Modeling and Simulation of a Dynamic Voltage Restorer (DVR) for Power Quality Problems-Voltage Sags and Swells

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***Abstract*— This paper presents the systematic procedure of the modeling and simulation of a Dynamic Voltage Restorer (DVR) for power quality problems, voltage sag and swell based on Sinusoidal Pulse Width Modulation (SPWM) technique. Power quality is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure of end use equipments. The major problems dealt here is the voltage sag and swell. To solve this problem, custom power devices are used. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. The control of the Voltage Source Converter (VSC) is done with the help of SPWM. The proposed DVR is modeled and simulated using MATLAB software.**

***Index Terms*— Dynamic Voltage Restorer (DVR), Power quality problems, Sinusoidal Pulse Width Modulation (SPWM), Voltage sag and swell, Voltage Source Converter (VSC)**

I. INTRODUCTION

NOW a days, modern industrial devices are mostly based on the electronic devices such as programmable logic controllers and electronic drives. The electronic devices are very sensitive to disturbances and become less tolerant to power quality problems [1] such as voltage sags, swells and harmonics. Voltage dips are considered to be one of the most severe disturbances to the industrial equipments [2]. Voltage support at a load can be achieved by reactive power injection at the load point of common coupling. The common method for this is to install mechanically switched shunt capacitors in the primary terminals of the distribution transformer. The mechanical switching may be on a schedule, via signals from a supervisory control and data acquisition (SCADA) system, with some timing schedule, or with no switching at all. The disadvantage is that, high speed transients cannot be compensated. Some sags and swells are not corrected within the limited time frame of mechanical switching devices. Transformer taps may be used, but tap changing under load is costly.

Another power electronic solution to the voltage regulation is the use of a dynamic voltage restorer (DVR). DVRs are a class of custom power devices for providing reliable distribution power quality. They employ a series of voltage boost technology using solid state switches for compensating voltage sags and swells. The DVR applications are mainly for sensitive loads that may be drastically affected by fluctuations in the system voltage [3], [4].

II. POWER QUALITY PROBLEMS

The power disturbances occur on all electrical systems, the sensitivity of today's sophisticated electronic devices make them more susceptible to the quality of power supply. For some sensitive devices, a momentary disturbance can cause scrambled data, interrupted communications, a frozen mouse, system crashes and equipment failure etc [5]. A power voltage spike can damage valuable components. Power quality problems encompass a wide range of disturbances such as voltage sags, swells, flickers, harmonic distortion, impulse transients, and interruptions.

A. Sources of Power Quality Problems

- Large motor starting
- Different faults
- Lightning

} High currents and large drop in lines } Leads to voltage sag

- Capacitive loads
- Open circuits

} Leads to voltage swell

B. Solutions to Power Quality Problems

There are two approaches to mitigate power quality problems. The solution to the power quality can be done from customer side or from utility side; first approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under

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significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteract the power system disturbances. Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series. Some of the effective and economic measures can be identified as following [5]:

1. Lightning and surge Arresters
2. Thyristor Based Static Switches
3. Energy Storage Systems
4. Electronic tap changing transformer
5. Harmonic filter

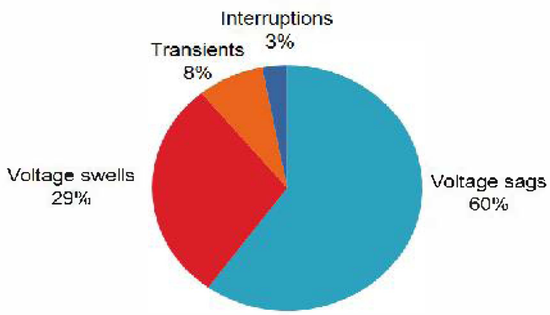


Fig. 1. Percentages of the power quality problems.

III. Dynamic Voltage Restorer (DVR)

The DVR is a powerful controller that is commonly used for voltage sags and swells mitigation at the point of connection [6], [7]. The series voltage controller is connected in series with the protected load. Usually the connection is made via a coupling transformer in series with the ac system [1]. The energy storage can be different depending on the needs of compensation [7], as illustrated in Fig. 2.

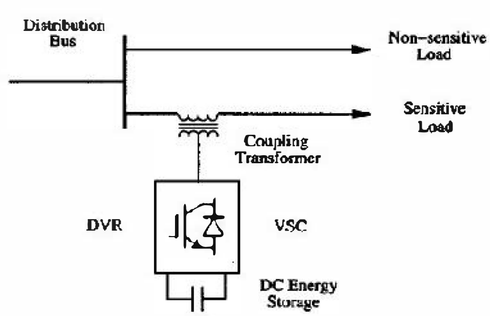


Fig. 2. Schematic representation of the DVR for a typical custom power application.

A. Equations Related to DVR

The system impedance Z_{TH} depends on the fault level of the load bus. When the system voltage (V_{TH}) drops, the DVR injects a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be maintained.

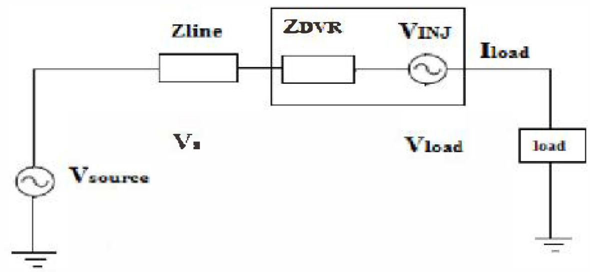


Fig. 3. Equivalent circuit diagram of the DVR.

From the Fig. 3, the series injected voltage of the DVR can be written as

$$V_{DVR} = V_L + Z_{TH} I_L - V_{TH} \quad (1)$$

Where V_L is the desired load voltage magnitude.

Z_{TH} is the load impedance.

I_L is the load current.

V_{TH} is the system voltage during fault condition.

The load current I_L is given by

$$I_L = \frac{P_L + jQ_L}{V} \quad (2)$$

When V_L is considered as a reference equation can be written as

$$V_{DVR}\angle\alpha = V_L\angle 0 + Z_{TH}\angle(\beta - \theta) - V_{TH}\angle\delta \quad (3)$$

Where α , β , δ are the angles of V_{DVR} , Z_{TH} , V_{TH} respectively and θ is the load power angle.

$$\theta = \tan^{-1}\left(\frac{\theta_L}{P_L}\right) \quad (4)$$

The complex power injection of the DVR can be written as

$$S_{DVR} = V_{DVR} I_L^{*} \quad (5)$$

B. Operating Modes of the DVR

The basic function of the DVR is to inject a dynamically controlled voltage V_{DVR} generated by a forced commutated converter in series to the bus voltage by means of a booster transformer. The momentary amplitudes of the three injected phase voltages are controlled such as to eliminate any detrimental effects of a bus fault to the load voltage V_L . This means that any differential voltages caused by transient disturbances in the ac feeder will be compensated by an equivalent voltage generated by the converter and injected on the medium voltage level through the booster transformer. The operating modes of the DVR are [8]:

1. Protection mode
2. Standby mode
3. Injection/Boost mode

C. Voltage Injection Methods of the DVR

Voltage injection or compensation methods by means of a DVR depend upon the limiting factors such as, DVR power ratings, various conditions of load, and different types of voltage sags and swells. Some loads are sensitive towards phase angle jump and some are sensitive towards change in magnitude and others are tolerant to these. Therefore the control strategies depend upon the type of load characteristics. There are four different methods of DVR voltage injection which are:

1. Pre-sag compensation method
2. In-phase compensation method
3. In-phase advanced compensation method
4. Voltage tolerance method with minimum energy injection

D. *Voltage Source Converter (VSC)*

A voltage source converter (VSC) is a power electronic device, which can generate a three-phase ac output voltage is controllable in phase and magnitude [1]. These voltages are injected into the ac distribution system in order to maintain the load voltage at the desired voltage reference. VSCs are widely used in adjustable-speed drives, but can also be used to mitigate the voltage sags and swells. The VSC is used to either completely replacing the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual voltage. The converter is normally based on the some kind of energy storage, which will supply the converter with a dc voltage [2], [9].

IV. SINUSOIDAL PWM BASED CONTROL

The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbance. The control system only measures the rms voltage at the load point i.e., no reactive power measurements are required [10]. The VSC switching strategy is based on sinusoidal PWM technique which offers simplicity and good response.

The PI controller process identifies the error signal and generates the required angle δ to drive the error to zero, i.e., the load rms voltage is brought back to the reference voltage. In the PWM generator, the sinusoidal signal $V_{control}$ is compared against a triangular signal (carrier) in order to generate the switching signals for the VSC valves [1], [2]. The main parameters of the sinusoidal PWM scheme are the amplitude modulation index M_a of signal $V_{control}$, and the frequency modulation index M_f of the triangular signal. The amplitude index M_a is kept fixed at 1 pu.

$$M_a = \frac{V_{control}}{V_{tri}} \tag{6}$$

Where $V_{control}$ is the Peak amplitude of the signal.

V_{tri} is the peak amplitude of the Triangular signal.

In order to obtain the highest fundamental voltage component at the controller output [11], the switching frequency is set at 1080 Hz. The frequency of modulation index is given by,

$$M_f = \frac{F_s}{F_f} = \frac{1080}{60} = 18 \tag{7}$$

Where M_f is the frequency of modulation index.

F_s is the switching frequency.

F_f is the fundamental frequency.

In this paper, balanced network and operating conditions are assumed. The modulation angle δ is applied to the PWM generator in phase A. The angle for phases B and C are shifted by 240^0 and 120^0, respectively [2].

V.MODELING THE DVR USING THE SIMULINK POWER SYSTEM BLOCKSET

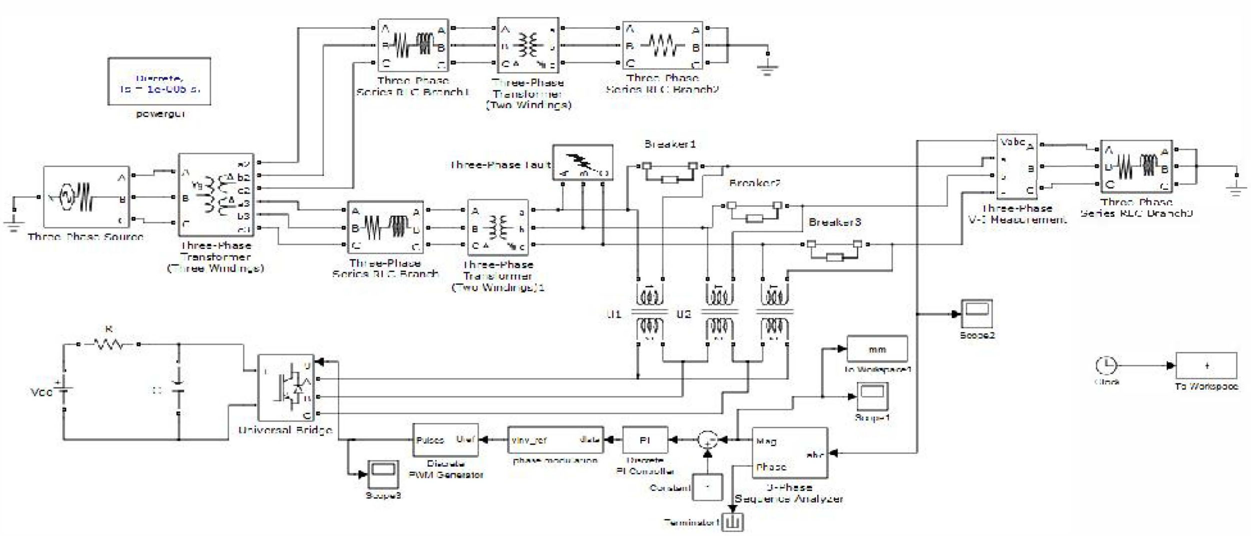
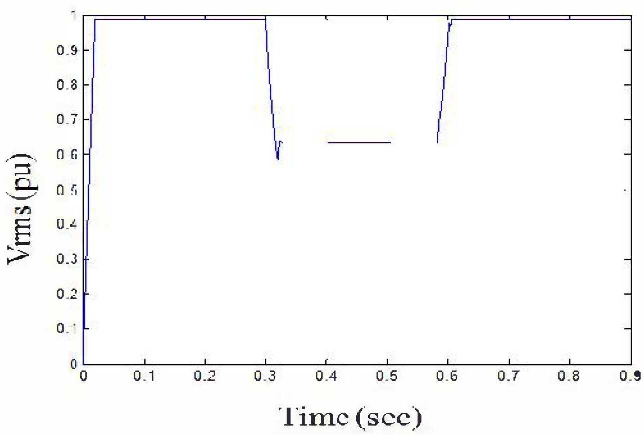


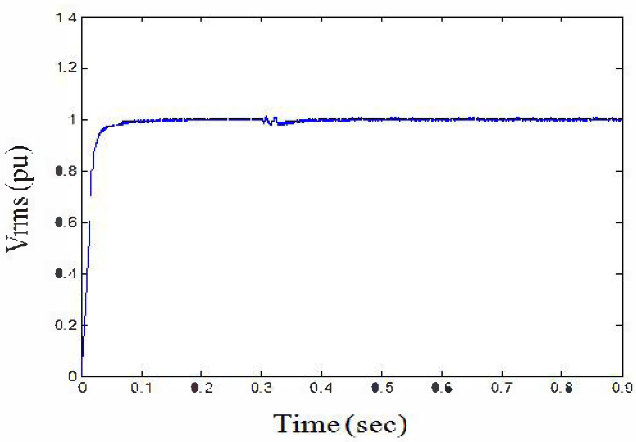
Fig. 4. Test system implemented in MATLAB/SIMULINK to carry out the various DVR simulations.

A. DVR Simulations and Results for Voltage Sags

Fig. 4 shows the test system used to carry out the various DVR simulations are presented in this section. The DVR coupling transformer is connected in delta in the DVR side, with leakage reactance of 0.01. Such system is composed by a 13 kV, 50 Hz generation system, feeding two transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/115 kV. Such transmission lines feed two distribution networks through two transformers connected in Δ/Y, 15/11 kV. The simulations are carried out as follows.



(a)

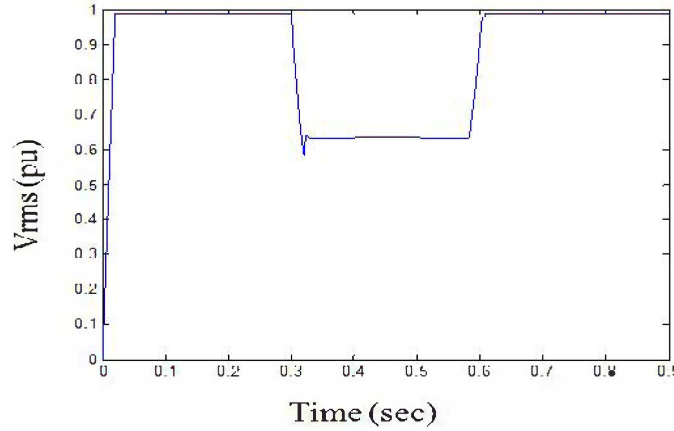


(b)

Fig. 5. Voltage V_{rms} at load point, with three-phase fault: (a) Without DVR and (b) With DVR.

1) The first simulation contains no DVR and a three-phase short-circuit fault is applied at point A, via a fault reisitance of 0.4 Ω, during the period 300-600 ms. The voltage sag at the load point is 45% with respect to the reference voltage.

2) The second simulation is carried out using the same scenario as above, but now DVR is connected to the system, then the voltage sag is mitigated almost completely, and the rms voltage at the sensitive load point is maintained at 99% as shown in Fig. 5(b).



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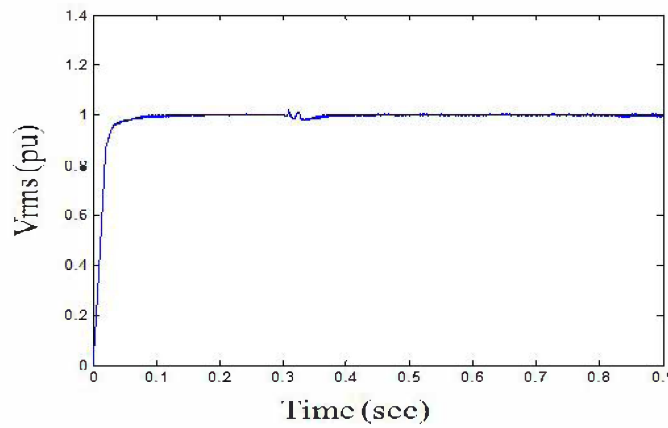
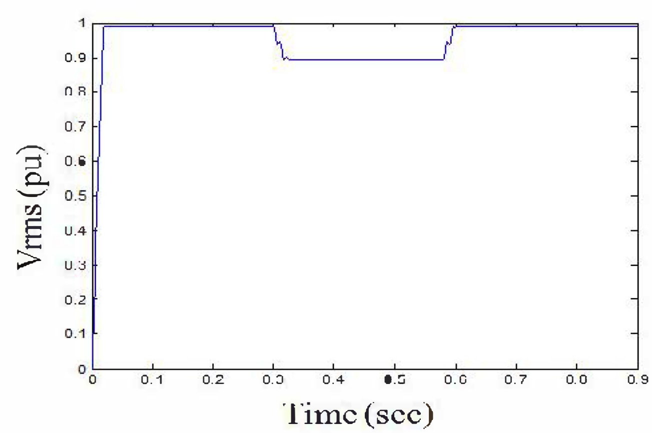


(b)

Fig. 6. Voltage V_{rms} at load point, with three phase-ground fault: (a) Without DVR and (b) With DVR.

1) The first simulation contains no DVR and a three phase-ground fault is applied at point A, via a fault reisitance of 0.4 Ω, during the period 300-600 ms. The voltage sag at the load point is 48% with respect to the reference voltage.

2) The second simulation is carried out using the same scenario as above, but now DVR is connected to the system, then the voltage sag is mitigated almost completely, and the rms voltage at the sensitive load point is maintained at 99% as shown in Fig. 6(b).



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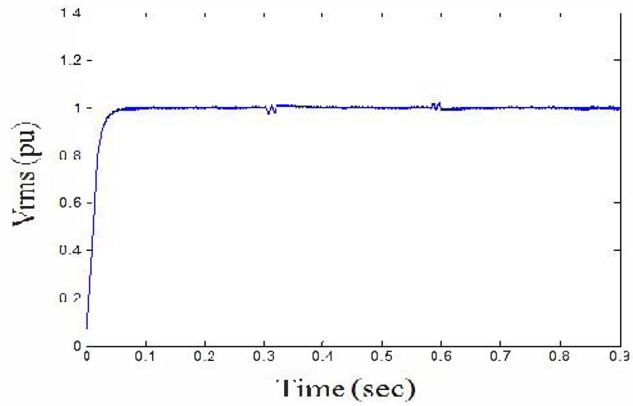
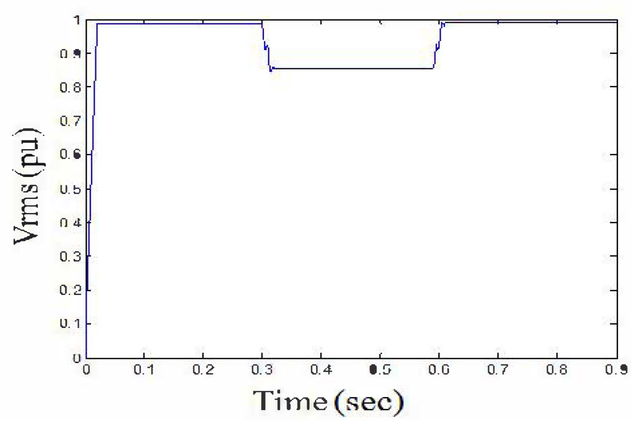


(b)

Fig. 7. Voltage V_{rms} at load point, with line-ground fault: (a) Without DVR and (b) With DVR.

1) The first simulation contains no DVR and a line-ground fault is applied at point A, via a fault reisitance of 0.6 Ω, during the period 300-600 ms. The voltage sag at the load point is 12% with respect to the reference voltage.

2) The second simulation is carried out using the same scenario as above, but now DVR is connected to the system, then the voltage sag is mitigated almost completely, and the rms voltage at the sensitive load point is maintained at 99% as shown in Fig. 7(b).



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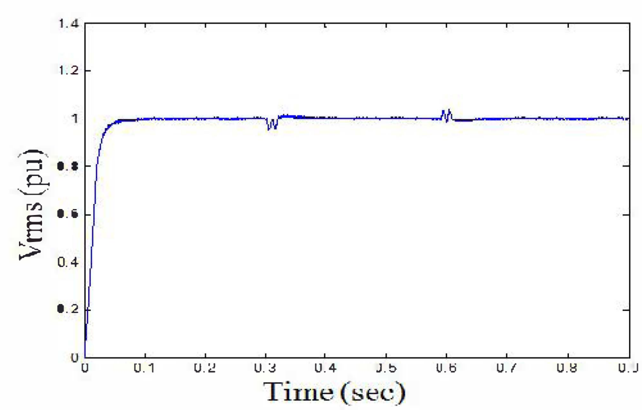
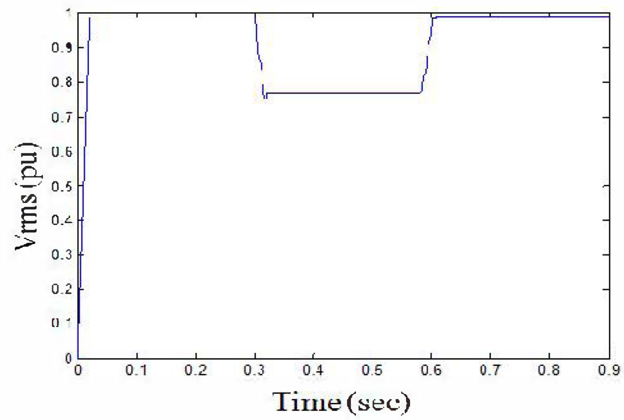


(b)

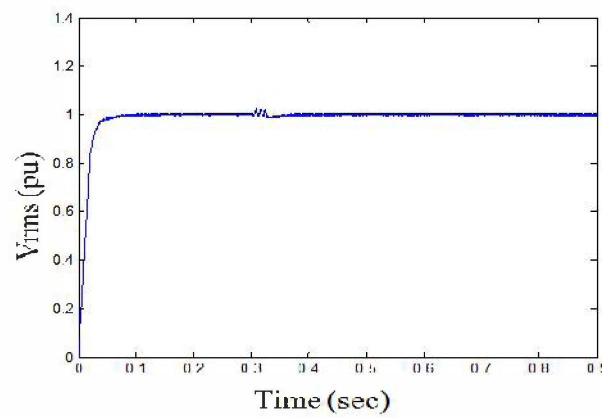
Fig. 8. Voltage V_{rms} at load point, with line-line fault: (a) Without DVR and (b) With DVR.

1) The first simulation contains no DVR and a line-line fault is applied at point A, via a fault reisitance of 0.66 Ω, during the period 300-600 ms. The voltage sag at the load point is 18% with respect to the reference voltage.

2) The second simulation is carried out using the same scenario as above, but now DVR is connected to the system, then the voltage sag is mitigated almost completely, and the rms voltage at the sensitive load point is maintained at 98% as shown in Fig. 8(b).



(a)



(b)

Fig. 9. Voltage V_{rms} at load point, with line-line-ground fault: (a) Without DVR and (b) With DVR.

1) The first simulation contains no DVR and a line-line-ground fault is applied at point A, via a fault reisitance of 0.5 Ω, during the period 300-600 ms. The voltage sag at the load point is 25% with respect to the reference voltage.

2) The second simulation is carried out using the same scenario as above, but now DVR is connected to the system, then the voltage sag is mitigated almost completely, and the rms voltage at the sensitive load point is maintained at 99% as shown in Fig. 9(b).

B. DVR Simulations and Results for Voltage Swell

Fig. 4 shows the test system used to carry out the various DVR simulations are presented in this section. The DVR coupling transformer is connected in delta in the DVR side, with leakage reactance of 0.01, and capacitor bank of 75μF is connected to the high voltage side of the network. Such system is composed by a 13 kV, 50 Hz generation system, feeding two transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/115 kV. Such transmission lines feed two distribution networks through two transformers connected in Δ/Y, 15/11 kV. The simulations are carried out as follows.

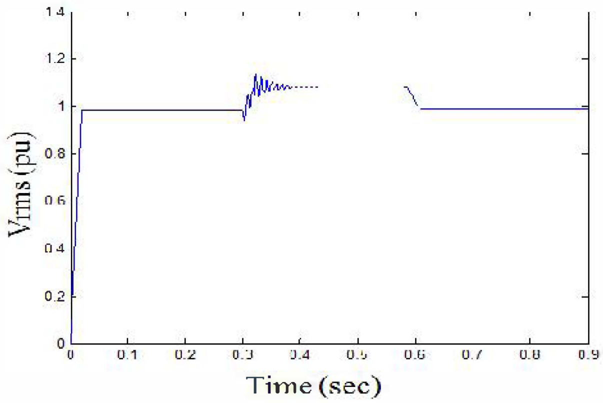


Fig. 10. Voltage V_{rms} at load point, with three-phase fault , Without DVR.

1) The first simulation contains no DVR and a three-phase fault is applied at point A, during the period 300-600ms. The voltage swell at the load point is 18% with respect to the reference voltage.

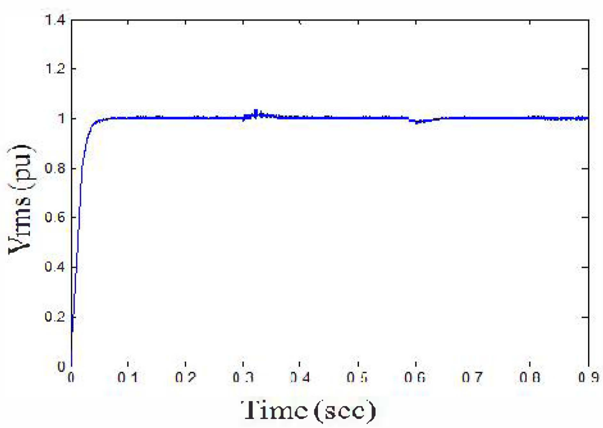


Fig. 11. Voltage V_{rms} at load point, with three-phase fault , With DVR.

2) The second simulation is carried out using the same scenario as above, but now DVR is connected to the system, then the voltage swell is mitigated almost completely, and the rms voltage at the sensitive load point is maintained at 98% as shown in Fig. 11.

VI. Conclusions

This paper has presented the power quality problems such as voltage sags, swell. Compensation techniques of custom power electronic device DVR was presented. The design and applications of DVR for voltage sags, swells and comprehensive results were presented. The Voltage Source Convert (VSC) was implemented with the help of Sinusoidal Pulse Width Modulation (SPWM). The control scheme was tested under a wide range of operating conditions, and it was observed to be very robust in every case. For modeling and simulation of a DVR by using the highly developed graphic facilities available in MATLAB/SIMULINK were used. The simulations carried out here showed that the DVR provides relatively better voltage regulation capabilities.

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