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DVR Based On Fuel Cell: An Innovative Back-Up System

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***Abstract*—The aim of the paper is to evaluate the technical aspect feasibility related to the use, in a (DVR) dynamic voltage restorer (DVR), of fuel cells instead of traditional DC storage systems. The proposed system, named DVR FCB (Fuel Cell Based) presents a modular and versatile system configuration; it is possible to integrate it with traditional DVR. Moreover the system feature can be modified in terms of power, reliability and voltage sag compensation. A detail analysis has been carried out on a passive stand–by DVR integrated with a FCB; experimental result can be easily extended to the other possible system architectures.**

***Index Terms*—DC Energy Storage, Dynamic Voltage Restorer, Voltage Sag, Silicon Oxide Fuel Cell.**

I. Introduction

A fuel cell converts chemical energy into electric energy by electrochemically conversation. In this system generated electric energy as long as fuel is supplied continuously from outside, it can also be considered a generating system similar to conventional generating systems [1]. Fuel Cells produce DC voltage outputs. SOFC fuel cell is attractive because they are modular, capable, and environmentally friendly.

Understanding the transient behavior of SOFC is important for controlling the stationary utility in power supply in DVR during power system faults, surges and switching. SOFC operating temperature is 900^{o}-$1000\ ^{o}$ and efficiency 50-60% [2]. One of the main weak points of fuel cell is its slow dynamics response. To solve these problems, the system must have a fast auxiliary source, to supply or absorb high transient energy. The new high current super capacitor topology has been developed for this purpose [3]. In this topology placing the super capacitor in parallel with the SOFC fuel cell. The control circuit monitors the utility and the fuel cell status continuously. When the system detects a utility disturbance condition, it controls the fuel cell and power converter modules to supply more power [4]. Presently, the majority of power quality problems are due to different fault conditions. These conditions cause voltage sag [5]. Dynamic voltage restorer (DVR) can provide the Cost of effective solution to mitigate voltage sag by establishing the appropriate voltage quality level, required by the customer [6] [7]. The basic structure of a DVR is shown in Fig.1. It is divided into six categories:

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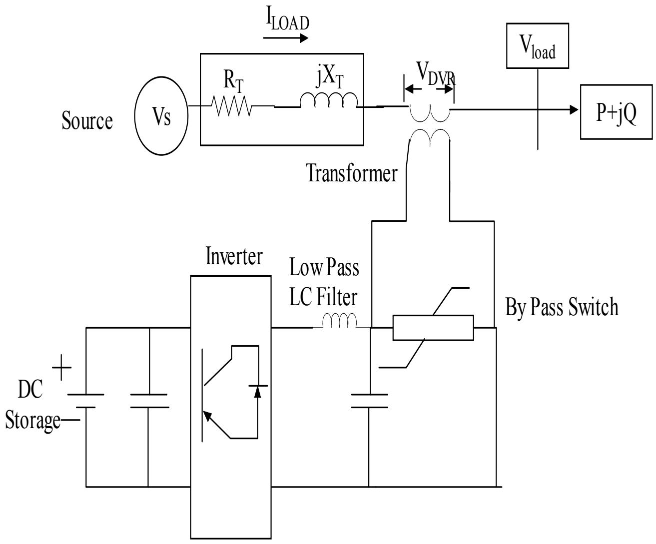

Fig.1. Basic Structure of Dynamic Voltage Restorer

(i) ***Voltage Injection Transformers:*** In a three-phase system, either three single-phase transformer units or one three phase transformer unit can be used for voltage injection purpose. [5].

(ii) ***Capacitor:*** DVR has a large DC capacitor to ensure stiff DC voltage input to inverter.

(iii) ***Inverter:*** An Inverter system is used to convert dc storage into ac form [8]. Voltage source inverter (VSI) of low voltage and high current with step up injection transformer is used for this purpose in the DVR compensation technique [7].

(iv) ***Passive Filters:*** Filters are used to convert the inverted PWM waveform into a sinusoidal waveform. This is achieved by eliminating the unwanted harmonic components generated VSI action. Higher orders harmonic components distort the compensated output voltage [5].

(v) ***By-Pass Switch:*** It is used to protect the inverter from high currents in the presence of faulty conditions [9].

(vi) ***Energy Storage Unit:*** It is responsible for energy storage in DC form. Flywheels, batteries, superconducting magnetic energy storage (SMES) and supercapacitors can be used as energy storage devices. It is supplies the real power requirements of the system when DVR is used for compensation [7]. Fuel cells are environmentally sound renewable energy sources that are capable of operating at efficiency grater than the traditional energy production method [14]. DVR FCB (Fuel Cell Based) structure is shown in Fig.2.

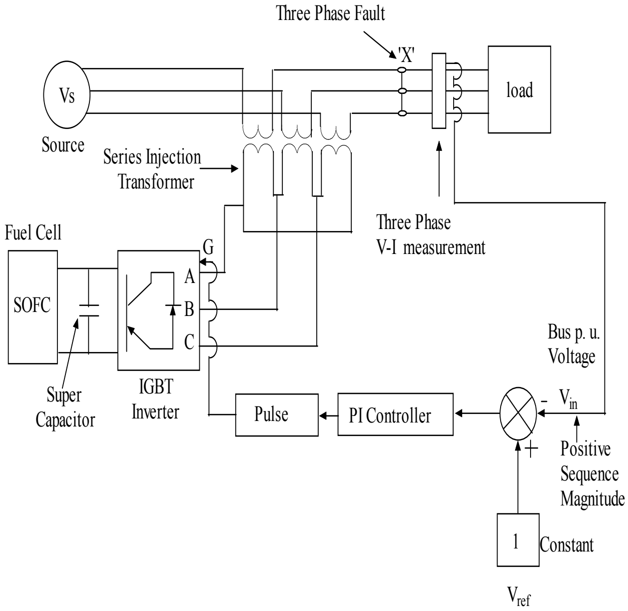

Fig.2. DVR FCB (Fuel Cell Based)

Basic principal of DVR is to transfer the voltage sag compensation value from DC side of the inverter to the injected transformer after filter. The compensation capacity of a particular DVR depends on the maximum voltage injection capability and the active power that can be supplied by the DVR. When DVR's voltage disturbance occurs, active power or energy should be injected from DVR to the distribution system [10]. A DC system, which is connected to the inverter input, contains a large capacitor for storage energy. It provides reactive power to the load during faulty conditions. When the energy is drawn from the energy storage capacitors, the capacitor terminal voltage decrease. Therefore, there is a minimum voltage required below which the inverter of the DVR cannot generate the require voltage thus, size and rating of capacitor is very important for DVR power circuit [11]. The DC capacitor value for a three phase system can be derived [12]. The most important advantage of these capacitors is the capability to supply high current pulses repeatedly for hundreds of thousands of cycles. Selection of capacitor rating is discussed on the basis of RMS value of a capacitor current, rated voltage of a capacitor and VA rating of the capacitor [13].

Section II discusses the PI controller strategy employed for inverter switching in the DVR. The simulation model is developed using MATLAB SIMULINK in section III. Section IV presents and discusses simulation results with different Fuel cell rating.

II. CONTROL PHILOSOPHY

Voltage sag is created at load terminals by a three-phase fault as shown in Fig.2. Load voltage is sensed and passed through a sequence analyzer. The magnitude is compared with reference voltage (V_{ref}). Pulse width modulated (PWM) control technique is applied for inverter switching so as to produce a three phase 50 Hz sinusoidal voltage at the load terminals. Chopping frequency is in the range of a few KHz. The IGBT inverter is controlled with PI controller in order to maintain 1 p.u. voltage at the load terminals i.e. considered as base voltage =1p.u.

A proportional-integral (PI) controller (shown in Fig. 3) drives the plant to be controlled with a weighted sum of the error (difference between the actual sensed output and desired set-point) and the integral of that value. An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the V_{ref} and $V_{in.}$ Output of the controller block is of the form of an angle δ, which introduces additional phase-lag/lead in the three-phase voltages. The output of error detector is

$$V_{ref} - V_{in.} \quad (1)$$

V_{ref} equal to 1 p.u. voltage
V_{in} voltage in p.u. at the load terminals.

The controller output when compared at PWM signal generator results in the desired firing sequence.

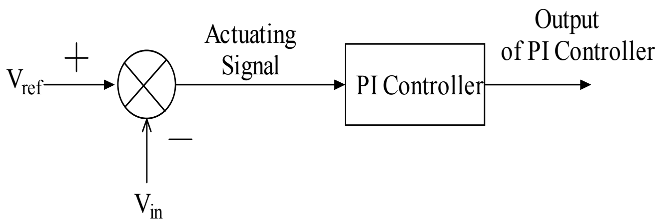

Fig.3. Schematic of a typical PI Controller.

The modulated angle is applied to the PWM generators in phase A as shown in (2). The angles for phases B and C are shifted by 120^o and 240^o, respectively as shown in (3) and (4). In this PI controller only voltage magnitude is taken as a feedback parameter in the control scheme [8].
The sinusoidal signal $V_{control}$ is phase-modulated by means of the angle δ and the modulated three-phase voltages are given by

$$V_a = \sin(\omega t + \delta) \quad (2)$$
$$V_b = \sin(\omega t + \delta + 2\pi/3) \quad (3)$$
$$V_c = \sin(\omega t + \delta + 4\pi/3) \quad (4)$$

III. PARAMETERS OF DVR TEST SYSTEM

Electrical circuit model of DVR FCB (Fuel Cell Based) test system is shown in Fig.2. System parameters are listed in Table 1. Voltage sag is created at load terminals via a three-phase fault as shown in Fig.2. Load voltage is sensed and passed through a sequence analyzer. The magnitude is compared with reference voltage (V_{ref}).

TABLE 1: SYSTEM PARAMETERS

S.No.	System Quantities	Standards
1	Inverter Specifications	IGBT based,3 arms , 6 Pulse, Carrier Frequency =1080 Hz, Sample Time= 5 μs
2	Load	R=0.1 ohms , L=0.1926 H
3	Transmission Line Parameter	R=0.001 ohms ,L=0.005 H
4	PI Controller	K_P=0.5 K_i=50 Sample time=50 μs

MATLAB Simulation diagram of the test system is shown in Fig.4. System comprises of 13 kV, 50 Hz generator, feeding transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/ 11kV.

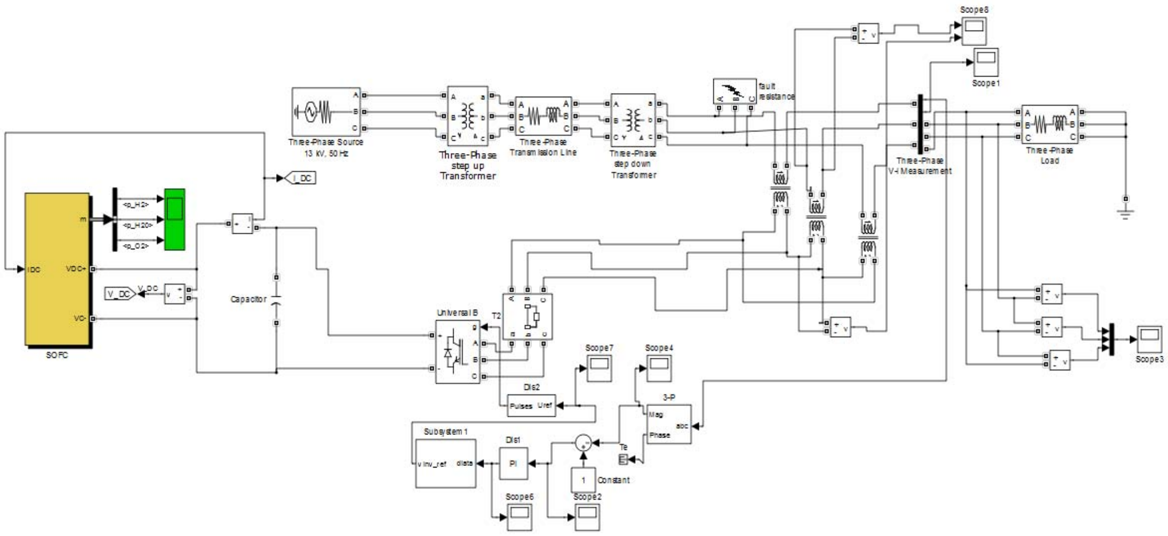

Fig.4. Simulation Model of DVR Test System [15]

IV. SIMULATION RESULTS

Detailed simulations are performed on the DVR test system using MATLAB SIMULINK. System performance is analyzed for compensating voltage sag with different fuel cell rating so as to achieve rated voltage at a given load. Various cases of different voltage levels are considered to study the impact of fuel cell rating on sag compensation. These various cases are discussed below:

Case I: A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 17.02 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig.5. The simulation results without DVR compensation technique are shown in Fig.6 on p.u basis. Fig.7 shows the DVR performance in presence of fuel cell (SOFC) with different parameter viz. shown in Table 2.

TABLE 2: FUEL CELL (SOFC) PARAMETERS

S.No.	System Quantities	Standards
1	Absolute Temperature (K)	1273
2	Initial Current(A)	100
3	Faradays Constant (C/kmol)	96.487×10^{6}
4	Universal Gas Constant (J/kmol K)	8314
5	Ideal Standard Potential (V)	1.18
6	No. of Cell in Series	3200

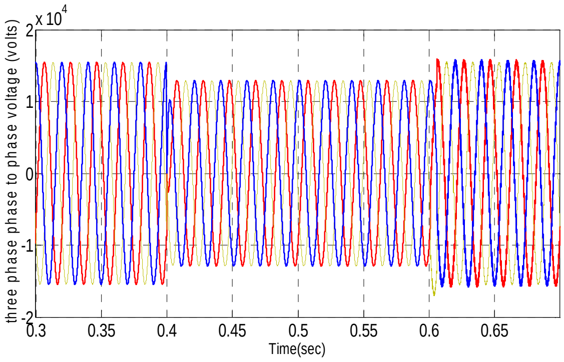

Fig.5. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

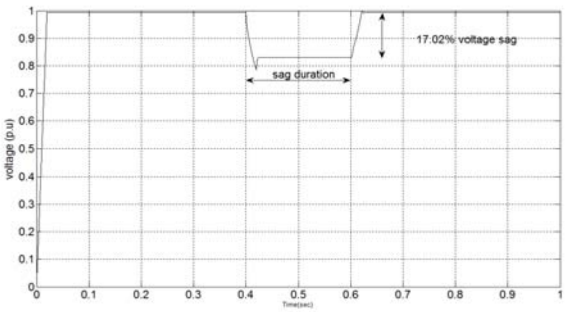

Fig.6.Voltage p.u. at the Load Point without DVR System.

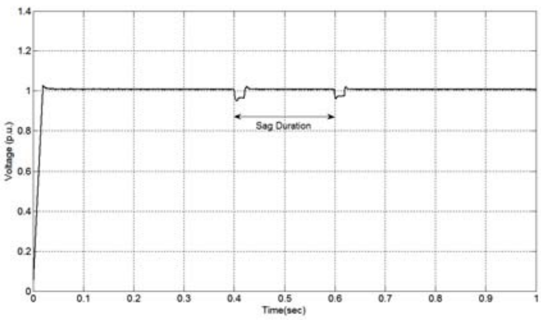

Fig.7. Voltage p.u. at the Load Point with Fuel Cell Rating as Shown Table 2.

Case II: A three-phase fault is created at point X via a resistance of 0.50 Ω which results in a voltage sag of 23%. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig.8. The simulation results without DVR compensation technique are shown in Fig.9 on p.u basis. Fig.10 shows the DVR performance in presence of fuel cell (SOFC) with different parameter viz. shown in Table 3.

TABLE 3: FUEL CELL (SOFC) PARAMETERS

S.No.	System Quantities	Standards
1	Absolute Temperature (K)	1273
2	Initial Current(A)	100
3	Faradays Constant (C/kmol)	96.487×10^{6}
4	Universal Gas Constant (J/kmol K)	8314
5	Ideal Standard Potential (V)	1.18
6	No. of Cell in Series	3500

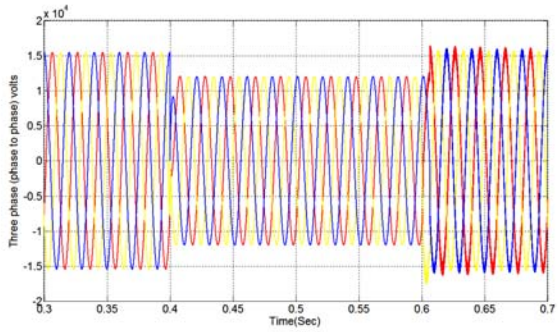

Fig.8. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

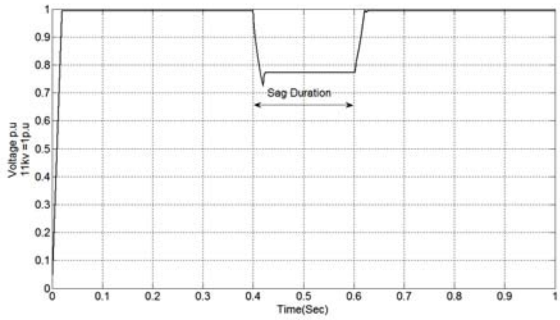

Fig.9. Voltage p.u. at the Load Point without DVR System.

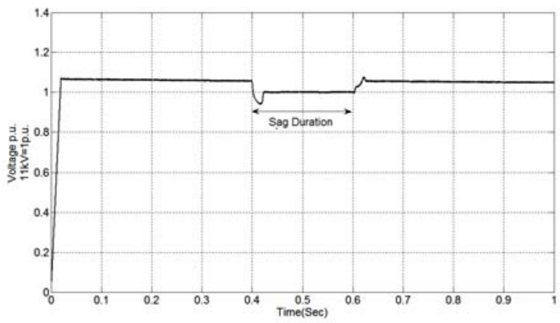

Fig.10. Voltage p.u. at the Load Point with Fuel Cell Rating as Shown Table 3.

Case III: A three-phase fault is created at point X via a resistance of 0.45 Ω which results in a voltage sag of 26 %. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig. 11. The simulation results without DVR compensation technique are shown in Fig. 12 on p.u basis. Fig.13 shows the DVR performance in presence of fuel cell (SOFC) with different parameter viz. shown in Table 3.

TABLE 4: FUEL CELL (SOFC) PARAMETERS

S.No.	System Quantities	Standards
1	Absolute Temperature (K)	1273
2	Initial Current(A)	100
3	Faradays Constant (C/kmol)	96.487×10^{6}
4	Universal Gas Constant (J/kmol K)	8314
5	Ideal Standard Potential (V)	1.18
6	No. of Cell In Series	3700

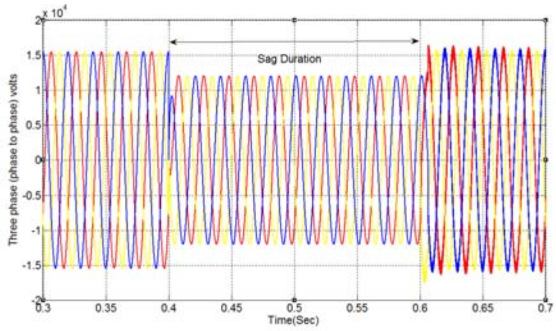

Fig.11. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

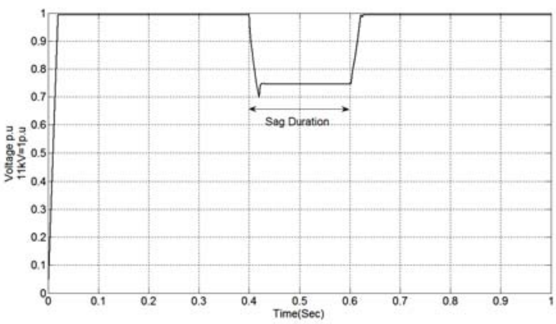

Fig.12. Voltage p.u. at the Load Point without DVR System

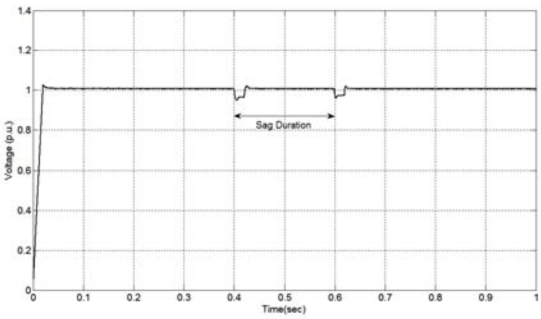

Fig.13. Voltage p.u. at the Load Point with Fuel Cell Rating as Shown Table 4.

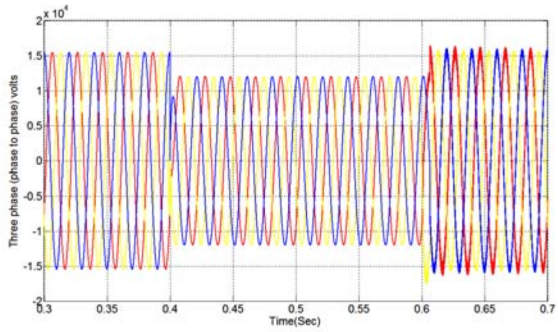

Fig.14. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

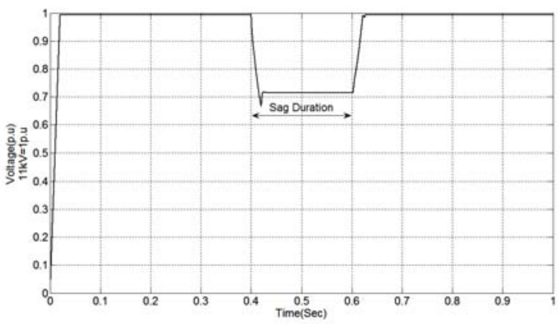

Fig.15. Voltage p.u. at the Load Point without DVR System

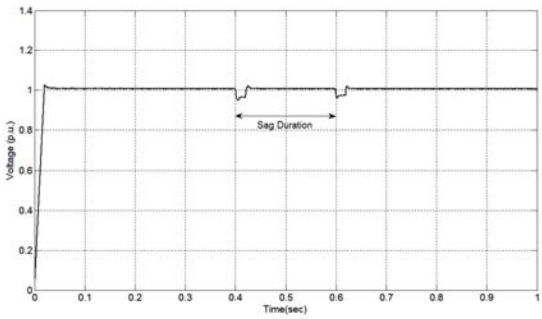

Fig.16. Voltage p.u. at the Load Point with Fuel Cell Rating as Shown Table 5.

Case IV: A three-phase fault is created at point X via a resistance of 0.40 Ω which results in a voltage sag of 29%. Transition time for the fault is considered from 0.4 sec to 0.6 sec as shown in Fig.14. The simulation results without DVR compensation technique are shown in Fig.15 on p.u basis. Fig.16 shows the DVR performance in presence of fuel cell (SOFC) with different parameter viz. shown in Table 5.

TABLE 5: FUEL CELL (SOFC) PARAMETERS

S.No.	System Quantities	Standards
1	Absolute Temperature (K)	1273
2	Initial Current(A)	100
3	Faradays Constant (C/kmol)	96.487×10^6
4	Universal Gas Constant (J/kmol K)	8314
5	Ideal Standard Potential (V)	1.18
6	No. of Cell In Series	3900

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V. CONCLUSION

A new DVR design which incorporates a silicon oxide fuel cell module as a DC voltage source to mitigation voltage sags in a distribution system has been presented. The DVR is modeled with a PI controller scheme to control the switches of the inverter. Simulation results prove that the SOFC fuel cell can be a useful alternative DC source for the DVR.

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