SINGLE-PHASE TRANSFORMER-LESS BUCK-BOOST RESIDENTIAL FUEL CELL BASED DG

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ABSTRACT

The aim of this paper is to evaluate the technical feasibility and aspects related to use, a Fuel Cell based Distributed Generation (FC-DG) in the residential single-phase applications with premium voltage quality. The paper presents a new topology of buck-boost inverter, where this single stage transformer-less inverter is employed to energize the residential load. With this new topology, the proposed DG can maintain the desired ac output voltage with high efficiency, low harmonics, fast response and good steady-state performance. It can operate as an Uninterruptable Power Supply (UPS), too. The proposed configuration is simulated using PSCAD/EMTDC software and simulation results and analytical analysis are presented to validate its effectiveness.

INTRODUCTION

The use of energy sources such as internal combustion engines and lead-acid batteries are facing a great opposition due to environmental and economically problems. In the last few years other kinds of electrical sources have been studied and provide solutions to face these problems. One of these new electrical sources is Fuel Cells (FC) systems. They are electrochemical devices, generating electric power without process of burning. FCs use chemical way, almost the same as battery. The difference is that in them other chemical substances are used, such as hydrogen and oxygen; and a product of the chemical reaction is water, making them electrical sources environmentally safe and very efficient[1,2]. Differently from batteries, which storage energy inside, the combustible (hydrogen) feeds FC by an external storage system so it is possible to obtain the expected range furthermore the recent drastic drop in costs of FC systems makes them a viable alternative option to existing backup power solutions [3].

Most widespread investigation is carrying out on two classes of FCs: low temperature FCs – Proton Exchange Membrane Fuel Cells (PEMFCs) for application in transport and stationary low power sources, and high temperature ones – such as Molten Carbonate Fuel Cells (MCFCs) and Solid Oxide Fuel Cells (SOFCs) for stationary electrical power generation applications. PEMFCs are quiet, applicable to very low size modules, making them a possibility for individual residential and small remote-site applications [4].

Uninterruptible Power Supplies (UPSs) are used to supply clean and uninterrupted high-quality power to critical loads, such as computers, communication systems, medical support systems, etc. According to the increase of the utilization of such sensitive equipment in the world, their interruption due to an input-power failure may lead to critical accidents, so The UPS system is indispensable. Generally, the UPS system requires the regulated sinusoidal output voltage with low Total Harmonic Distortion (THD) that is independent from the changes in the input voltage or in the load, low transient response time from online mode to backup mode and vice versa, low THD sinusoidal input current and unity power factor, high reliability, high efficiency, low cost, low weight, small size, etc[5].

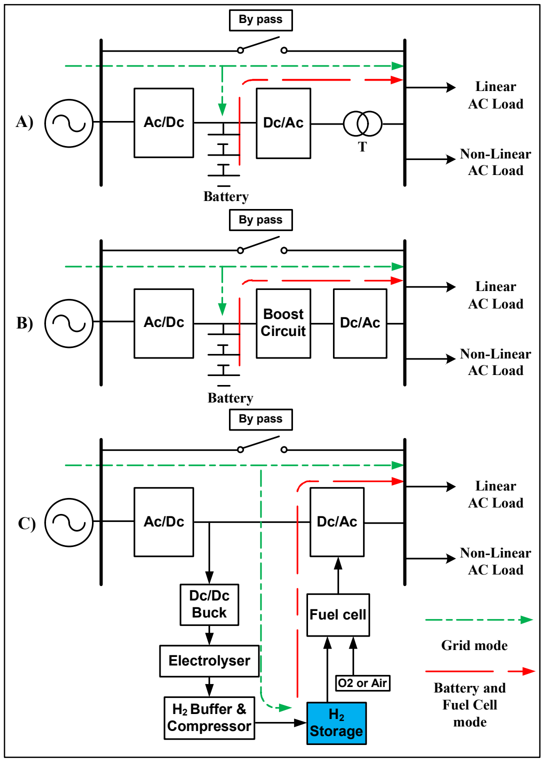

Fig.1. Topologies of UPS, (a) dc/ac inverter + transformer. (b) dc/dc booster + dc/ac inverter. (c) Proposed Buck-Boost inverter + Fuel Cell.

In general, there are two types of traditional single phase UPSs. The first one couples a battery bank to a half or full-bridge inverter with a low-frequency transformer [6], as shown in Fig. 1(a). In this type of UPSs, the ac output voltage is higher than that of the battery bank; thus, a step-up transformer is required to boost voltage.

Due to the presence of the step-up transformer, the inverter current is much higher than the load current, causing high current stress on the switches of the inverter. The transformer also increases the weight, volume, and cost of the system. The second one couples a battery bank to a dc/dc booster with a half- or full bridge inverter [7], [8], as shown in Fig. 1(b). In this type of UPSs, the additional booster is needed, leading to high cost and low efficiency. The controlling of the switches in the booster also complicates the system. Furthermore, the dead time in the Pulse Width Modulation (PWM) signals to prevent the upper and lower switches at the same phase leg from shooting through has to be provided in the aforementioned two types of UPSs, and it distorts the voltage waveform of the ac output voltage[9].

SYSTEM CONFIGURATION AND OPERATING PRINCIPLE

Topology Description

Fig. 1(c) shows a new topology of the FC-DG with a buck-boost inverter. In the normal operation, the rectifier provides power to the inverter. In the case of power outage, the FC supplies the inverter, so it can operate as a reliable UPS.

The proposed FC-DG offers the following salient advantages over the traditional DG's inverter system:

1) The dc/dc booster and the inverter have been combined into one single-stage power conversion; 2) Distortion of the ac output-voltage waveform is reduced and FC-DG system can maintain load voltage at desired value even if input voltage is not too weak in comparison with its nominal value; 3) The system has achieved fast transient response and good steady state performance; 4) Proposed topology is simple, symmetrical and requires a simple sine triangle PWM control for its operation; 5) The number of power devices is optimal, the system is reliable, efficient and economical; 6) Optimal switching and conduction losses, in addition to the optimal utilization of switching devices, result in low losses and hence low cooling requirements. Only one device at a time is switched at high frequency, reducing the EMI concerns. Also number of devices conducting during any mode is optimum, resulting in minimum conduction losses apart from lowering the cost; and 7) Power handling capacity of the proposed configuration is higher because for each half cycle, there is a separate, dedicated inductor and switch to handle the power. Also, there are no coupled inductors or fly back transformer for intermediate power transfer.

This topology is built around a buck-boost inverter topology capable of inversion (dc–ac), boosting and bucking the voltage as shown in Fig. 2. Each of these converters operates in Discontinuous Current Mode (DCM) for a half cycle. The resulting circuit acts as a current source inverter which feeds sinusoidal current into a low value capacitor across the load.

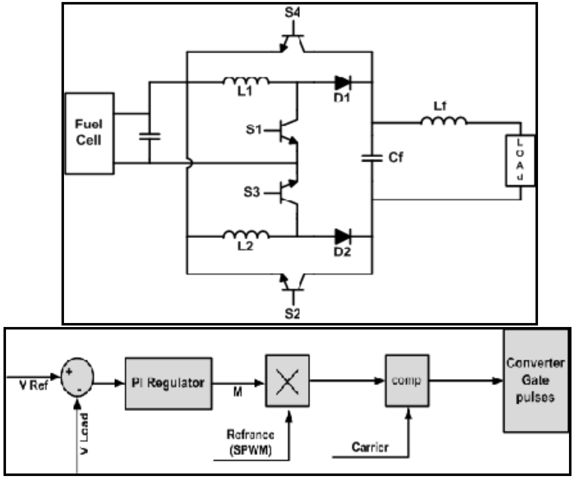

Fig.2. Schematic diagram of the proposed single-stage buck-boost inverter and it’s simple control.

DCM operation helps in feeding sinusoidal current into the load and the energy’s magnitude vary in a sinusoidal manner. The power device S1 (or S3) is switched at high frequency while S2 (or S4) is kept continuously ON during the positive half cycle (or negative half cycle). S1 (or S3) is switched as per Sine triangle Pulse Width Modulation (SPWM) method. When S1 is ON, energy is stored in the buck-boost inductor ‘L1’ by the FC source. When S1 is OFF, D1 (or D2) gets forward biased, discharging the stored inductor energy into capacitor which feeds sinusoidal current into the load [10].

For the load voltage the following expression may be written:

$$V_{load} = V_m \sin(\omega t) \tag{1}$$

To feed unified power factor sinusoidal power into the load, the energy that should be transferred during the switching interval is:

$$E = I_m V_m \sin^2(\omega t) \times T_s \tag{2}$$

Where I_m is the amplitude of the current fed into the load and T_s is the switching time period. Due to DCM operation, a definite amount of energy can be transferred during each switching cycle. Thus, for injecting sinusoidal current into the load, the expression for duty ratio, required in switching cycle is derived as follows:

$$E = \frac{V_m{}^2}{2L_1} D^2 T_s{}^2 \tag{3}$$

Where D is the duty ratio during the switching cycle, so equating (2) and (3) and solving for D yields:

$$D = \sqrt{(2V_m I_m L_1 \sin^2(\omega t) / V_m{}^2 T_s)} \tag{4}$$

Modes of Operation

The operation of the proposed FC-DG can be divided into two modes, as shown in Fig. 1.(c): *The grid mode*, which is also sometimes referred to as normal mode, and *the fuel cell powered mode*.

1) Grid Mode:

During the normal mode, i.e., under the condition in which there is no power failure or the utility is not too weak in comparison of its rated operating condition, the rectifier stage, buck-boost inverter stage, and electrolyser circuit are operating.

In this mode the linear and non-linear loads connected to grid through rectifier stage and inverter stage. By explained control strategy and using PI regulator the load voltage is maintained in desired value. One of the most important properties of this topology is that, this inverter has the capability of boosting the input voltage, so, even when the utility is weak and it's voltage is lower than it's rated operating voltage, the output (load) voltage will be constant, thus FC operating voltage could be lower than the load voltage either. On the other hand the electrolyser circuit operates to store hydrogen in a tank which will be used by FC in next mode.

An electrolyser is a device that produces hydrogen and oxygen from water. Water electrolysis can be considered a reverse process of a hydrogen fueled FC. Opposite to the electrochemical reaction occurring in FC, an electrolyser converts the DC electrical energy into chemical energy stored in hydrogen. To control this hydrogen production and store it in the tank, a commen *dc-dc buck converter* controls the input current to the electrolyser cells. This buck converter is a dc voltage reducer designed to maximize the power transfer from the dc bus to the electrolyser cells. The buck converter has the advantage of having high current at the output that helps in increasing the production of hydrogen by electrolysis [11]. So the power transmitted to the electrolyser can be regulated by controlling the buck converter duty ratio.

2) Fuel cell-Powered Mode:

When the supervisory circuit detects an input ac line failure, the rectifier stage is turned off and FC starts transferring power through the inverter to the load. In this operating mode, the electrolyser circuit is disabled and same controller will be used to maintain load voltage at desired value and provide sufficient energy to the inverter. When the supervisory circuit detects ac line voltage reestablishment in normal operating ranges, the rectifier stage is turned on and FC is turned off, so the load will be fed by grid.

SIMULATION RESULTS OF THE PROPOSED FC-DG TOPOLOGY

Computer simulation is provided to verify the well performance of the proposed FC-DG configuration. The system is simulated by PSCAD/EMTDC software. Fig. 3 shows the output voltage of the proposed FC-DG as well as load current with the buck-boost inverter for different loads. As shown in Fig. 3, the system is operating with linear load at first 0.02 sec interval, at t=0.04sec the non-linear load suddenly connected to the system and at t=0.06sec the linear load is disconnected. It can be seen that the voltage distortion is negligible and voltage is almost sinusoidal with less than 1% THD and constant peak.

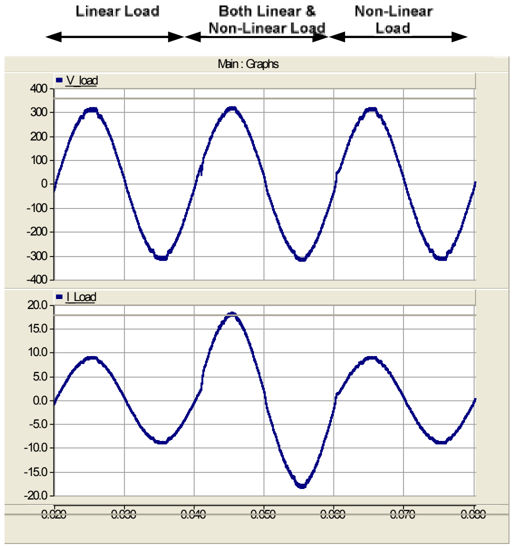

Fig.3. Output voltage (Volt) of the proposed FC-DG and load current (Ampere), respectively, with defferent loads.

Fig.4. shows the output voltage, load current and grid voltage in the interchange between *Grid operating mode* and *Fuel cell- powered mode*. It can be pointed out that the load is feeding by grid until the supervisory circuit detects an input ac line failure at t=0.0575sec. So, the rectifier stage is turned off and FC starts transferring power through the inverter to the load. Fig. 5 shows the output voltage and load current when the grid voltage is decreased. As explained before, the proposed inverter has the capability of boosting the input voltage. As a result, it can maintain the load voltage at the rated value when the grid voltage is decreased and its voltage becomes lower than its rated operating voltage. The design specifications of the proposed FC-DG are shown in Table I, which the switching frequency for both modes is f_s= 10 KHz.

Table I. Developed FC-DG Specification

Input Voltage	150-220 (rms)
Output Voltage	220 (rms)
Grid frequency	50 HZ
Output frequency	50 HZ
Number of High frequency switches	2
Number of Low frequency switches	2
Output Power	1.5 KVA

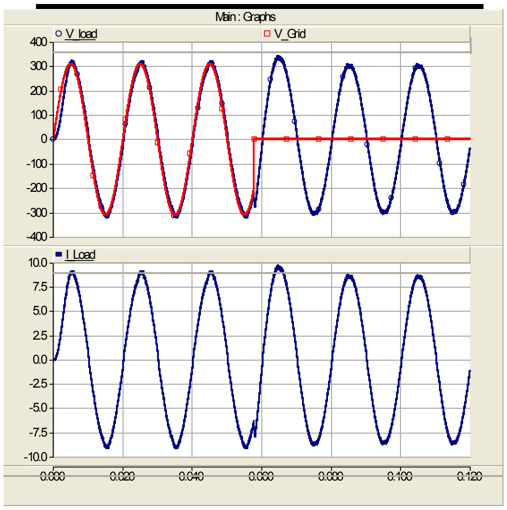

Fig. 4. Output and grid voltage (Volt), and load current (Ampere) in the interchange between Grid operating mode and Fuel Cell- powered mode.

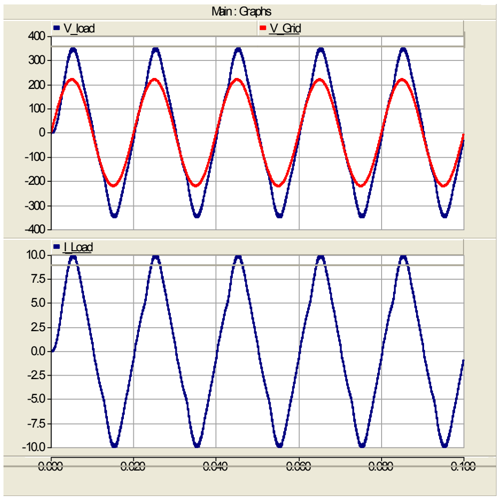

Fig. 5. Output and grid voltage (Volt), and load current (Ampere) when grid voltage is lower than rated voltage.

CONCLUSION

In this paper, a new topology of the FC-DG based on the buck-boost inverter has been presented where this single stage transformer-less inverter is used to couple the main power source and FC to the load. The technical feasibility and aspects related to the use of FCs in this structure instead of traditional electrochemical batteries is evaluated. DCM operation ensures good control apart from facilitating the generation and feeding the high quality current into the load. As it was explained the proposed topology can operate as a reliable UPS and shows the strong regulation capability to maintain the ac output voltage at the desired value as well as good steady-state performance even the grid voltage becomes lower than its rated value. All these advantages were verified by simulation. As the proposed configuration uses a single stage inverter, no transformer is needed which causes to reduce the cost, size and the power loss of the system. The inverter stage generates a sinusoidal output voltage when it supplies linear or nonlinear loads. The topology is simple, symmetrical and easy to control. The other desirable features are good efficiency and reduced switching losses due to optimal number of switching devices.

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