International Conference on Green Energy & Environmental Engineering (GEEE-2018)
Proceedings of Engineering and Technology – PET
Vol.37 pp.1-6

A Power System Connected Fuel Cell Based On Dynamic Voltage Restorer (DVR)

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***Abstract*— This paper is about the active and reactive power flow analysis inside the Dynamic Voltage Restorer (DVR) during several cases, when this DVR is powered by Fuel Cell. The system is the unification between DVR and shunt inverter, and they still provide one of the best solutions by mitigating the voltage sags and swells problems on distribution network. This analysis can provide the helpful information to well understanding the interaction between the DVR, the inverter, the Fuel Cell and electrical network. The mathematical analysis is based on active and reactive power flow through the system. Wherein DVR can absorb or deliver the active power from the Fuel Cell to mitigate a swell or sage voltage, in the both cases it absorbs a small reactive power quantity, whereas the inverter supply linear loads with energy from fuel cells and to compensate reactive current. The voltage sag and voltage swell are usually interpreted through the DC bus voltage curve. These two phenomena are introduced in this paper with a new interpretation based on the active and reactive power flow analysis inside the DVR. The simulation results are carried out to confirm the analysis done.**

***Keywords* — Fuel Cell, DVR, Power flux analysis, Power factor, Sag and Swell voltage.**

I. INTRODUCTION

Actually, the low costs of power electronic devices has led to the wide spread increase of power electronic loads in industry. As a result the significant non-linear loads, mass inductive loads and sensitive loads appear in a considerable amount of harmonics injection, low power factor and voltage disturbances in power systems [1-5]. They tend to introduce voltage sag/swell, flicker, harmonics and asymmetries at the point of common coupling (PCC). These instabilities cause devices malfunctioning, overheating of power factor correction condensers, motors, transformers and cables. In addition, sensitive loads may not tolerate sags and/or swells and the electrical energy distributor may penalize low power factor at the PCC. Customers describe equipment tripping resulting from perturbation in the supply voltage as "poor power quality".

Specific devices are used as solutions for immediate treatment of each individual problem, such as using the Shunt APF to absorb the current harmonics, and Series APF to mitigate the voltage harmonics, and using the DVR to adjust the sensitive load voltage at the time when the sag and swell voltage occur, and using the SVG to generate the reactive power for the load.

This paper presents a custom power device, which combines the series and shunt active inverter functioning together, integrating these two inverters. On the DC side, the two inverters are connected back-to-back sharing a common Fuel Cell [6]. The DVR component inserts a voltage in order to maintain the load terminals voltage at a certain level. This voltage is proceeded from a voltage source inverter (VSI) operated under pulse width modulation (PWM). At the same time, the system shunt component injects current in the AC system to compensate for reactive current in order to correct the power factor of the supply side near to unity, as well as to inject the Fuel Cell power into the utility grid under fixed fuel cells power conditions Fig. 1 shows a basic system configuration. This paper interests with the active and reactive power flow analysis between DVR and the system components during voltage sag and swell at steady state. Aim is to maintain the load bus voltage at desired constant level in all operating conditions. This power flow analysis plays an important role to well understanding the relationship between the DVR during the compensation of some problems.

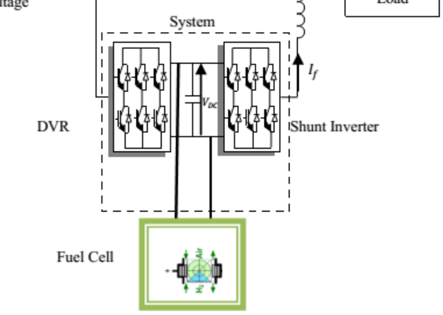

Fig. 1 DVR circuit configuration

ISSN 2356-5608

II. THE POWER FLOW STUDY IN THE DVR.

The DVR is controlled in such a way that the voltages across the load are always equal to a desired value. Therefore, the voltage injected by the DVRequals to the difference between the supply voltage and the ideal desired voltage across the load. The function of a shunt active inverter is to maintain the DC bus voltage at a constant value and to compensate the reactive powers required by the load; hence, the network provides onlythe active power.

In what follows, the load voltage is considered in phase with the supply voltage. This is done by injecting a voltage in phase or in opposition phase with the source voltage respectively in cases of voltage sag or voltage swell, this leads to a bidirectional power flow (System-Network) through the DVR. The voltage injected by the DVR must be positive or negative, according to the source voltage amplitude, voltage swell or sag. On account of this, the active power is absorbed or supplied by the DVR. In this case the reactive power is fully compensated by the parallel active inverter.

The load used has been assumed linear with a power factor equals 0.87. The equivalent system model single phase circuit is presented in the figure below.

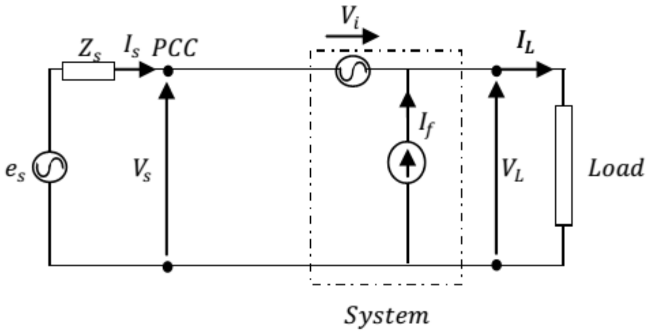

Fig. 2 Equivalent circuit of the System

With:

I_s,e_S: The supply current and supply voltage respectively
V_s: the voltage at the point of common coupling (PCC)
I_L, V_L: The load current and load voltage respectively
V_i: DVR inserted voltage.
If: Shunt inverter injected current.

V_L is taken as reference phasor and $\cos\phi_L$ is the power factor corresponding to the load, it can be written that :

$$v_L = V_L \angle 0^0 \tag{1}$$

$$i_L = I_L \angle -\phi_L \tag{2}$$

$$v_s = V_L(1+k)\angle 0^0 \tag{3}$$

Where k is the voltage fluctuation factor at the point of common coupling (PCC), defined as:

$$k = \frac{V_S - V_L}{V_L} v_L \tag{4}$$

The series injected voltage equals:

$$v_i = v_L - v_s = -kV_L \angle 0^0 \tag{5}$$

Supposing that DVR is without losses, the active power required by the load equals to that at PCC and the power injected by the Fuel Cell. This power can be expressed as follows:

$$P_s + P_{FC} = P_L \tag{6}$$

$$V_s . I_s + P_{FC} = V_L \cdot I_L \cos\phi_L \tag{7}$$

$$V_L(1+k).I_s + P_{FC} = V_L \cdot I_L \cos\phi_L \tag{8}$$

$$I_s = \frac{I_L}{(1+k)}\cos\phi_L - \frac{P_{FC}}{V_L(1+k)} \tag{9}$$

Equation (9) shows that the source current depends on the $k, \cos\phi_L$ factor, load current I_L and the Fuel Cell power P_{FC} .

The apparent power absorbed by the DVR can be written as:

$$\bar{S}_i = \bar{v}_i \bar{I}_s \tag{10}$$

$$P_i = V_i \cdot I_S \cos\phi_S = -kV_L \cdot I_S \cos\phi_S \tag{11}$$

$$Q_i = V_i \cdot I_S \sin\phi_S \tag{12}$$

$\phi_S \cong 0$, the Shunt inverter of the Fuel Cell maintains the unit power factor on the supply side:

$$P_i = V_i \cdot I_S = -kV_L \cdot I_S \tag{13}$$

$$Q_i \cong 0 \tag{14}$$

The apparent power absorbed by the inverter of the Fuel Cell is:

$$\bar{S}_f = \bar{v}_L \bar{i}_f \tag{15}$$

The current provided by the shunt inverter equals the difference between the source current and load current including both active and reactive currents, thereby having:

$$i_f = i_S - i_L \tag{16}$$

$$i_f = I_S \angle 0^0 - I_L \angle -\phi_L \tag{17}$$

$$i_f = I_S - (I_L \cdot \cos\phi_L - jI_L \cdot \sin\phi_L) \qquad (18)$$

$$i_f = (I_S - I_L \cdot \cos\phi_L) + jI_L \cdot \sin\phi_L \qquad (19)$$

$$P_f = V_L I_f \cdot \cos\phi_f \qquad (20)$$

$$P_f = V_L (I_S - I_L \cdot \cos\phi_L) \qquad (21)$$

$$Q_f = V_L I_f \cdot \sin\phi_f = V_L I_L \cdot \sin\phi_L \qquad (22)$$

III. PEM FUEL CELL GENERATOR MODELLING

Electrical energy needs are still increasing over these last years but production constraints like pollution and global warming lead to development of renewable energy sources, particularly chemical energy. Fuel cells (FCs) are static energy conversion devices that convert the chemical energy of fuel directly into DC electrical energy [10]. The fuel cell consists of two porous electrodes (anode and cathode) and an electrolyte layer in the middle. Figure (3) illustrateFuel cell (PEMFC) [6].

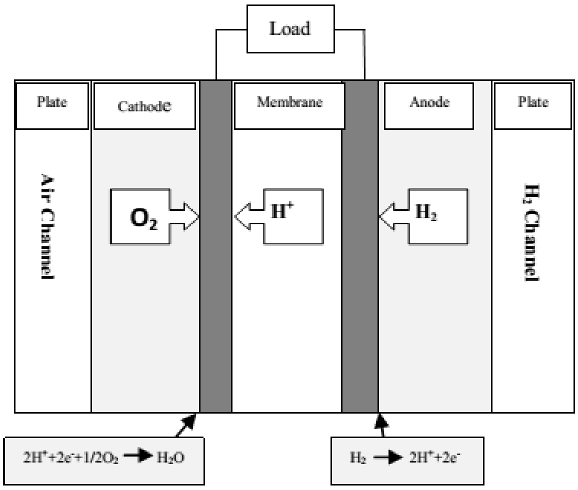

Fig. 3 Basic PEMFC operation

The chemical energy of a fuel is converted, the fuel H2is supplied under certain pressure. The hydrogen concentration should be determined in the mixture. The fuel spreads through the electrode until it reaches the catalytic layer of the anode where it reacts to form protons and electrons, as given in the following reaction:

$$H_2 + 1/2O_2 \rightarrow H_2O + \text{heat} + \text{electrical energy} \qquad (23)$$

Hydrogen oxidation and oxygen reduction are separated by a membrane, which is conducting protons from the anode to the cathode side [9].

$$H_2 \rightarrow 2\,H^+ + 2\,e^- \quad \text{anode} \qquad (24)$$

$$O_2 + 4\,e^- \rightarrow 2\,O^-_2 \quad \text{cathode} \qquad (25)$$

The protons are diffused through the membrane, and the electrons are carried across an electric circuit, the electrical energy is produced. The cell voltage was defined as:

$$V_{FC} = E_{nernst} - V_{act} - V_{ohm} - V_{conc} \qquad (26)$$

E_{nernst} is the thermodynamic potential of the cell and its represents reversible voltage; V_{act} is the voltage drop due to the activation of the anode and of the cathode. V_{ohmis} the ohmic voltage drop, a measure of the ohmic voltage drop associated with the conduction of the protons through the solid electrolyte and electrons through the internal electronic resistances. V_{conc} represents the voltage drop resulting from the concentration or mass transportation of the reacting gases. V_{FC} represents the open circuit voltage. Each term in (26) can be calculated by the following equations [10].

$$E_{nerst} = 1{,}229 + 0{,}85.10^{-3}(T - 298{,}15) + 4{,}31.10^{-5}.T.\ln(P_{H2} \cdot P_{O2}^{0.5}) \qquad (27)$$

P_{H2} and P_{O2} are the partial pressures of hydrogen and oxygen (atm) respectively, T the cell operation temperature (K).

$$V_{act} = -\left\lfloor \xi_1 + \xi_2 T + \xi_3 .T.\ln(Co_2) + \xi_4 .\ln(I_{stack}) \right\rfloor \qquad (28)$$

Where I_{stack} is the cell operating current (A), and the ξ_i 's represent parametric coefficients for each cell model, whose values are defined based on theoretical equations with kinetic, thermodynamic, and electrochemical foundations [6]. Co2 is the concentration of oxygen in the catalytic interface of the cathode mol/cm, determined by:

$$Co_2 = \frac{Po_2}{5{,}08.10^6.e^{(-498/T)}} \qquad (29)$$

$$V_{ohmic} = I_{stack}.(R_m + R_c) \qquad (30)$$

Where Rc represents the resistance to the transfer of protons through the membrane, usually considered constant and: $R_m = \frac{\rho.l}{A}$ with:

ρ : is the specific resistivity of the membrane for the electron flow (cm)

A is the cell active area (cm)

l is the thickness of the membrane (cm), which serves as the electrolytic of the cell.

$$V_{conc} = B.\ln\left(1 - \frac{J_n}{J_{\max}}\right) \tag{31}$$

Where B (V) is a parametric coefficient, which depends on the cell and its operation state, Jn represents the actual current density of the cell (A/cm).

Due to very limited conversion efficiency, it is necessary to optimize all the conversion chain and specifically DC-DC converters [7].There are many types of DC/DC converters, in this paper; only typical boost converter is discussed. Figure (4) shows the circuit diagram of a boost DC/DC converter (inside the rectangle). The average value of the output voltage is given as:

$$V_{FCout} = \frac{V_{FCin}}{(1-d)} \tag{32}$$

Where d is the duty ratio of the switching pulse.

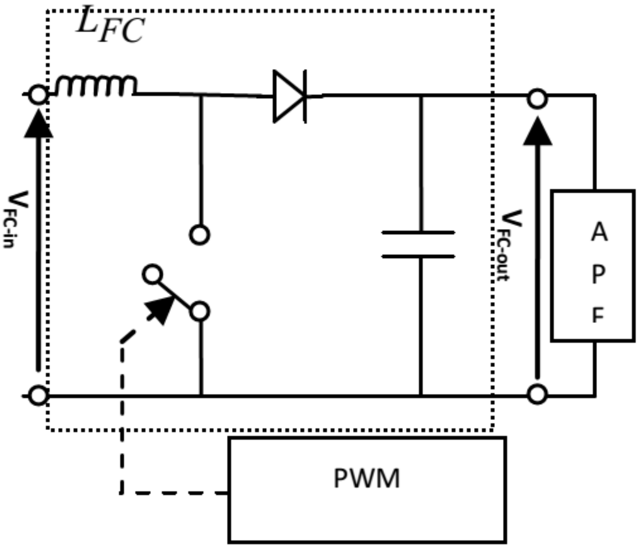

Fig. 4 Boost DC/DC converter

Since $0 \leq d \prec 1$, the output voltage is always higher than the input voltage. That is why the circuit in Figure (4) is called a boost DC/DC converter. PWM used to generate a pulse with the right duty ratio so that the output voltage follows the reference value.

Our PEMFC generators consist of two modules interconnected in parallel for a given operating voltage an output power. The VSI is controlled in such a way that it can be used to inject sinusoidal current into the grid for energy extraction from the PEMFC cells during linear or non-linear load conditions.

IV. SIMULATIONS AND DISCUSS

Figure 1 shows the test system implemented using MATLAB SIMULINK software. The test system comprises a utility with sinusoidal and symmetrical voltage at frequency of 50Hz, a constant RMS value 220 V (feeding a fixed inductive load (94.2 Kw, 16.5Kvar). A DVR is connected to a power system to keep load voltage at nominal value. This DVR is supplied by Fuel Cell. To show the effectiveness of this controller in providing continuous voltage regulation; simulations are carried out with and without disturbance voltage.

Firstly the terminal voltage decreases with 50 %at 0.5s to 0.6 s (Voltage Sag), than the supply voltage is increased to 50 % at 0.8s to 0.9 s (Voltage Swell). The three-phase load voltage waveforms are presented in Fig. 3.

The system uses tow Fuel Cell Stack. Each Stack is modelled at 625Vdc, 50kW PEM Fuel Cell Stack, connected to a 1515Vdc DC/DC converter. The converters are connected to shunt inverter. The utilization of the hydrogen is constant to the nominal value (Uf-H_2 = 99.25%) and oxygen (Uf-O_2=56.67%), each Stack has 900 cells; nerst voltage of one cell is about 1.138v.

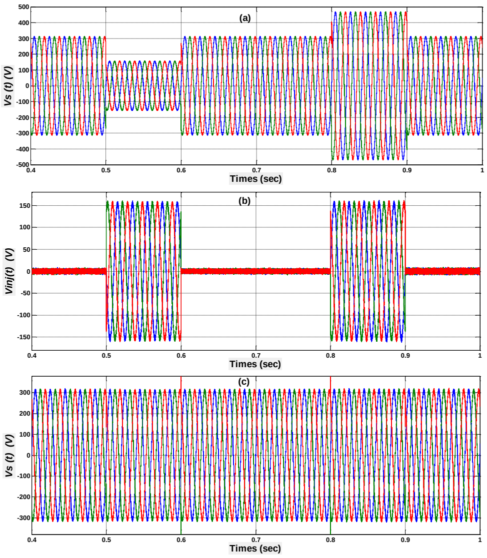

Fig. 5 (a) Supply voltages (V), (b) The DVR injected voltages (V), (c)The load voltages (V).

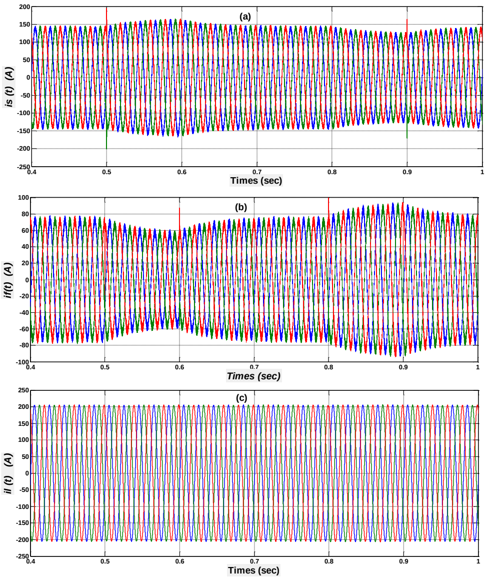

Fig. 6 (a) Supply currants (A), (b) The (Fuel Cell and shunt inverter) injected currants (A), (c) The load currents (A).

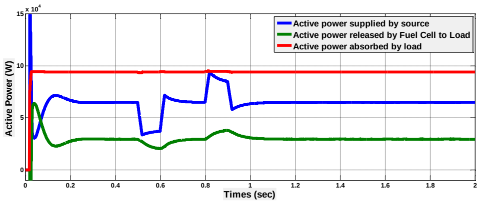

Fig. 7 Mutual active powerflow between the systemcomponents

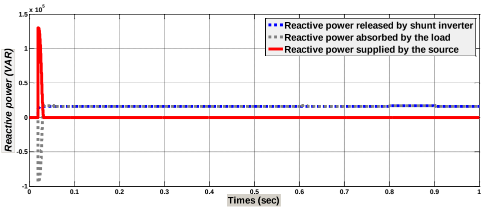

Fig. 8 Mutual reactive powerflow between the systemcomponents

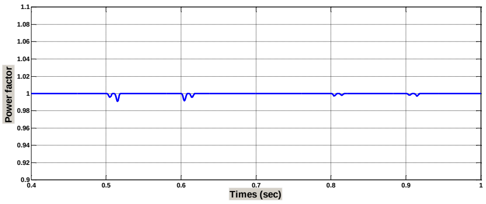

Fig. 9 Power factor variations(sourceside)

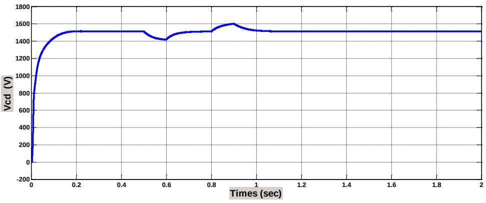

Fig. 10 The average voltage across the Fuel Cell terminals

A. Normal case

In normal operation, the shunt inverter (SI) injects the Fuel Cell powerto the load and compensates the load reactive power through the semiconductor devices, while the DVR does not exchange any active or reactive power with the electrical network, the shunt inverter power depends mainly on the injected current to the network, which depends on the load power factor and the source currents. So, the power flow is summarized by the following schemes:

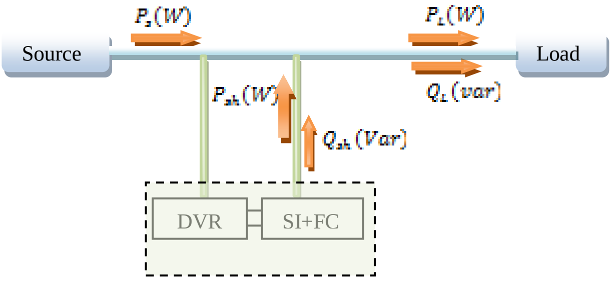

Fig. 11 Power flow during normal operation

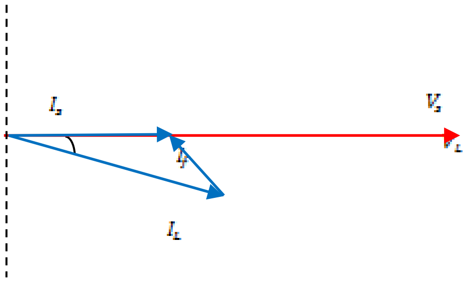

Fig. 12 Vector diagram representing the operating conditions during the normal operation

B. Voltage sag case

In voltage sags case: $VS<VL$, and according to equation (4), where $k<0$, it signifies that the DVR injects an active power to electrical network (PDVR). (See figure 7). The decrease in current injected by the Fuel Cell to the load is caused by the fact that a part of Fuel Cell power feeds the DVR, in order to compensate the sag voltage, so the source current will be increased to meet the requirement of load power (see figure 6). At all the time the shunt inverter compensates the load reactive power by injecting a reactive power (Q_{sh}) in order to keep the power factor at the unite value ,figures 8 and 9 .Then, the power flow is summarized by the following scheme:

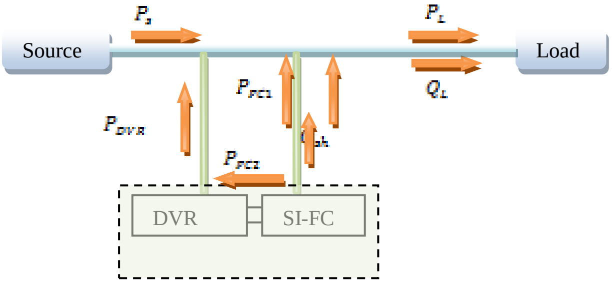

Fig. 13 Power flow during sag voltage.

C. Voltage swell case

In voltage swell case: $V_S>V_L$, where $k>0$, it signifies that the DVR absorbs an active power (PDVR) from the electrical network (See figure 7), while the supply current decreasing (i_S) means that the Fuel Cell active power injected by the shunt inverter (P_{sh}) is increased by the addition of that is absorbed by DVR this excess power is released to stabilize the DC bus condenser at a constant value (see figure 6). Concerning the reactive power, during the voltage swell time, the shunt inverter compensates, during all the time, the load reactive power by injecting reactive power (Q_{sh}) figures 8 and 9. Thus, the power flow is summarized by the following scheme:

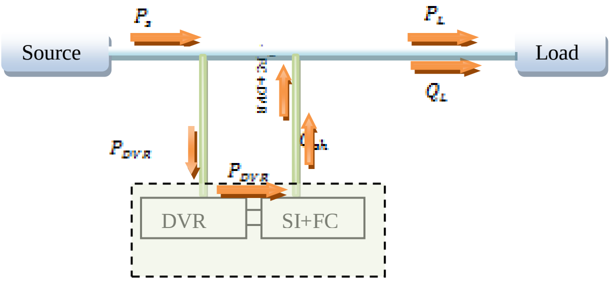

Fig. 14 Power flow during voltage swell.

V. CONCLUSION

For well understanding the functioning of the DVR supplied by Fuel Cell, an analysis of active and reactive power has been presented in this paper. The paper system is designed to compensate, sometimes, several disturbances at the same time. So it can compensate simultaneously such voltage sag and swell by the DVR and a reactive current through the shunt inverter, as well as the system releasethe excess power in order to stabilize the DC bus voltage. As a result a new interpretation of the compensation phenomena for a voltage sage or swell with improving the power factor, based primarily on an analysis of the power flow has been presented in this paper.

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