Operation and Control of Hybrid Fuel Cell/ Energy Storage Distributed Power Generation System during voltage Sag Conditions

A. Hajizadeh, M. A. Golkar

Abstract — This paper presents a control strategy for fuel cell/energy storage power generation system during voltage sag conditions. The hybrid DC power sources are connected to grid using power electronic converters include DC-DC converter and grid connected voltage source inverter. The power from hybrid power sources is controlled during voltage sag by designing of control strategy for DC-DC converter. Moreover, a robust control strategy of voltage source converter for both positive and negative symmetrical components is presented to control of inverter current under unbalanced voltage sag. Simulation results for 25 KW PEM fuel cell of TALEGHAN site are given to show the response of system under voltage sag and illustrate the performance including active power control and voltage sag ride-through capability of the proposed control strategy.

Index Terms - control, distributed generation, fuel cell, energy storage, voltage sag.

I. INTRODUCTION (HEADING 1)

NOWADAYS the power system is in a process of undergoing from regulated market to the deregulated one, centralized to more localized systems that are situated nearer to the load centers. The reasons behind are; increased concern for environment, utilization of renewable energy technologies, flexibility of operation, lower initial investment costs, lower time of project completion, electricity market liberalization, developments in Distributed Generation (DG) technology, constraints on the construction of new transmission lines and increased customer concern for highly reliable electricity etc [1]. Many of the renewable power generation systems like wind turbine, photovoltaic and fuel cell are connected to the grid via power electronic converters to improve the system integrity, reliability and efficiency [2-4]. With the increasing power capacity of DG systems, it is important to design control strategy to keep the safe operation of these system during voltage and load disturbances. The grid-connected power electronic converters are highly sensitive to voltage disturbances. This makes it necessary to reduce the effects of voltage disturbances on their operations [5]. A voltage sag is a drop in voltage with duration between one half-cycle and one minute [6], which is, in most cases, caused by a short-circuit fault. The operation of fuel cell distributed generation units under voltage sag has not received much attention in the past. Moreover, many grid operators demand the immediate shutdown of DG in case of grid disturbances as a prerequisite for grid connection. As the power generated by DG units increases, this behavior stresses the utility grid and could cause power unbalance; which may turn into instability. So, the interaction between DG units and the grid during the voltage sag is very important and it must be considered when designing the proper control strategy. In this paper a control strategy has been proposed for renewable power generation system during voltage sag conditions. First, description of renewable power generation system include power electronic converters are presented. Then control structure of the hybrid power generation system is investigated. Simulation results prove the effectiveness of the proposed control strategy.

II. DESCRIPTION OF HYBRID FUEL CELL/ ENERGY STORAGE POWER GENERATION SYSTEM

Hybrid fuel cell/energy storage distributed generation system (HDHS) need an electronic converter to interface with the AC system. Fig.1 shows the block diagram of the HDGS proposed in this paper. As shown in the Fig.1, it consists of a fuel cell, a super capacitor, DC to DC power converters, a 3-phase DC to AC inverter and an output filter. The mathematical models describing the dynamic behavior of each of these components are given as follow.

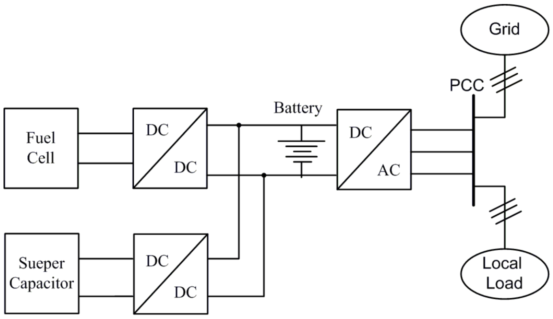

Figure 1. Topology of Hybrid Distributed Power System

A. Modeling of PEM Fuel Cell Subsystem

Since the fuel cell system here is required to work under steady state conditions as explained earlier, a steady-state model is sufficient to model its output. The Fuel Cell model used in this paper is based on the empirical model proposed in

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[7].To extract a steady state model for fuel cell, a measurement on 25KW (2×12.5KW) grid connected PEM fuel cell on Taleghan site (Fig.2) has been performed. The V-I characteristic of 12.5KW PEM fuel cell has been shown in Fig.3.

Figure 2. 25kW (2×12.5KW) grid connected PEM fuel cell in Taleghan

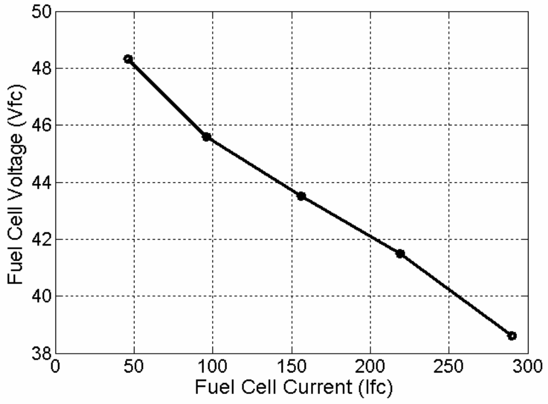

Figure 3. V-I specification of 12.5KW PEM fuel cell

Non linear regressive fitting is used to fit measured cell or stack V-I polarization data to the empirical equation (1) at given operating temperature, pressure and oxygen composition. E_0, b, R, m and n are parameters to be determined, and V and i are respectively fuel cell voltage and current.

$$V = E_0 - b\log i - Ri - m\exp(ni) \qquad (1)$$

The logarithmic term is related physically to the activation voltage drop and has pronounced effect on the voltage at lower currents while the exponential term is related to the concentration voltage drop and dominates at higher currents [9]. R is numerically equal to the ohmic resistance. E_0 is given by (2) Where E_r is the reversible potential and i_0 is tafel parameter [8].

$$E_0 = E_r + b\log i_0 \qquad (2)$$

The model was implemented using Simulink blocks and Simpower controlled voltage source block. Usually to connect a fuel cell to an external power system, it is necessary to boost the fuel cell voltage or to increase the number of cells. The role of the DC/DC boost converter is to increase the fuel cell voltage, to control the fuel cell power, and to regulate the voltage [9]. The DC/DC converter that interfaces the fuel cell to the dc-link Fig.4 shows the DC/DC converter model.

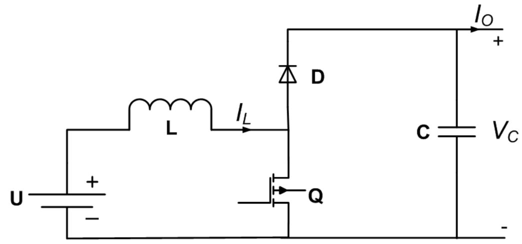

Figure 4. Boost DC/DC Converter Model

B. Super capacitor Model

Super capacitors store electrical energy by accumulating charge on two parallel electrodes separated by a dielectric material. The capacity represents the relationship between the electric charge stored in the capacitor and the voltage between the two electrodes of the capacitor. The classical equivalent circuit of the super capacitor is shown in Fig. 5 [10].

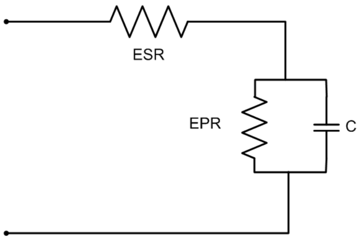

Figure 5. Equivalent model for the super capacitor bank

The super capacitor is connected to dc bus by a buck-boost converter. This converter topology is slightly more complex than the boost converter since includes one additional switch. But it has the advantage of allowing bidirectional power flow, which means energy can flow from the energy source to the load and back from the load to the energy source. This feature is very convenient for energy storage devices like batteries and super capacitors; because it allows recharging the device after each time their energy is used. The schematic of buck boost converter is shown in Fig.6. The super capacitor is connected to dc bus by a buck-boost converter. This converter topology is slightly more complex than the boost converter since includes one additional switch. But it has the advantage of allowing bidirectional power flow, which means energy can flow from the energy source to the load and back from the load to the energy source. This feature is very convenient for energy storage devices like batteries and super capacitors; because it allows recharging the device after each time their energy is used. The schematic of buck boost converter is shown in Fig.6.

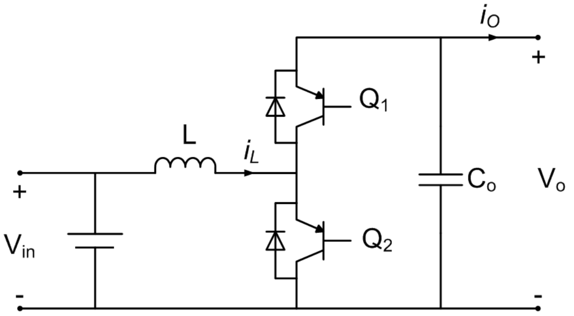

Figure 6. Buck-Boost DC/DC Converter Model

III. POWER FLOW CONTROL OF FUEL CELL/ENERGY STORAGE DISTRIBUTED GENERATION SYSTEM

In this section, the control strategy of the hybrid fuel cell/energy storage distributed generation system has been presented. During the voltage sag, a decrease in voltage amplitude occurs at the converter terminal. To keep the power supplied to the grid constant, the current should increase. It will be limited by the current controller however, to avoid overloading of the converter. This will thus limit the power that the DG unit can supply to the grid during sag, results the dc-link voltage will increase. To avoid a too high dc-link voltage, the power balance between inverter power and DG power must be satisfied. In fact, during voltage sag conditions, the power flow control strategy must be designed to stabilize the dc link power and regulate the dc link voltage consequently. The dc-link voltage is given by:

$$C_{dc}v_{dc}\frac{dv_{dc}}{dt} = P_{DG} - P_{inv} \qquad (3)$$
$$P_{DG}(k) = P_{FC}(k) + P_{ES}(k)$$

With P_{DG} and P_{inv} the DG power supplied to the dc-link and the inverter power absorbed the dc-link respectively. Also P_{FC} and P_{ES} are the fuel cell and energy storage power respectively.

During the voltage sag, the reference power of inverter is determined by the maximum power that can be supplied to the grid. So, the DG power must be decreased to avoid a too high dc-link voltage. Hence, the power management in hybrid fuel cell/energy storage distributed generation system is very important task and it affects on the operation of the system during voltage sag. So it should be robust under any variations in voltage and power. One existing method to solve these issues is to install energy storages which absorb power from fuel cell power source. According to the equation (3), in order to regulate the dc link voltage it is necessary to keep the power balance in dc link. Moreover, to meet the power balance in dc link it is important to consider the dynamic limitations of fuel cell power. In this case, the fuel cell power could not change rapidly and the fuel cell controller with DC-DC converter should regulate the operating point of fuel cell. The details of fuel cell and DC-DC converter control strategy are presented in next part. But the amount of power that should be absorbed by super capacitor to balance the power in dc link is very important and it depends on the dc link energy. The dc link energy measurement is carried out by means of the following calculation:

$$E_{dc}(k) = (\frac{1}{2})C_{dc}V_{dc}^{2}(k) \qquad (4)$$

In this paper, a power flow control structure has been developed for hybrid power sources during voltage sag. It is based on self tuning fuzzy control strategy that determines the super capacitor power according to the following inputs:

$$e(k) = E_{dc-ref}(k) - E_{dc}(k)$$
$$\Delta e(k) = e(k) - e(k-1) \qquad (5)$$

Where E_{dc-ref} is the reference dc link energy which calculated by reference dc link voltage. The detail of the self tuning fuzzy controller has been given in [11-12].

A. Control strategy of DC-DC Converter

In this paper the current mode control of dc/dc converter has been used to regulate the fuel cell current. The control structure for current control of renewable power source has been shown in Fig.7. In this structure, the transfer function of PWM block can be modeled as:

$$T_{PWM} = \frac{1}{K_{PWM}} \qquad (6)$$

Where K_{PWM} is the amplitude of the PWM saw tooth carrier signal.

The transfer function of fuel cell converter controller is as the following form:

$$G_c(s) = \frac{K_p}{s}.(\frac{1+sT}{1+aTs}) \qquad (7)$$

The parameter of controller is determined according to the frequency response design method. The gain Kp (2.1), a (0.0763) and the time constant T (4.6ms) are set to obtain a phase margin of 57° at a crossover frequency of 1500 rad/s.

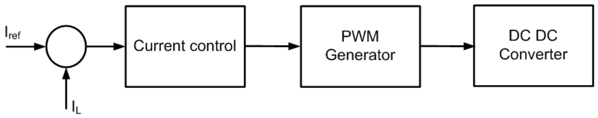

Figure 7.Block diagram of DC-DC converter control strategy

B. Control Strategy of Shunt-Connected Voltage Source Converter

Control of grid connected voltage source converter (VSC) is an important problem during voltage disturbances like voltage sag. Voltage sag is a reduction in the RMS voltage in the range from 0.1 to 0.9 p.u. of the nominal voltage for duration greater than half cycle and less than one minute. The drawback of using VSC is its sensitivity to voltage disturbances. For a VSC, a sudden decrease in grid voltage normally causes an increase in current, as the control attempts at maintaining the power to the DC link constant. Moreover, most faults are unbalanced and result in unbalanced voltage sag, which produce undesirable power oscillations of low order frequencies in current harmonics and poor DC-link voltage regulation. Ultimately, this can also lead to tripping of the converter due to DC overvoltage. The VSC is connected to the grid via a filter inductor. The state space model in positive and negative synchronous reference frames for the grid connected inverter is shown in (8), respectively.

$$\begin{aligned}
\frac{d}{dt}i_{dp} &= \omega i_{qp} - \frac{R_L}{L}.i_{dp} + \frac{1}{L}.v_{i,dp} - v_{sdp}\\
\frac{d}{dt}i_{qp} &= -\omega i_{dp} + \frac{R_L}{L}.i_{qp} + \frac{1}{L}.v_{i,qp} - v_{sqp}\\
\frac{d}{dt}i_{dn} &= -\omega i_{qn} - \frac{R_L}{L}.i_{dn} + \frac{1}{L}.v_{i,dn} - v_{sdn}\\
\frac{d}{dt}i_{qn} &= \omega i_{dn} - \frac{R_L}{L}.i_{qn} + \frac{1}{L}.v_{i,qn} - v_{sqn}
\end{aligned} \qquad (8)$$

i_{dp}, i_{qp} positive-sequence dq grid currents

i_{dn}, i_{qn} negative-sequence dq grid currents

$v_{i,dp}$, $v_{i,qp}$ positive-sequence dq voltages at inverter terminals

$v_{i,dn}$, $v_{i,qp}$ negative-sequence dq voltages at inverter terminals
$v_{s,dp}$, $v_{s,qp}$ positive-sequence dq grid voltages
$v_{s,dn}$, $v_{s,qn}$ negative-sequence dq grid voltages

The VSC controller is required to have main functions: Current control and DC link voltage regulation. The current controller used in this paper consists of Dual Sliding mode Vector Current Controllers (DSVCC) that control the positive and negative sequence current separately and are implemented in two different rotating coordinate systems. A simplified scheme for the DSVCC is shown in Fig.8. The VSC is connected to the grid via filter inductors. The three phase grid currents and voltages are sampled and transformed into its positive and negative sequence components. The positive and negative sequence of dq-components are then used along the with the reference current signals in the DSVCC to produce the reference voltage signals for the PWM regulator.

According to the proposed control strategy, the purpose of the current controller is to synthesize a voltage correction vector so that the current error vector can be kept to a minimum value. The error current-vector is defined as:

$$\Delta i(k) = i_{ref}(k) - i(k) \qquad (9)$$

Where $i_{ref}(k)$ is the specified current vector command for the positive and negative sequence of dq-components and i(k) is the measured current vector feedback. The proposed sliding controller is used to generate the required voltage vector according to the error current-vector [13]. Where $i_{ref}(k)$ is the specified current vector command for the positive and negative sequence of dq-components and i(k) is the measured current vector feedback.

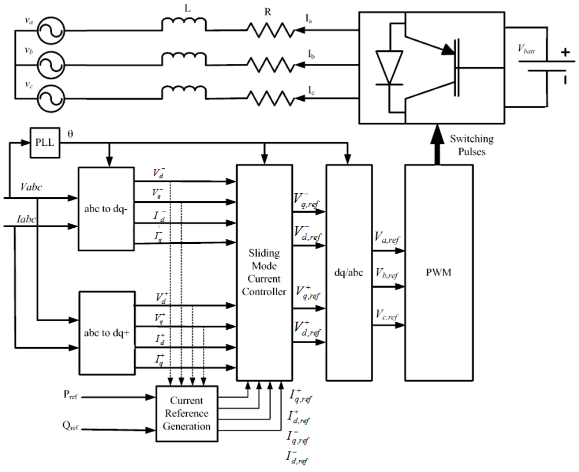

Figure 8. Block diagram of dual vector current controller.

In order to generate proper current references, consider the complex apparent power from the grid:

$$\begin{aligned} S_g &= (e_{dqp}e^{j\omega t} + e_{dqn}e^{-j\omega t}).(i_{dqp}e^{j\omega t} + i_{dqn}e^{-j\omega t})^* \\ &= (P + P_{2c}.\cos(2\omega t) + P_{2s}.\sin(2\omega t)) + \\ &\quad j(Q + Q_{2c}.\cos(2\omega t) + Q_{2s}.\sin(2\omega t)) \end{aligned} \qquad (10)$$

In order to work with an invertible matrix (4×4), oscillating reactive power (Q_{2c}, Q_{2s}) cannot be included in the current reference calculation. Therefore, oscillating reactive power is not controlled and will flow through the system. By expanding Equation (10), the following expression in matrix form can be written:

$$\begin{bmatrix} P_g \\ Q_g \\ P_{s2g} \\ P_{c2g} \end{bmatrix} = \begin{bmatrix} e_{dp} & e_{qp} & e_{dn} & e_{qn} \\ e_{qp} & -e_{dp} & e_{qn} & -e_{dn} \\ e_{qn} & -e_{dn} & -e_{qp} & e_{dn} \\ e_{dn} & e_{qn} & e_{dp} & e_{qp} \end{bmatrix} \begin{bmatrix} i_{dp} \\ i_{qp} \\ i_{dn} \\ i_{qp} \end{bmatrix} \qquad (11)$$

Where P_g and Q_g are the constant active and reactive power, respectively, while the subscripts P_{s2g} and P_{c2g} represent the second harmonic sine and cosine component of the active power. These are the oscillating powers due to the unbalance in the grid voltages. The reference currents can be calculated as follow:

$$\begin{bmatrix} i_{dp}^* \\ i_{qp}^* \\ i_{dn}^* \\ i_{qn}^* \end{bmatrix} = \begin{bmatrix} e_{dp} & e_{qp} & e_{dn} & e_{qn} \\ e_{qp} & -e_{dp} & e_{qn} & -e_{dn} \\ e_{qn} & -e_{dn} & -e_{qp} & e_{dn} \\ e_{dn} & e_{qn} & e_{dp} & e_{qp} \end{bmatrix}^{-1} \begin{bmatrix} P^* \\ Q^* \\ -\Delta P_{s2} \\ -\Delta P_{c2} \end{bmatrix} \qquad (12)$$

$$\Delta P = R.(i_{dp}^2 + i_{qp}^2 + i_{dn}^2 + i_{qn}^2) \qquad (13)$$

$$\Delta P_{c2} = 2R(i_{dp}.i_{dn} + i_{qp}.i_{qn}) + 2\omega L(i_{dp}.i_{qn} - i_{qp}.i_{dn}) \qquad (14)$$

$$\Delta P_{s2} = 2R(i_{dp}.i_{qn} - i_{qp}.i_{dn}) + 2\omega L(-i_{dp}.i_{dn} - i_{qp}.i_{qn}) \qquad (15)$$

This algorithm calculates current references by setting active and reactive power references (P^*, Q^*), and by forcing the oscillating active power demanded by the filter to be delivered from the grid ($P_{2c}^* = -\Delta P_{2c}$; $P_{2s}^* = -\Delta P_{2s}$). Then, no oscillating active power flows between the dc link and the filter.

IV. RESULTS AND DISCUSSION

This section presents simulation results for the system shown in Fig.1. In order to show the effectiveness of proposed control strategy, the simulation model of the proposed hybrid DG system has been built in Matlab/Simulink environment. The parameters of the hybrid fuel cell/ super capacitor distributed generation system in this study are given in Table 3. The energy storage bank operates as a buffer of energy to meet load demand that cannot be met by the FC system, particularly during transient or disturbances periods. In this case study, the output power of the FC system is limited to 25 kW and the super capacitor bank has is capable of sustaining the extra load of 20 kW during the voltage disturbances. For the evaluation of proposed control strategy, these objectives must be considered: i) evaluate the robust current controller; ii) dc-link voltage ripple during voltage sag; iii) power flow between fuel cell and super capacitor; iv) evaluate the operating performances of each power source under voltage sag. The system has been tested under a 50% unbalanced voltage sag type C [12]. The voltage sag starts at 4.3sec and ends at 4.4sec. Simulations for the voltage sag type C are shown in Figs. 6-10. It is supposed that the requested active and reactive powers are 25KW and 5KVAR. The injected currents to grid during voltage sag type C are shown in Fig.9. They are limited by current controllers to avoid overloading of the converter.

Also after voltage sag, the current controllers adapt fast according to the new current references to shape the grid currents. During the voltage sag, there are distortions in currents, but the system performance is not affected by this distortion.

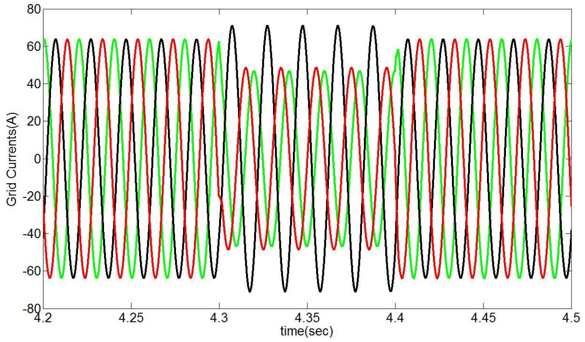

Figure 9. Grid currents during voltage Sag

As shown in Fig.10, the generated active power of the hybrid distributed generation system decreases during voltage disturbances to increase the voltage sag ride-through capability.

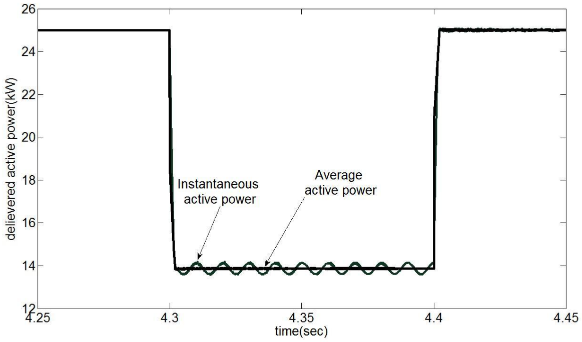

Figure 10. delivered active power to grid from hybrid distributed generation system

In fact, during the voltage sag, the current controllers limit the output current to avoid the overloading of the converter. As a result the power that converter supplies to the grid deceases, resulting in an oscillations in dc link voltage. The grid converter now controls the power (with its set point determined by the maximum current). There are oscillations on the generated active and reactive power of the hybrid system during voltage sag (Figs.10 and 11).

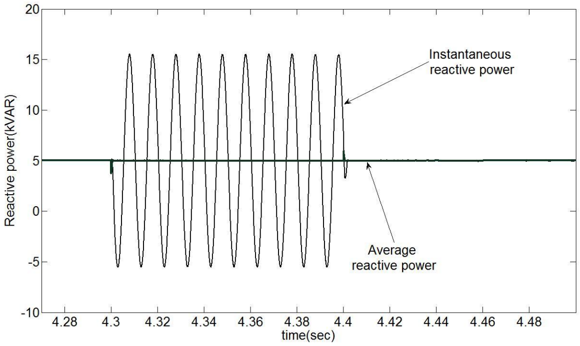

Figure 11. delivered active power to grid from hybrid distributed generation system

A possible reason of this can be found in the oscillating power reference calculation (13) (14) (15), which depend on the actual current values. In this case, according to the robust properties of sliding mode controller, the system instability does not occur. The DC-link voltages are shown in Fig.12. DC-link voltages show a oscillations during the transients at the beginning and end of the sag. However, the ripple during the transient is not bigger than 10% peak-to-peak and is quite quickly damped to almost zero. In these conditions, to stabilize the dc-link power and voltage consequently, the fuzzy controller manages the power flow between fuel cell and super capacitor, resulting the reference power of the energy storage bank changes for decreasing the input power to dc bus during voltage disturbances and the proposed control strategy switches the energy storage bank to the charging mode.

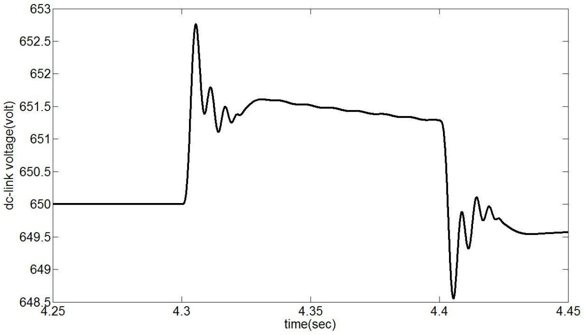

Figure 12. DC-link voltage during voltage Sag

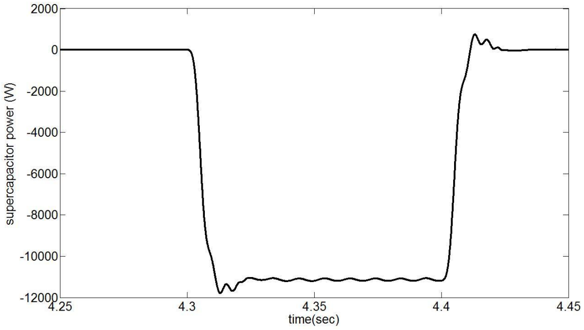

Figure 13. Super capacitor power during voltage sag

From Figs. 13-14, it is evident that the FC system and energy storage bank together share this load requirement. Because of the slow variations of the SOFC, the output power of the fuel cell power plant remains constant during the voltage sag (Fig.14). Also, the output voltage of fuel cell has not changed during the occurring the voltage disturbances in distribution systems (Fig.15). These parameters are very important on the life time of fuel cell system.

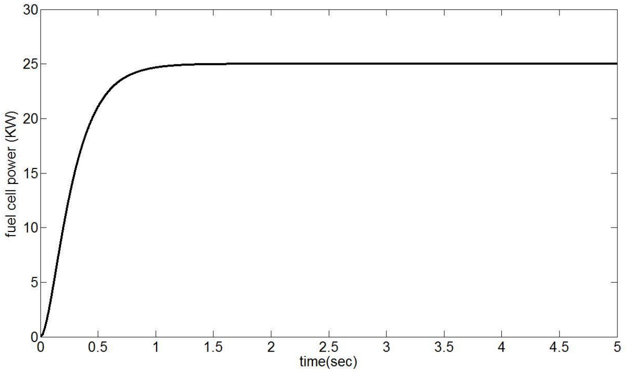

Figure 14. Fuel Cell Power during voltage sag

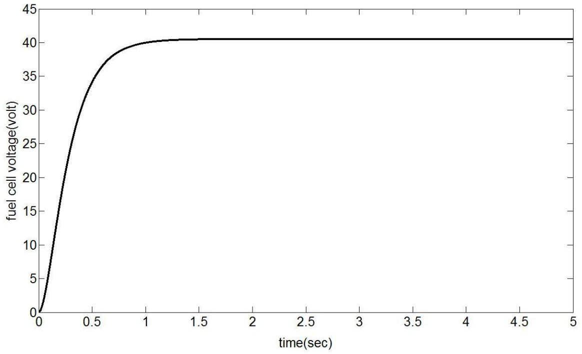

Figure 15. Fuel Cell Power during voltage sag

V. CONCLUSION

In this paper, a new control strategy is proposed for the hybrid fuel cell/ energy storage distributed generation system to evaluate the performance of this system during voltage sag in distribution system. For the evaluation of proposed control strategy, the hybrid DG system is tested under unbalance voltage sag. Simulation results show that the proposed control strategy is able to tolerate under voltage sag and keep the system performances like active power control and stability of dc-link.

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