special conditions that may not be provided bythe sliding mode control, such as nonlinear loads, abrupt loadvariations, and transient short-circuit situations [8]. Using this controlmethod, the inverter maintains a stable operating conditionby means of limiting the inductor current. Because of this abilityto keep the system under control even in these situations, theinverter achieves a very reliable operation.

The reference voltage of the boost inverter is provided fromthe PQ control algorithm being able to control the active and reactivepower. The voltages across C1 and C2 are controlledto track the voltage references using proportional-resonant(PR) controllers [9]. Compared with the conventional proportional integral(PI) controller, the PR controller has the ability to minimizethe drawbacks of the PI one such as lack of tracking asinusoidal reference with zero steady-state error and poor disturbance rejection capability.

Backup Energy Storage System (BESS):

The functions of the backup energy storage system are dividedinto two parts. First, the backup unit is designed to support theslow dynamics of the FC. Second, in order to protect the FCsystem, the backup unit provides low-frequency ac current thatis required from the boost inverter operation. The low-frequencycurrent ripple supplied by the batteries has an impact on their lifetime [10], but between the most expensive FC componentsand the relatively inexpensive battery components, the latter ispreferable to be stressed by such low-frequency current ripple.

The backup system comprises of a current-mode controlledbidirectional converter and a battery as the energy storage unit.For instance, when a 1-kW load is connected from a no-load condition,the backup unit immediately provides the 1-kW powerfrom the battery to the load. On the otherhand, when the load is disconnected suddenly, the surplus powerfrom the FC could be recovered and stored into the battery toincrease the overall efficiency of the energy system.

CONTROL SYSTEM

Control of Boost Inverter

The control block diagram for the boost inverter is shown in Fig. 3. The output voltage reference is divided to generatethe two individual output voltage references of the two boostconverters with the dc bias, Vdc. The dc bias can be obtainedby adding the input voltage Vin to the half of the peak outputamplitude. Vdc is also used to minimize the output voltages ofthe converters and the switching losses in the variable input voltage condition.

Therefore, the grid connected FC system as parallel operation of voltage sourceinverters requires a precise control. Grid-compatible frequencyand voltage droop were introduced to control active and reactivepowers in this paper. The droop control for the boost inverterrequires the fast acquisition of P and Q.

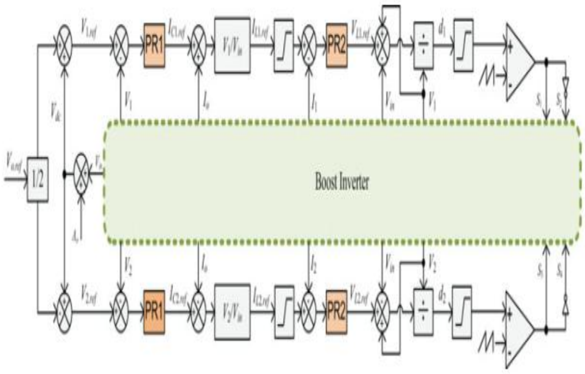

Fig 3: Boost-inverter control block diagram

The output voltage reference is determined by

$V_{o.ref} = (V_{pp} + dV_{pp}) \cdot \sin(\omega_o t + \delta)$,

When

$A_o = V_{pp} + dV_{pp}$ and $\theta = \omega_o t + \delta$

WhereVpp is the peak value of the typical grid voltage, dVpp isa small variation of the output voltage reference affecting to the reactive power, ωo is the grid fundamental angular frequency, and δ is the phase difference between Vo and Vg relating withthe active power.

BESS controller

The backup unit controller is designed to control the outputcurrent of the backup unit in Fig. 4. The reference of ILb1 is determined by Idc through a high-pass filter and the demanded current I_{demand} that is related to the load change. The accomponent of the current reference deals with eliminating the acripple current into the FC power module while the dc componentdeals with the slow dynamics of the FC.

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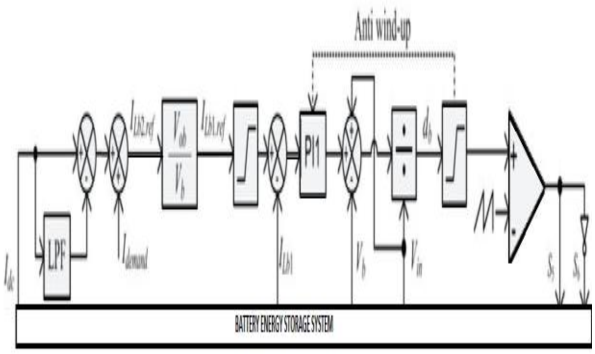

Fig. 4: Backup unit control block diagram.

SIMULATION RESULTS

The proposed FC system has been analyzed,designed, simulated, and tested experimentally to validate itsoverall performance. The simulations have been done usingSimulink/MATLAB t to validate the analyticalresults. The ac output voltage of the systemwas chosen to beequal to 220 V, while the dc input voltage varied between 43 and69 V.

The simulation results show the operations of the boost inverter and the backup unit. In particular, Figure 5(a) illustrates the output voltages of the boost inverter (V1, V2 and V0) and Figure 5(b) shows the grid voltage and grid current at the PCC. The input currents of each boost converter flowing through the inductors L1 and L2 are shown in Figure 5(c), Figures 5(d)-(f) illustrates the waveforms of the inverter input current Idc, the FC output current Ifc, and the output current ILb2 of the backup unit, respectively. Figure 5(e) and (f) also illustrates how the backup unit supports the FC power in transients.

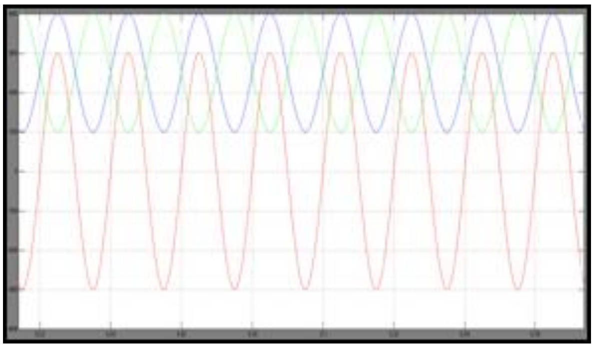

Fig 5(a): Output voltages of the boost inverter

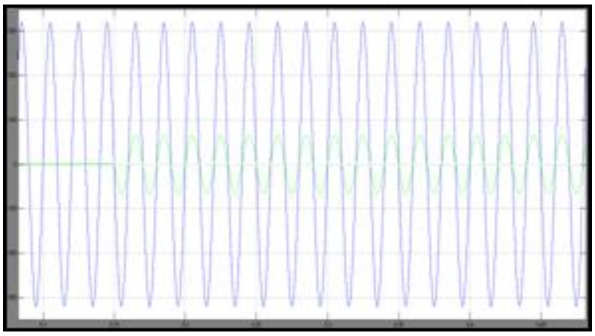

Fig 5(b): Grid voltage Vg and current Ig with full power feeding to the grid

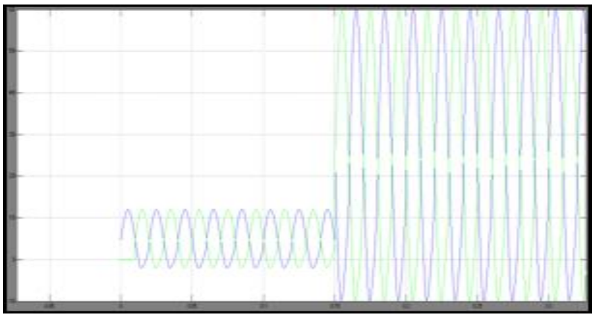

Fig 5(c): Current waveforms of L1 and L2

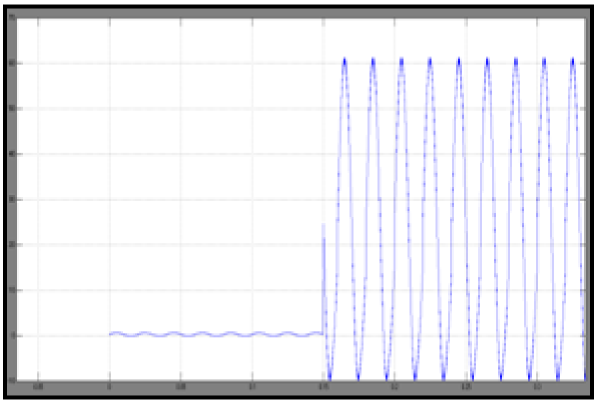

Fig 5(d): Input current of the boost inverter, Idc.

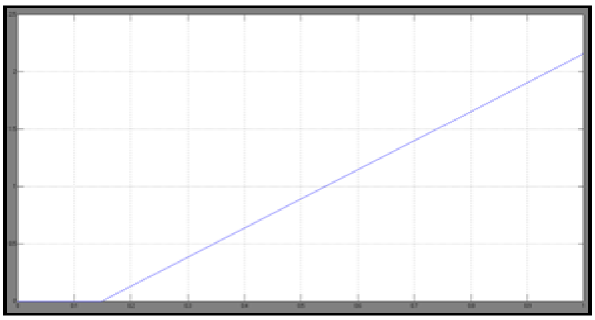

Fig 5(e): FC output current during transient,Ifc.

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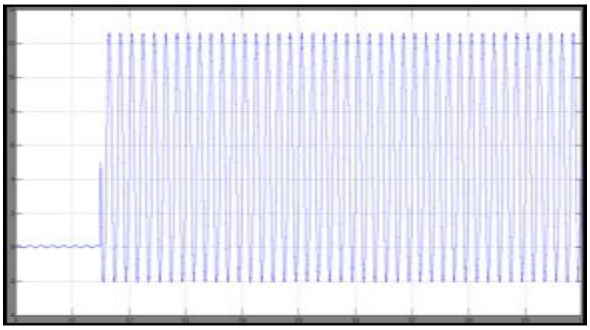

Fig 5(f): Output current of the backup unit,ILb2

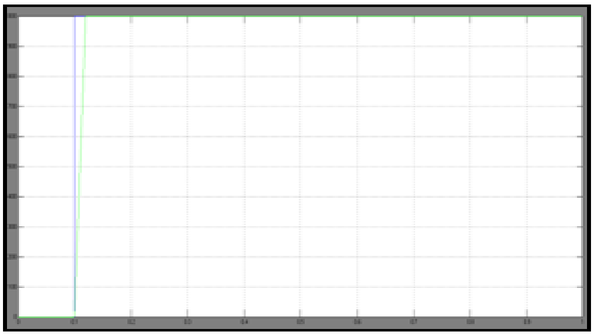

Fig 6(a): Active power measurement and its reference.

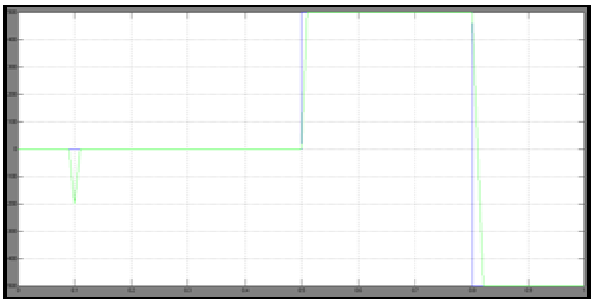

Fig 6(b): Reactive power measurement and its reference

CONCLUSION

A single-phase single power stage grid-connected FC system based on the boost-inverter topology with a backup battery based energy storage unit is proposed in this paper. The simulation results and selected laboratory tests verify the operation characteristics of the proposed FC system. In summary, the proposed FC system has a number of attractive features, such as single power conversion stage with high efficiency, simplified topology, low cost, and able to operate in stand-alone as well as in grid-connected mode. Moreover, in the grid-connected mode, the single-phase FC system is able to control the active and reactive powers by a PQ control algorithm based on SOGI which offers a fast signal conditioning for single-phase systems. However, it should be noted that the voltage-mode control adopted for the boost inverter may result in a distorted grid current (under given THD) if the grid voltage includes a harmonic component.

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