NOVEL CIRCUIT TO COMPENSATE THE EFFECT OF SOURCE OPEN CIRCUIT FAULT IN DISTRIBUTED GENERATION SYSTEM

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ABSTRACT

In this paper a novel compensating circuit, composed of capacitors, one IGBT switch, and a diode bridge is designed and employed within a SOFC distributed generation system connected to a micro-grid. The DG system consists of the FC stack, a Cuk converter, a three phase inverter, the proposed compensating circuit, and Type 2 Fuzzy logic controller to adjust the output voltage to its reference value, to manage the charging of the compensating circuit capacitors during normal operation, and to manage the discharge of the compensating circuit during fault to ensure the continuous power supply to the load during the open circuit fault of the SOFC. A detailed description of the managing controllers and switching sequences is also given. Results proved the validity of the compensating circuit in supplying the load during the absence of the main source, hence preventing serious consequences of shutting down important loads.

INTRODUCTION

Fuel Cells are applied in stationary and mobile power generation and can be connected to distribution grid. The distributed generation (DG) is defined by the Electric Power Research Institute (EPRI) as a small scale (0–50 MW) energy resource connected directly to the distribution network [1]. DG has the advantage that, as the population expands and power generation needs change, the transmission network does not require expensive upgrades and extensions, as the generation source can be taken to the load efficiently. For the consumer, the potential lower cost, higher service reliability, high power quality, and increased energy efficiency, are all reasons for the increasing interest in distributed generation systems [2-3].

Fuel Cell stacks have been utilized for distributed power generation systems with the development of power-electronic system that converts a fuel cell's low-voltage output, which usually varies from 30 to 60 V for residential application, into commercial 120-V/60-Hz and 240-V/50-Hz ac outputs [4-6]. Power distribution systems, should ideally provide their customers with an uninterrupted flow of energy with a smooth sinusoidal voltage at the contracted magnitude level and frequency. However, in practice, power systems, especially distribution systems, have numerous nonlinear loads, which significantly affect the quality of the power supply. Also the probability of interruptions in the energy source itself exists, affecting critical loads and deteriorating the quality of power supply. Hence a back-up energy source must be added to the DG system, increasing the cost and complicating the control scheme. An alternative solution to this problem is adding a FACT device, which also adds to complexity and cost due to additional VSC and storage devices [7-8].

In this paper a novel simple compensating circuit, acting as a FACT device, composed of capacitors, one IGBT switch, and a diode bridge is designed and employed within a SOFC distributed generation system connected to a micro-grid. The operation of the whole FC-compensating circuit-DG system is investigated during the interruption of power generation from the SOFC. The steady state currents and voltage profiles at three points of connection within the generation system during normal operation are presented. The currents and voltages at these points during the supply interruption are then presented, with connection of the proposed compensating circuit. Results proved the continuous supply of power to the load, preventing shut-down of critical loads. The THD at these points are also investigated before and after the open circuit fault. Type-2 Fuzzy Logic control is applied to manage the DG system operation to ensure continuous supply of power to the microgrid.

THE DISTRIBUTED GENERATION SYSTEM DESCRIPTION

Figure 1 shows the block diagram of the proposed distributed generation system composed of a SOFC, a Cuk converter, a VSI PWM inverter and the proposed compensating circuit. Figure 2 shows the detailed system as modeled with Matlab/Simulink.

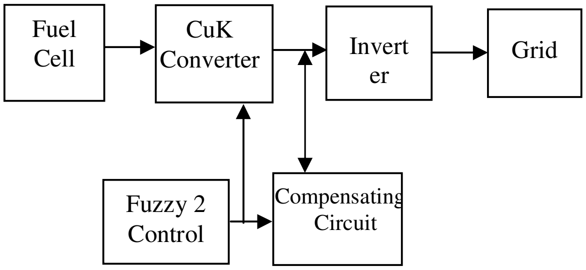

Fig. 1, Block diagram.

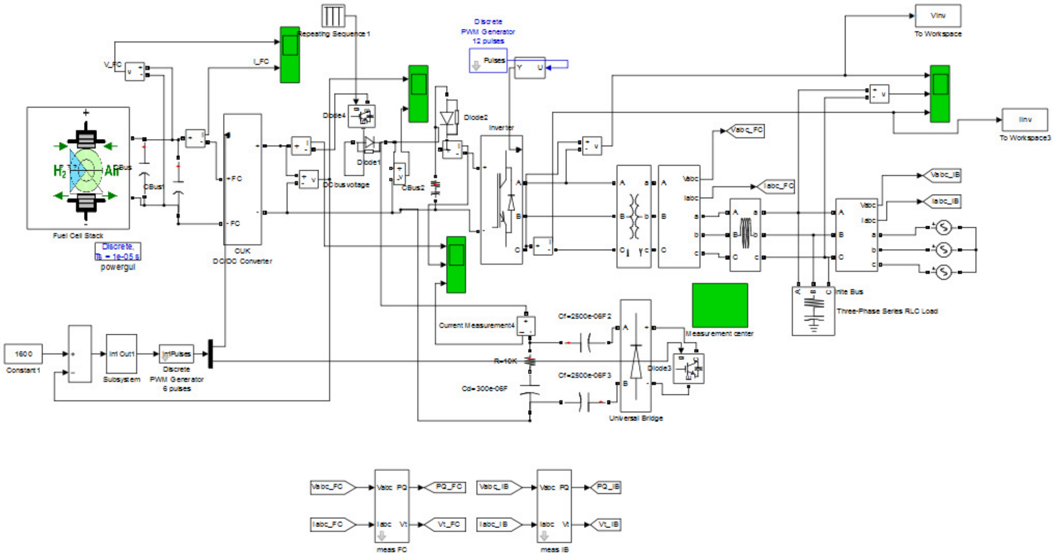

Figure 2 Generation System Simulink Model

The CuK converter adjusts the dc output of the SOFC, applies it to the PWM inverter with constant dc voltage to be supplied to the grid with constant frequency. The switch SW$_1$ connects the fuel cell output, in the case of normal operation, while the switch SW$_2$ at the output of the compensating circuit allows charging the circuit capacitors. The operation of the converter, inverter and switches is adjusted by Type-2 Fuzzy logic control.

The SOFC model

FC converts chemical energy to electrical energy. The amount of output voltage in each cell is small. Therefore, cells are connected in series to gain a higher output voltage. FC output voltage is given as [9]:

$$V_{FC} = E_{nernst} - V_{act} - V_{ohmic} - V_{con} \tag{1}$$

Where: E_{nernst} is the open circuit voltage defined as follows:

$$E_{nernst} = 1.229 - 0.85*10^{-3}(T - 298.15) + 4.3085*10^{-5}T[\ln(P_{H_2}) + 0.5\ln(P_{o_2})] \tag{2}$$

where: T is refers to FC operation temperature, [°K];

P_{H2} and P_{O2} is partial pressure of hydrogen and oxygen, [atm].

V_{act} is the activation voltage drops in FC electrodes caused by the slow reactions on the surface

V_{ohmic} is the ohmic voltage drop due to resistive losses in the cell

V_{con} is the voltage drop corresponding to mass transport

DC/DC converter with Type 2 Fuzzy Control

The dc output voltage of the CuK converter, shown in Fig. 3, is higher than its dc input voltage. The switch SW$_1$ is controlled with T2-FLC to produce constant dc voltage to supply the inverter connected to the ac microgrid.

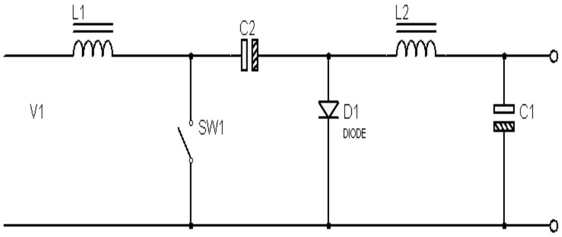

Fig. 3, CuK converter.

PWM Inverter

The simplified circuit diagram for a three-phase, two-level, IGBT voltage source converter (VSC) is illustrated in Fig. 4. The Flat Top PWM is used for switching the IGBTs. The inverter switches are controlled with T2-FLC to apply ac voltage with constant frequency to the microgrid.

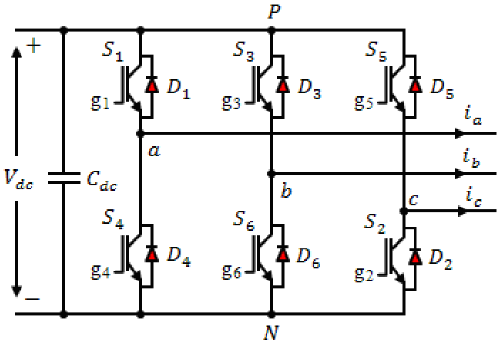

Fig. 4, Phase PWM Inverter.

The compensating Circuit

Figure 5 shows the proposed compensating circuit for mitigating the effect of open circuited FC, or loss of supply. The circuit comprises three capacitors (C_f, C_{f1}, and C_d), a diode rectifier-bridge, and a small smoothing reactor (L) with additional tuning resistor (R). The filter-compensator capacitors are charged via the FC during normal operation. If an open circuit fault takes place, i.e. the fuel cell fails to supply the load; the switch SW_2 of the compensating circuit supplies the AC microgrid with constant voltage, [10].

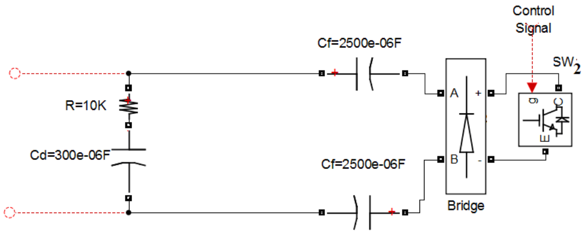

Fig. 5, The proposed compensating circuit

The Control technique

The control of dc CuK converter, the inverter supplying the load, and the compensating circuit operation is executed using type-2 Fuzzy logic control technique. The major structure difference between type 1 and type 2 FLC is that the defuzzifier block of a type-1 FLC is replaced by the output processing block in a type-2 FLC which consists of type-reduction followed by defuzzification block as shown in Fig. 6. T2- FLC, can be used when the circumstances are uncertain to determine exact membership grades such as when the training data is affected by noise. T2-FLC reaches steady state value faster than type-1 FLC, [11].

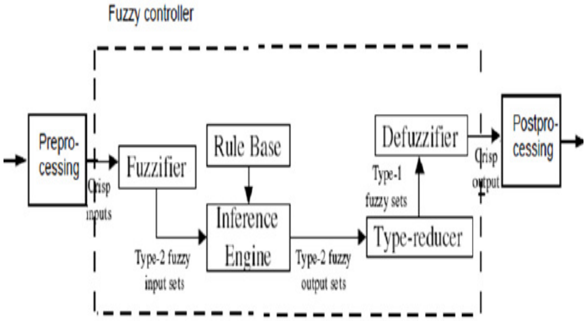

Fig. 6 the block diagram of type-2 FLS.

The control circuit depends on the magnitude of the output voltage of the dc converter. The control circuit controls the 2 switches SW_1 and SW_2. When a change in the voltage occurs, the controller operates SW_2 instead of SW_1 to compensate the voltage drop.

SIMULATION RESULTS

The steady state voltage and current of the FC are given on Figs 7 and 8 respectively.

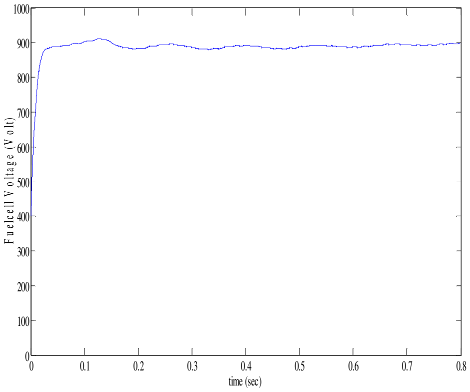

Fig 7, SOFC voltage at normal operation

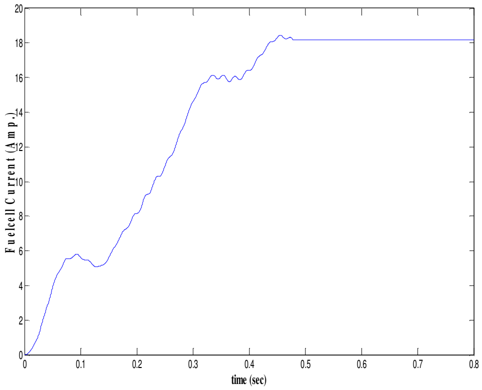

Fig 8 SOFC current at normal operation

An open circuit fault is assumed from 0.65 sec till 0.7 sec., i.e. the SOFC fails to supply the load. The converter output voltage during the fault is shown in Fig. 9. It shows that the proposed FACT circuit compensates the voltage drop to supply the inverter.

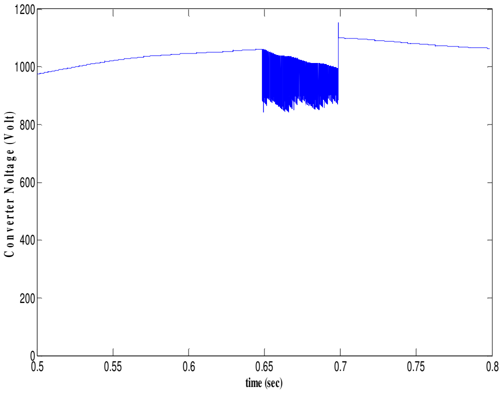

Fig 9, Output converter voltage during the fault.

Figure 10 demonstrates the FACT circuit current, showing the reversal of the current during the fault, due to the operation of SW_2 instead of SW_1.

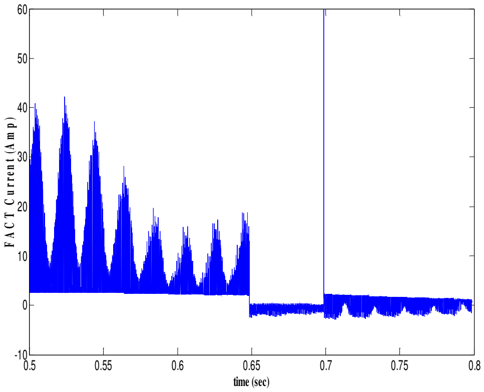

Fig. 10, The current of FACT during fault.

Figure 11 proves that the voltage and current of the inverter is not affected by the open circuit fault due to the operation of the FACT circuit.

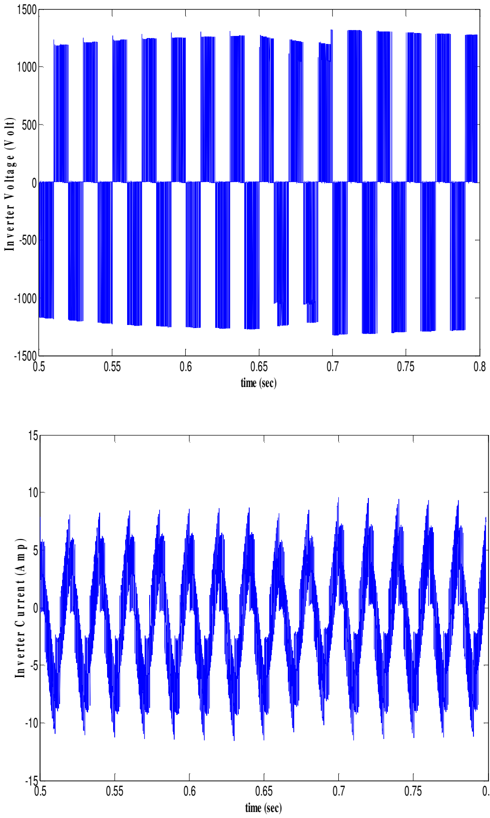

Fig 11, Output voltage and current of the inverter.

Analyzing the THD of the inverter voltage during normal operation and with fault occurrence, as shown in Figs. 12 and 13, it is shown that during normal operation THD is 30.93%, while due to fault occurrence it became 31.26%. This is an incremental change due to capacitors of the compensating (FACT) circuit. While, the THD of the inverter output current increased from 21.36% during normal operation to 22.35% due to the open circuit fault as shown in Figs. 14 and 15. This is an incremental increase.

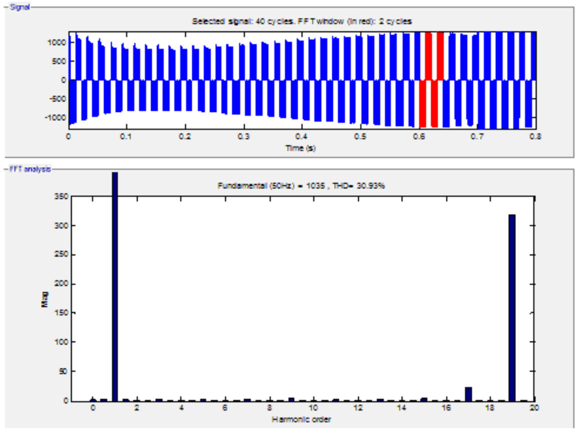

Fig. 12, The THD voltage of inverter at normal operation.

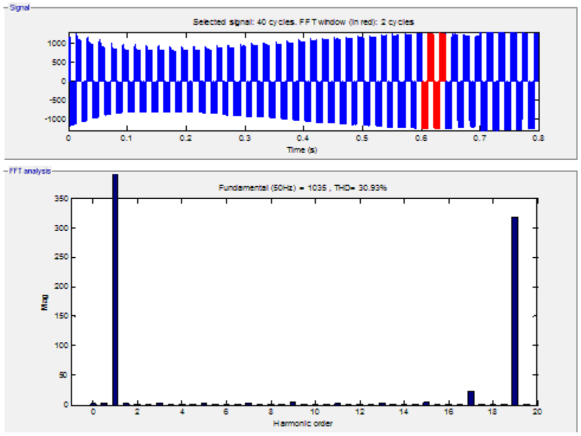

Fig. 13, The THD voltage of inverter at fault.

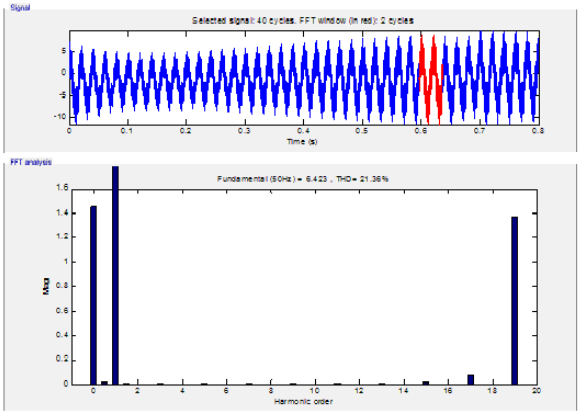

Fig. 14, The THD current of inverter at normal operation.

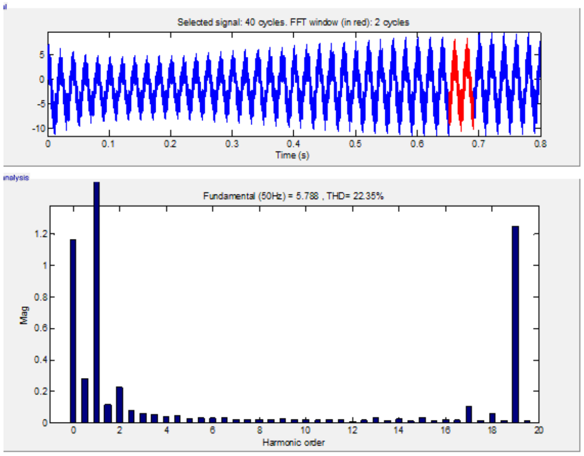

Fig. 15, The THD current of inverter at fault.

CONCLUSION

A compensating circuit, acting as a FACT device, is designed to provide continuous supply of load demand in a distributed generation system fed by a solid oxide fuel cell. The DG system consists of the FC stack, a CuK converter, a three phase inverter, the proposed compensating circuit, and Type 2 Fuzzy logic controller to adjust the output voltage to its reference value, to manage the charging of the compensating circuit capacitors during normal operation, and to manage the discharge of the compensating circuit during fault to ensure the continuous power supply to the load during the open circuit fault of the SOFC. The proposed circuit is characterized by its fewer devices and hence lower control complexity and lower cost. Results proved the continuous supply of the load demand during open circuit fault with an incremental increase in the THD of the inverter output voltage and current, proving the efficiency of the proposed circuit.

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