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Modeling and Simulation of Dynamic Voltage Restorer for Voltage Sag/Swell Compensation in Power Distribution Networks : A Review

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Abstract

As a consequence of sensitive, diverse and complex loads in today's distribution networks, improving power quality in distribution systems has attracted great attention. Power quality problems include voltage sags, transient interrupts and other distortions in sinusoidal waveforms. There are various methods for power quality modification. Using power electronic devices in the form of custom power devices is one of the methods by which power quality problems might be addressed. Dynamic Voltage Restorer (DVR) is one of these devices which is connected in series to distribution networks. It is able to control voltage amplitude and phase through injection of voltage to the network. It is employed to compensate for voltage sags via injecting series and synchronous three phase voltage. Consisting of three single phase inverters and a DC bus, it is able to protect sensitive loads against different types of voltage sags and other disturbances in the power supply. Moreover, it is capable of generating and absorbing active and reactive power. In this paper a DVR is modeled and simulated to investigate its application in improvement of distribution networks power quality.

Keywords: *Power Quality, Voltage Sag/Swell , Custom Power, Dynamic Voltage Restorer(DVR), Sensitive Load.*

1. Introduction

Distribution section is the main connection between power industry and consumers; so, it is constantly evaluated and judged by people. Thus, it is necessary to examine power quality on distribution section. On the other hand distribution networks are exposed to traditional disturbances for sinusoid waveforms including dynamic voltage sag and swell, harmonics and capacitive switching which damage power quality and network reliability. These disturbances are imposed by some consumers and they affect other consumers and network equipment. Besides, due to some accidents network may impose disturbances on sensitive consumers. Therefore, distribution companies are responsible for providing reliable and high quality power for their consumers. This duty necessitates use of power quality controller devices in the networks. This task might be performed using power electronic devices called custom power devices which are

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capable of improving disturbances. Dynamic Voltage Restorer is an example of such devices which is modeled and simulated in this paper. Also, its influence on disturbances in distribution networks is investigated. After mentioning the necessity of using DVRs , its structure, operation principles and control method are explicated. There are several control strategies for DVRs such as "sinusoid current control", line current based on instantaneous power theory and synchronous reference frame. Among these methods instantaneous power theory with new modifications was selected as it properly compensates for all harmonic components, negative and zero sequences of line current and other disturbances of load current. To illustrate performance of DVR a sample network consisting of unbalanced linear and nonlinear loads (e.g. induction motor and electric arc furnace) is simulated in presence of DVR and various types of disturbances are tested. Simulation results revealed that DVR is a powerful compensator for three phase current unbalance, reactive power compensation, voltage sag and voltage oscillations [1,2,3,5].

2. DEFINITION OF POWER QUALITY

Since late 1980s, power quality has become an important issue for electricity companies and consumers of low and medium voltage electricity. To appropriately meet consumers' requirements, electricity companies have tried to improve power quality. There are different definitions for power quality. For instance, electricity companies define power quality as reliability and they can statistically demonstrate how reliable a network is. In contrast, electrical equipment manufacturers define power quality as guaranteeing performance of devices based on power supply characteristics [2,3]. This definition may be interpreted differently by various electrical equipment and manufacturers. Yet, power quality is an issue associated with consumers and their opinion plays significant role in dealing with this issue. Hence, the definition used in this paper is as follows: "every problem and deficiency which may change voltage, current and/or frequency and damage equipment or avoid its correct operation". [3,4,5,6]

3. VOLTAGE SAG AND SWELL

Voltage sag is defined as a voltage drop between 10-90% of voltage rms value which may last from half-cycle to one minute. Voltage sag may affect either phase or amplitude. It mostly occurs when single line to ground fault (SLGF) happens (figure 1) because balanced fault rarely occurs. Unbalanced fault leads to unbalanced phase and shifts it from its nominal values. Furthermore, starting up high power motors may cause voltage sags (figure 2). The amplitude of voltage sag depends on several factors including fault type, fault location and fault impedance. Voltage sag in different Busbars differs with respect to their location. The duration of voltage sag is determined by the time span in which protection relays remove the fault i.e. the voltage sag continues as far as fault is eliminated and voltage swell, on the other hand is defined as a short duration increasing in rms supply with increase in voltage ranging from 1.1 p.u. to 1.8 p.u of nominal supply(figure 3) [9]. Though the voltage sag/swell lasts for a short time, it adversely affects sensitive loads such as computers, Programmable Logic Controllers (PLC) and adjustable Speed Drivers (ASD) while reducing their efficiency [3]. There are various solutions to this problem, such as designing inverter drives for process equipment to be more tolerant to voltage fluctuations or the installation of voltage correction devices. Dynamic voltage restorer (DVR) is a custom power device for mitigating voltage sags/swells. The applications of DVR are mainly for protecting sensitive loads that may be drastically affected by fluctuation in distribution system voltage[9].

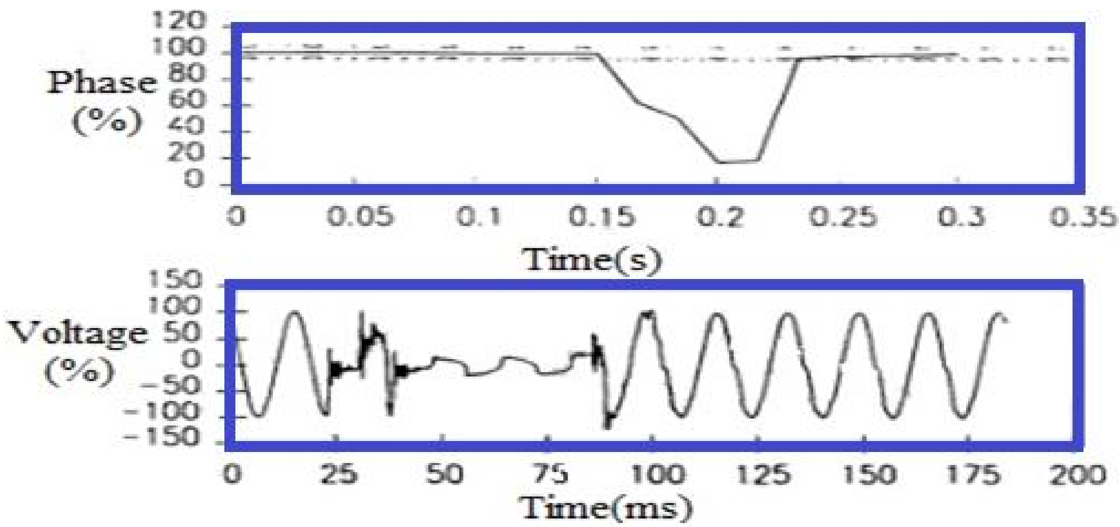

Figure 1: Instantaneous voltage sag resulted from single line to ground short circuit (SLG)

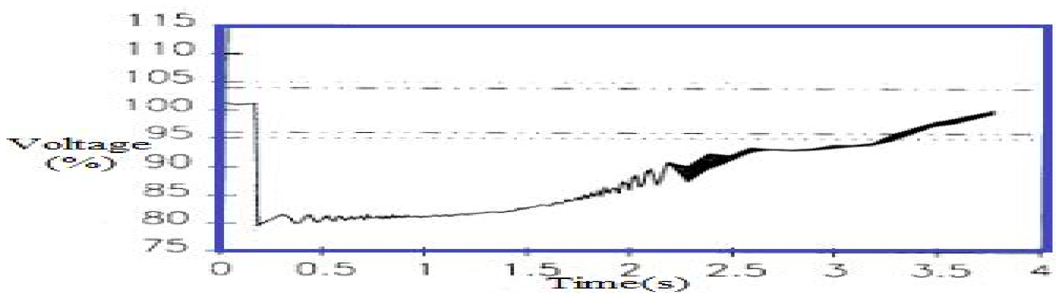

Figure 2: Temporary voltage sag resulted from motor starting

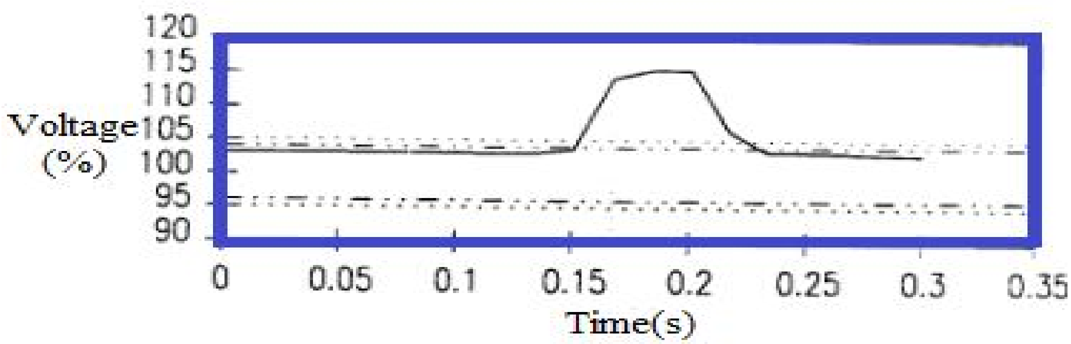

Figure 3: Instantaneous voltage swell resulted from single line to ground short circuit (SLG)

4. OPERATION PRINCIPLES OF DVR SYSTEM

The main principle of DVR operation is detection of voltage sag and injecting lost voltage to the network. To determine voltage sag quantity in radial distribution systems the divider model might be utilized. It is depicted in figure 4. In this method it is assumed that the fault current is much larger than the current of loads along the fault location. Point of Common Coupling (PCC) is the point by which both fault and load are supplied. Voltage sag is basically unbalanced and has phase angle jump. [11,12,16].

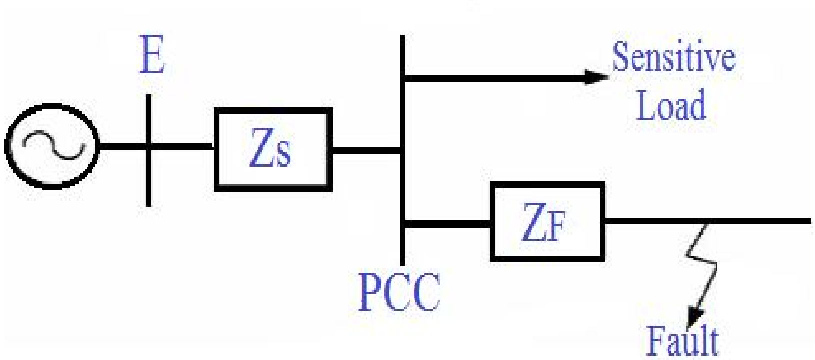

Figure 4 : Voltage divider model for voltage sag

According to figure 4, voltage in PCC and phase angle are calculated using the following equations:

$$Vsag = \frac{Zf}{Zs + Zf} E = \frac{Zf}{Zs + Zf} \qquad (1)$$

$$\Delta\Phi = \arg(Vsag) = \arctan(\frac{Xf}{Rf}) - \arctan(\frac{Xs + Xf}{Rs + Rf}) \qquad (2)$$

Where, Zs=Rs+jX is source impedance in PCC; Zf=Rf+JXf is the impedance between PCC and fault location; and E is source voltage which is 1pu. The power circuit of a DVR is illustrated in figure 6. It is composed of four parts: inverter (VSI), injection transformer, passive filter and energy storage and also figure 5 *shows: placement* of DVR's in distribution networks.

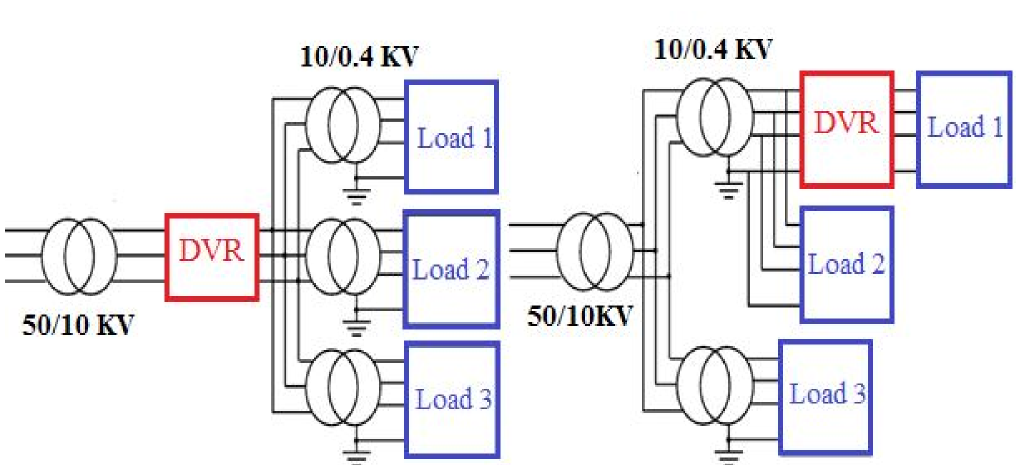

Figure5: *placement* of DVR's in *distribution networks*

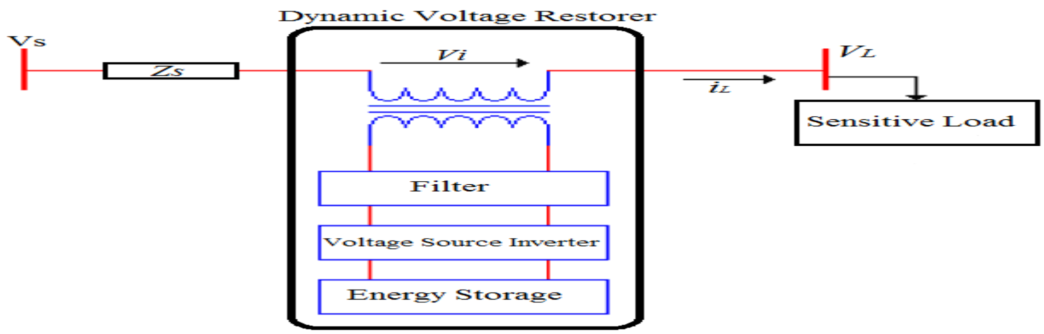

Figure6: Actual schemes of a DVR

To correct larger faults DVR may need to increase active power. For this purpose an energy storage system should be utilized. Recently, capacitive banks have been used in DVR system design. When the fault is corrected and system goes back to normal condition, DVR receives the consumed energy from the network and stores it. Capacitive banks classification considering energy storage capabilities depends on system factors such as load and predicted voltage sag. The DVR is connected in series to distribution lines using an injection transformer. In fact, three phase transformer in primary side must be designed such that it could tolerate all line current. Initial voltage amount is the maximum voltage which might be injected to circuit by DVR. Output voltage waveforms are generated by Pulse Width Modulation switching. When voltage sag reaches to its lowest voltage level, energy storage system embedded in DVR is exploited to modify the voltage. Ideal restore means that load voltage does not change at all. As a matter of fact, when DVR compensates for large voltage disturbances, active power must be transferred from DVR to distribution system. If DVR energy storage capacity is infinite, it would be able to maintain line voltage unchanged during all types of faults. However, in practice, the energy stored n DVR is limited by restricting DC link capacity. For example DVR is not able to maintain load voltage unchanged when DC link voltage decreases and the stored energy is lost in severe voltage sags. Therefore, decrease of injected energy is necessary for DVR. There are a few methods for injecting DVR reduced voltage to distribution system which are discussed in the following. [10,11,12,18].

5. VOLTAGE SAG COMPENSATION METHODS

The most common methods used up till now in order to compensate the voltage are as follows: Using Underground cables instead of aerial cables, Increasing the insulation surface of the equipment , Feeding the sensitive loads from two or more points , Installing error current limiter reactors , Isolating sensitive loads using separate lines , reducing shortage durations using rapid protection equipment , Installing voltage sag compensators. The first sex options require network management, use of human resources, and constant repair and maintenance costs, and on the other hand they exclusively apply to the voltage shortage matter, and they could not be developed. In opposition, by the rise of the topic “power quality” by *Hingorani* since 1998, the use of advanced compensators in the distribution networks known as “custom power devices” , with the goal of improving power quality and related to the consumer’s needs, has been suggested. The compensation capability of DVR might be limited by factors including DVR power, various load types and different types of voltage sags. Some loads are very sensitive to phase jump. Thus, control strategy depends on load characteristics. DVR injects voltage in three different methods according to type and sensitivity of the load to amplitude and phase variations. [10,14,20].

5.1. In the in-phase compensation method(IPC)

In IPC method the injected voltage is in-phase with voltage sag. So, during compensation, load voltage would be in-phase with source voltage. If supply voltage experiences a phase jump during voltage sag, load voltage experiences the same jump. As can be seen in Phasor diagram shown by figure 7 in this condition only voltage magnitude remains unchanged.

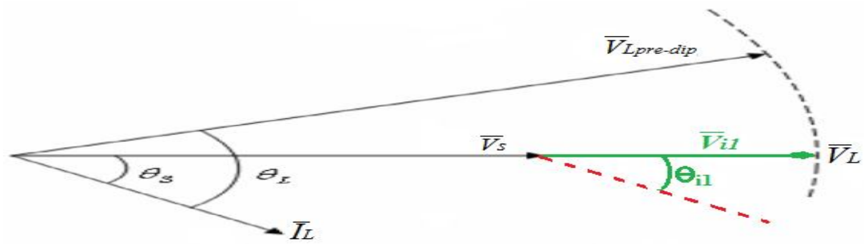

Figure7: Phasors diagram of the IPC method

Injected apparent and active power as well as phase and magnitude of injected voltage might be calculated using the following equations:

$$Si1 = ILVi = IL(VL - VS) \quad (3)$$

$$Pi1 = ILVi\cos\theta s = IL(VL - Vs)\cos\theta s \quad (4)$$

$$Vi1 = VL - Vs \qquad \theta i1 = \theta s$$

5.2. Pre-Dip compensation method (DPC)

Some loads are also sensitive to phase jump. So, in addition to voltage magnitude, voltage phase must become in-phase with the voltage before voltage sag. As a result, DVR has to inject a voltage which is equal to difference between load voltage before SAG (which is the same as voltage after sag) and network voltage during sag. It is realized using PDC methods as demonstrated in figure 8.

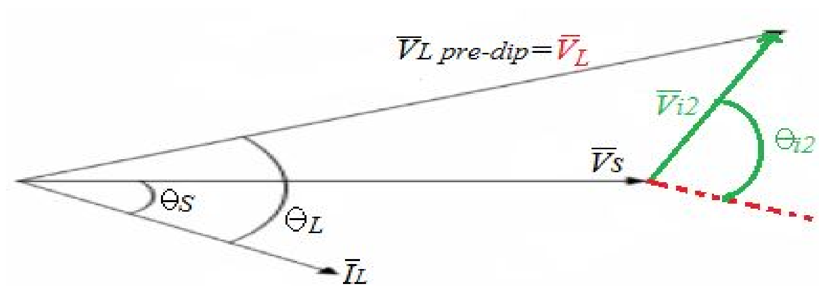

Figure 8: phasors diagram of the PDC method

This method is superior from power quality perspective as it maintains both amplitude and phase of load voltage. Injected apparent and active power as well as amplitude and phase of injected voltage might be achieved from the following equations:

$$Si2 = ILVi = IL\sqrt{VL^2 + Vs^2 - 2VLVs\cos(\theta L - \theta s)} \quad (5)$$

$$Pi2 = IL(VL\cos\theta L - Vs\cos\theta s) \quad (6)$$

$$Vi2 = \sqrt{VL^2 + Vs^2 - 2VLVs\cos(\theta L - \theta s)} \quad (7)$$

$$\theta i2 = \tan^{-1}\left(\frac{VL\sin\theta L - Vs\sin\theta s}{VL\cos\theta l - Vs\cos\theta s}\right) \quad (8)$$

5.3. Phase advanced compensation method (PAC)

To decrease injected energy in this method, the injected voltage should be lead in comparison with source voltage. Considering equation for Pi2, it can be concluded that inject power is zero when $\theta_s = 0$ i.e. VL and IL are in-phase. This scheme aims at minimizing DVR injected power during compensation. As can be seen in figure 9, the load voltage phasor moves around a circle with VL radius.

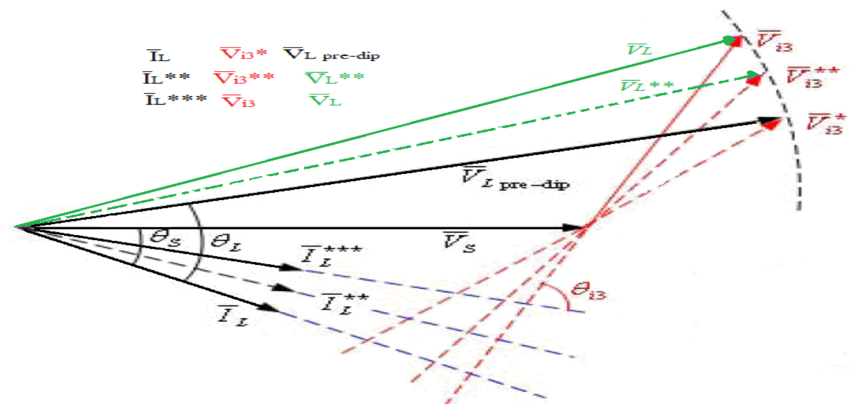

Figure9: phasors diagram of PAC method

It must be noticed that this method is not suitable for loads sensitive to phase shift. Another limitation associated with this method is large amplitude of injected voltage. In this condition injected apparent and active powers might be derived. Besides, injected voltage phase and magnitude could be obtained using the following equations.

$$Si3 = ILVi = IL\sqrt{VL^2 + Vs^2 - 2VLVs\cos\theta L} \quad (9)$$

$$Pi3 = IL(VL\cos\theta L - Vs) \quad (10)$$

$$\theta s = \cos^{-1}\left(\frac{VL\cos\theta Ls}{Vs}\right) \quad (11)$$

$$Vi3 = \sqrt{VL^2 + Vs^2 - 2VLVs\cos(\theta L - \theta s)} \quad (12)$$

$$\theta i3 = \tan^{-1}\left(\frac{VL\sin\theta L - Vs\sin\theta s}{VL\cos\theta l - Vs\cos\theta s}\right) \quad (13)$$

The above equations demonstrate that if VL.Cosθ >VS DVR should make VS and IL in phase via injecting voltage; however, if VL.Cosθ <VS Pi3 is negative and active power might be set to zero without adjusting θ_s to zero. In other words, voltage sag is compensated by reactive power. In this condition injected voltage is perpendicular to load current. Its value for zero power flow is derived using Pi3 equation [7,9].

6. Different types of DVR

Based on energy supply, DVRs are divided into two groups: 1) DVR with energy storage system, 2) DVR without energy storage system. (Figure 10) In the former, energy is supplied by capacitive bank or batteries; whereas, in the latter energy is provided using the network which might be connected to load or supply. [22,23].

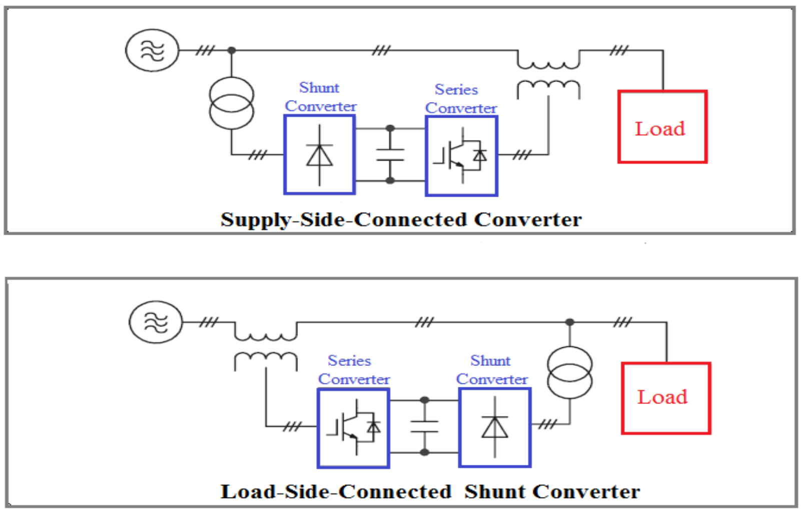

Figure10: Topologies for DVRs without energy storage

7. STRATEGY OF CONTROL

Control system design is extremely important in DVR structure because this section determines response time and how voltage sag is compensated. Control circuits are utilized for inferring control signal parameters such as amplitude, frequency, phase shift and so on which are injected by DVR. The injected voltage is generated by existing inverters with respect to control signals. For DVR either closed loop or open loop control schemes might be used. Closed loop approach has better performance while is more complex and expensive. Here, open loop scheme is explicated. Similar to SPLL three phase voltage of the source is transformed to two phase; then, values are obtained in synchronous reference frame (V_q, V_d) where values are DC and constant. During voltage sag these values decrease and the difference between their values before sag and during voltage sag will generate an error signal ($V_{q\ error}$,$V_{d\ error}$). Using inverse of the mentioned transforms and the same angle estimated by SPLL, the required pulses for switching of inverter are achieved. Indeed, information about voltage supply phase and amplitude are necessary for DVR. SPLL is employed to measure phase of voltage supply. When a single phase to ground short circuit fault occurs positive, negative and zero sequences are generated in voltage which, in turn, leads to errors in phase measurement. The Control strategy of DVR is illustrated in figure 11.

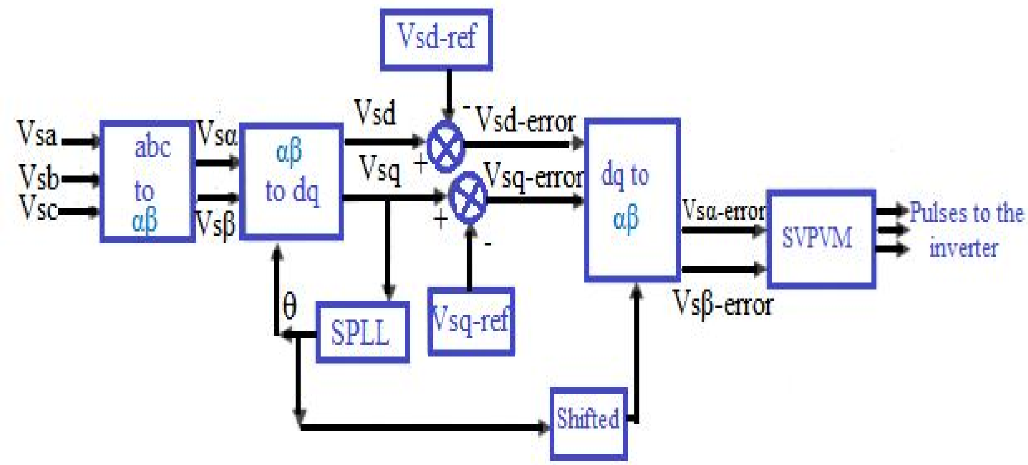

Figure11: Block diagram of control system

It is noteworthy that shift block is used to eliminate the shifting effect of injection transformer. Simulation results illustrated that DVR is able to appropriately compensate for three phase and single phase short circuit faults.

7.1. A three phase DVR and its control

A sample three phase DVR is discussed in this section. It is capable of protecting balanced load voltage constant amplitude against fluctuations, harmonics, voltage sag unbalanced condition and so on. A three phase inverter consists of three single phase inverters which are connected to primary side of a transformer using star connection. Secondary side is connected in series to lines. The nominal value of three phase transformer is 10kVA with 1:5 conversion ratio. It means that the inverter is able to inject 20% of nominal voltage. Inverter employs sinusoid PWM (single pole switching) with switching frequency of 20 kHz. Inverters transform stored DC voltage of energy storage system to a suitable injection voltage. The generated voltage is filtered and subsequently injected in series by injection transformer. The block diagram of control strategy for a DVR is shown in figure 12.

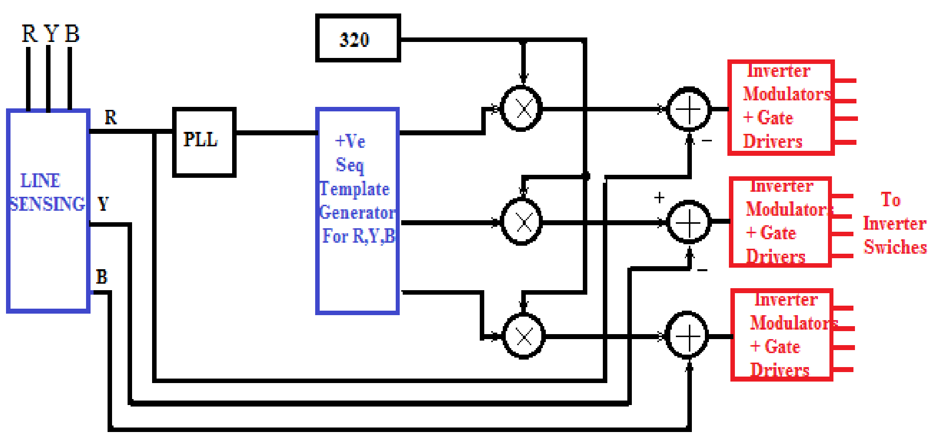

Figure12: Block diagram of Control strategy for a DVR

Load voltage decreases step by step using PTs and a PLL locked in R phase. Pure sinusoid wave phase synchronized with R is fed to a positive sequence generator (based on all pass filter). It generates positive sequence waves with unity amplitude. These patterns are magnified using a desired amplitude (320V for load voltage). Actual load voltage obtained by sensor circuits is reduced by these patterns so that the reference signals for inverter modulators could be generated. DC section is considered as a power source link or a converter. The SIMULINK simulation diagram for the system is depicted in the following.(Figure 13)

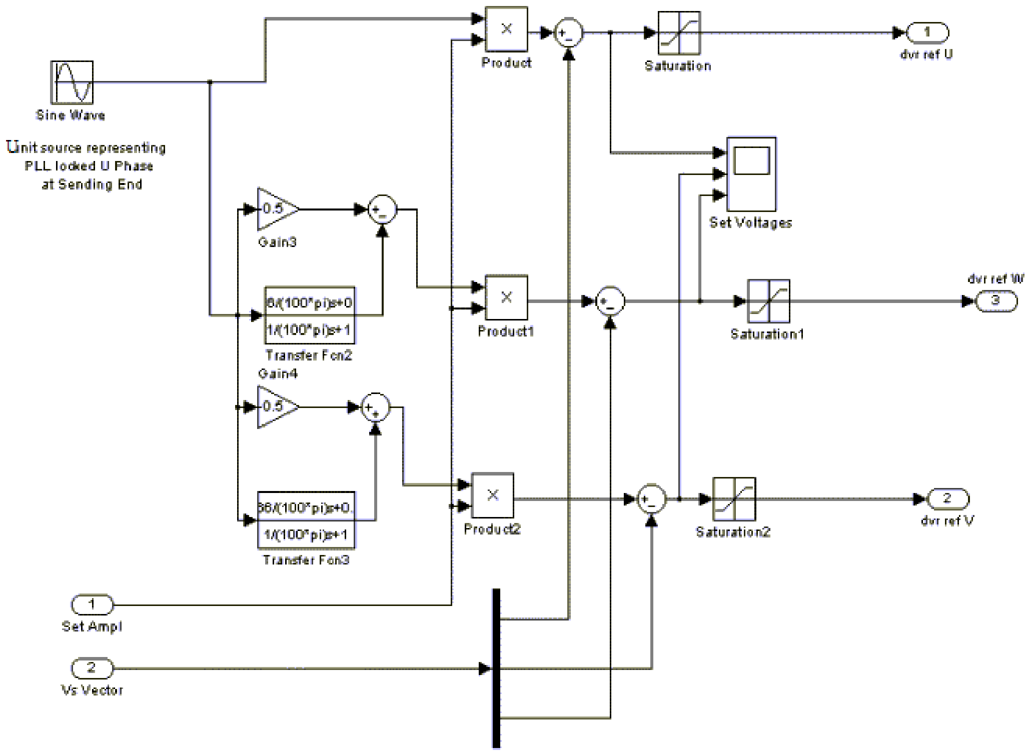

Figure13: Reference block of Inverter

The saturation block in this subsystem is set at ± 65 Volts to reflect the overmodulation limit of inverter. The first one models the inverter as an ideal voltage controlled voltage source and can be used only to illustrate the concepts involved. The second one models the inverter as an ideal voltage controlled voltage source but includes the filter at the output of the inverter.The third one includes the PWM switching also , but does not take care of the inverter losses. The first model will give very optimistic results under dynamic conditions – for example it will show that the output voltage is not even aware of a sudden phase change at input. This will not be true in practice. The various unmodelled delays along with the inverter filter response time will really pass the sudden changes in the input voltages at least partially to the output side. The first model will yield a performance, which simply does not depend on the load current, since this model has no impedance anywhere. But in practice the output voltage will get affected by load harmonics due to two reasons – the inverter output filter will call for harmonic drops when harmonic load currents flow through it and in the absence of feedback control the system does not correct anything to the right of inverter. Secondly the finite bandwidth of inverter (due to a finite switching frequency) will make it fail in generating high frequency content produced at the source bus by high frequency component of load currents flowing in source impedance (which is taken as zero in the first simulink model). When the amount of sag, swell or flicker or harmonic content is excessive the inverter will saturate and clip its output. This will lead to distortion in output voltage. But simulation runs reveal that this distortion remains under 10% even for sags which take source voltage to 100V peak. All three models include this clipping effect. The control of DVR is not a very complex problem and in fact field experience justifies feedforward control. However providing a suitable DC Side energy source to handle long periods of sag or swell or flicker throughout the day (like arc furnace) will be a problem. If it is a Battery it requires a charger. Some researchers have proposed drawing charging power from the line using the same inverter during periods which sag or swell is little and can be handled by 90-degree voltage injection. But that makes the control pretty complex. If it is a AC-DC Diode Rectifier the DVR can handle only sags and not swells since during swells the inverter will absorb power (in the 'inphase injection strategy' considered here) and dump it on the DC Side.So, then it has to be a Bilaterlal Converter based AC-DC Converter and then we get very close to what they call a 'Unified Power Quality Conditioner' – then it is no more a DVR alone, but can easily become a UPQC. Figure 14 demonstrates simple schematic of a DVR in distribution network. The most popular application for DVR is compensating voltage sags and voltage swells in distribution systems. [30,31,32].

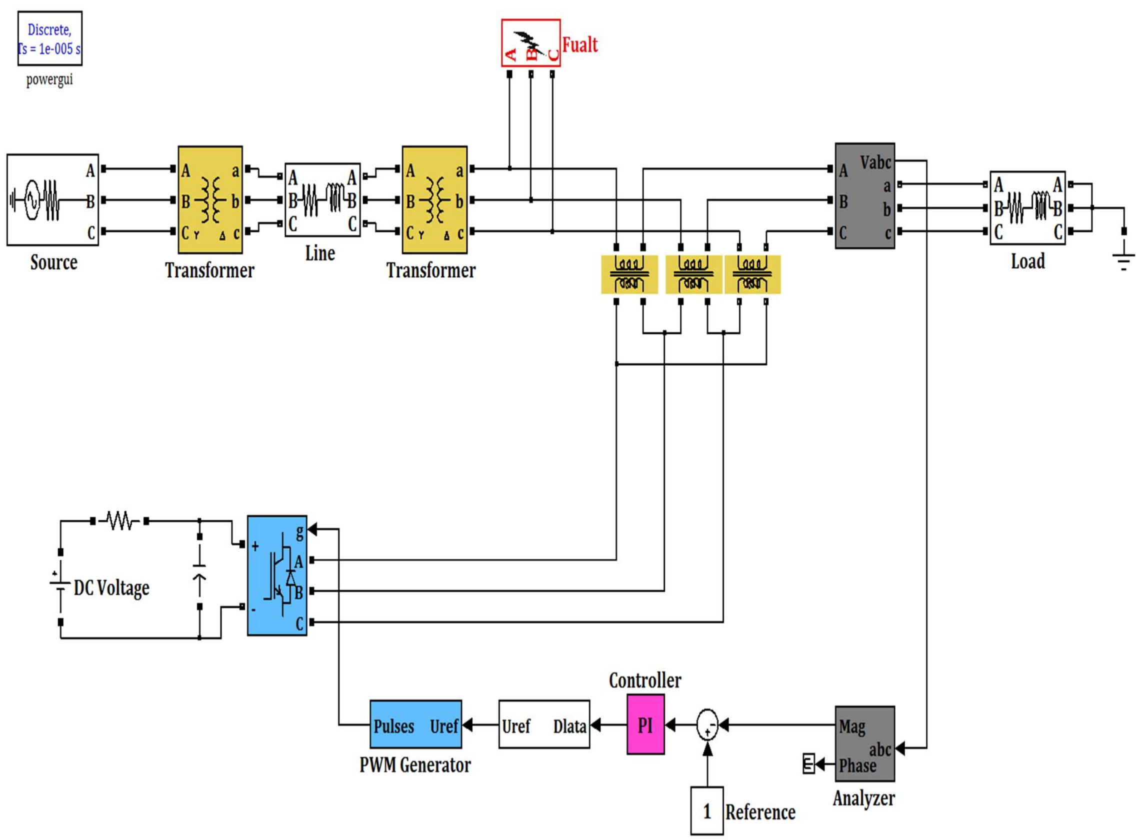

Figure14: Schematics of a simulated DVR and its performance

MATLAB Simulation diagram of the test system is shown in figure.15 in the Appendix and block diagram of asynchronous motor in distribution network is shown in figure.25 in the Appendix.

8 . SIMULATION RESULTS

In this section, a DVR's performance in a sample distribution network is investigated**.** Fig.16 ,and Fig.17 shows the voltage of one of the phases' load with and without DVR. It is illustrated that DVR is successful in compensation leading to power quality improvement in the distribution network.

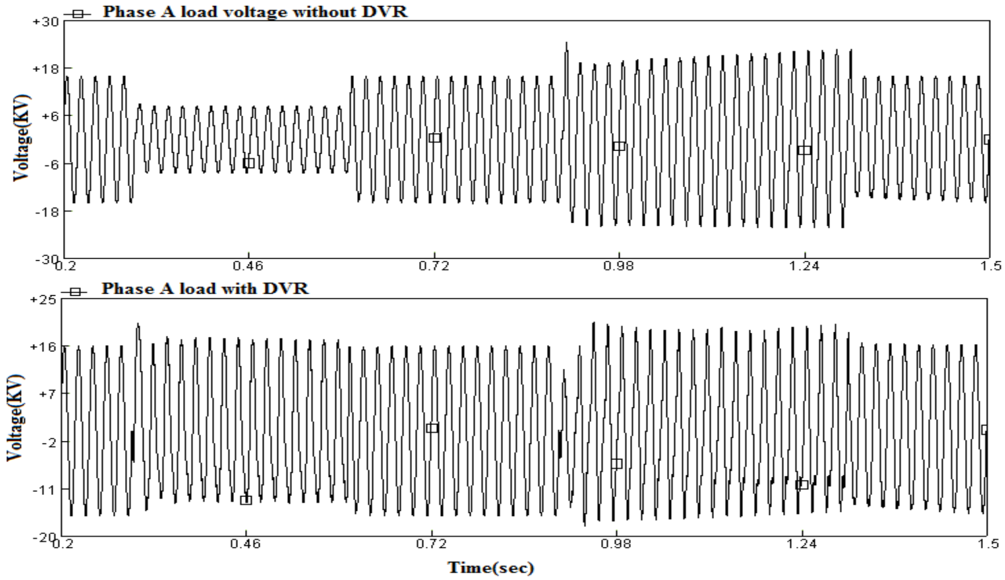

Figure16: Voltage of one of the phases' load (A) with and without DVR

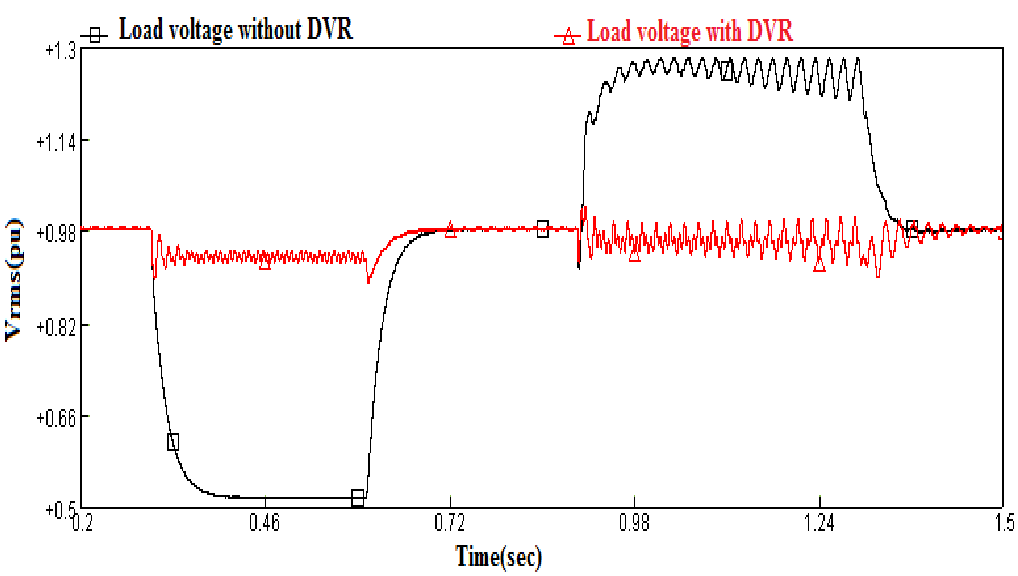

Figure 17: Voltage (pu) of one of the phases' load (A) with and without DVR

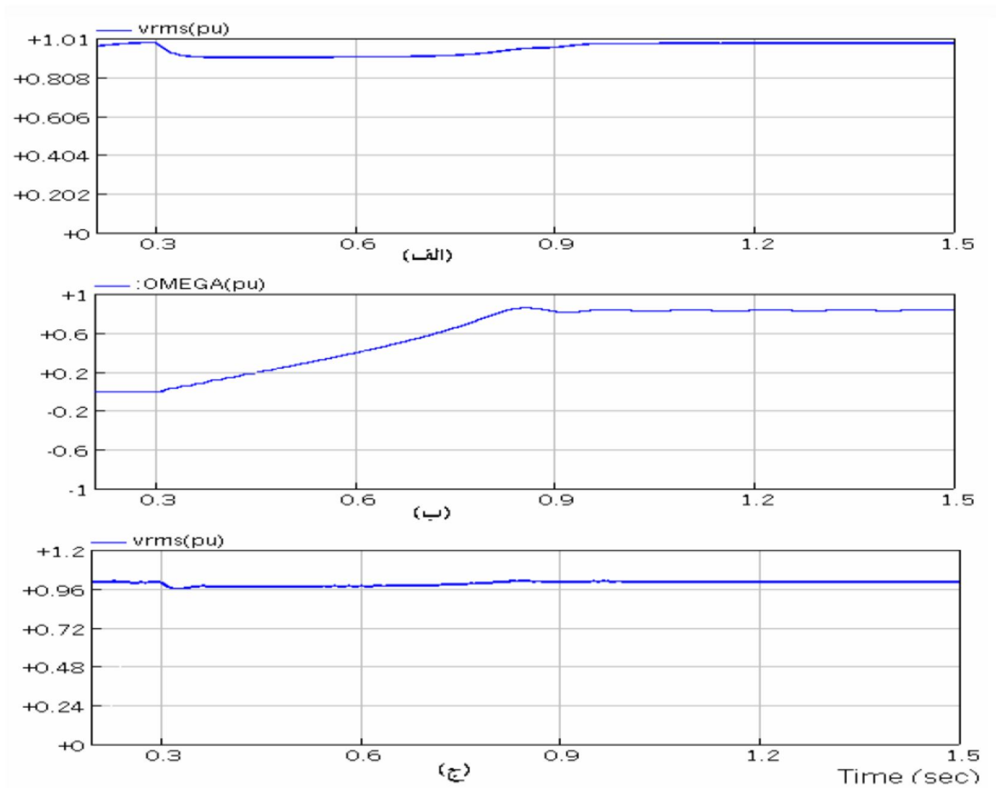

Figure18: Compensating for voltage sag resulted from motor start up,
a) bus voltage without DVR, b) motor speed during start up, c) bus voltage with DVR

Transition time for the fault is considered from 0.4sec to 0.6 sec as shown in Fig.19 [62,63].

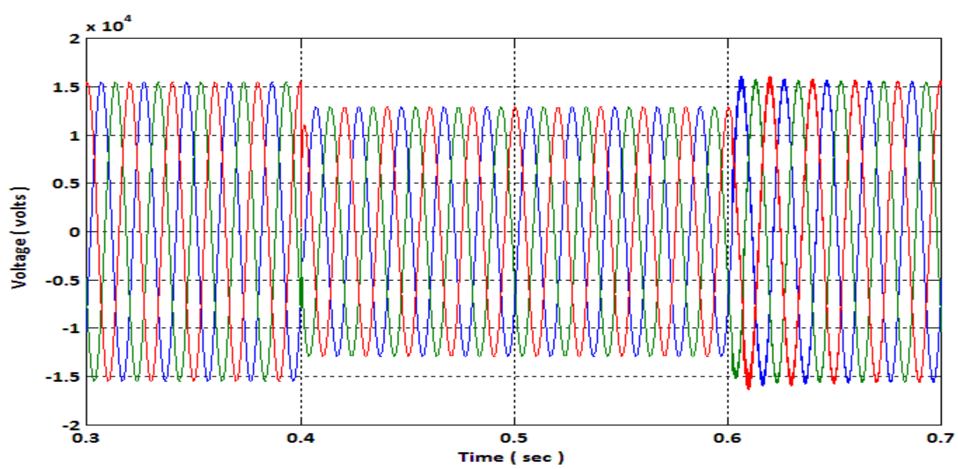

Figure19: Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

The simulation results without DVR compensation system are shown in Fig.20 on per- unit (pu) basis

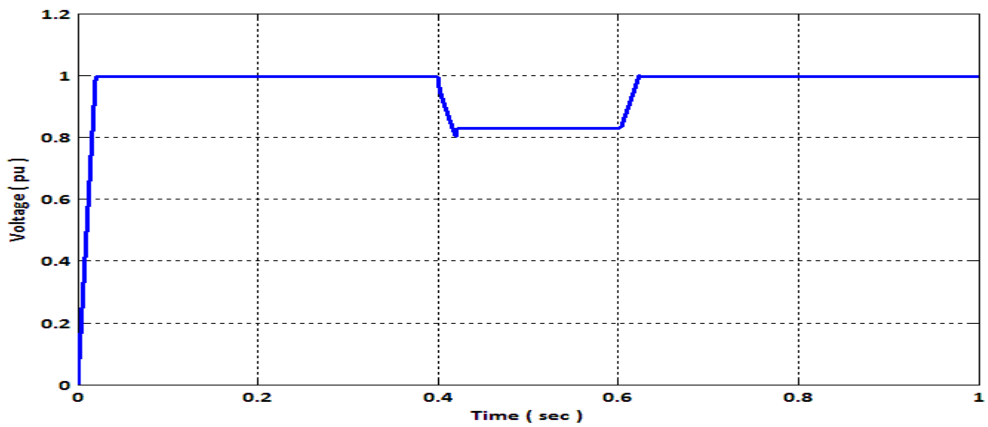

Figure20: Voltage *per- unit* (pu). at the Load Point: without DVR system

Fig. 21 shows the DVR performance in presence of capacitor rating of 750×10-6 F with energy storage devices viz. 3.1kV**.**

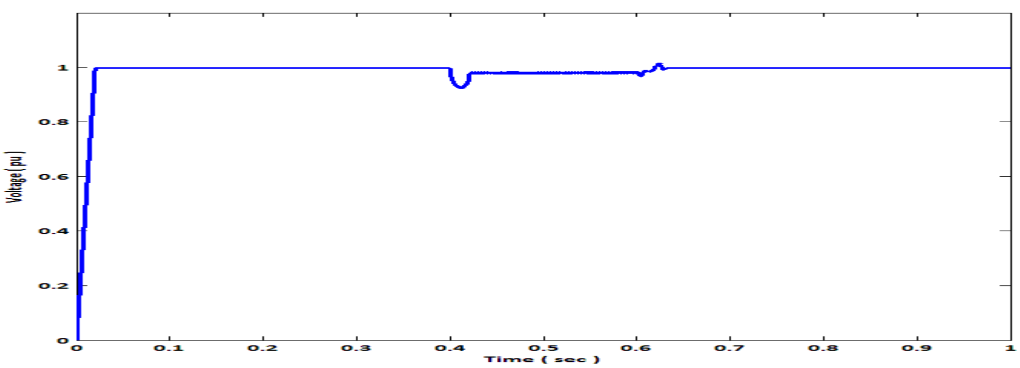

Figure21: Voltage Voltage *per- unit* (pu). at the Load Point with DC storage of 3.1 kV

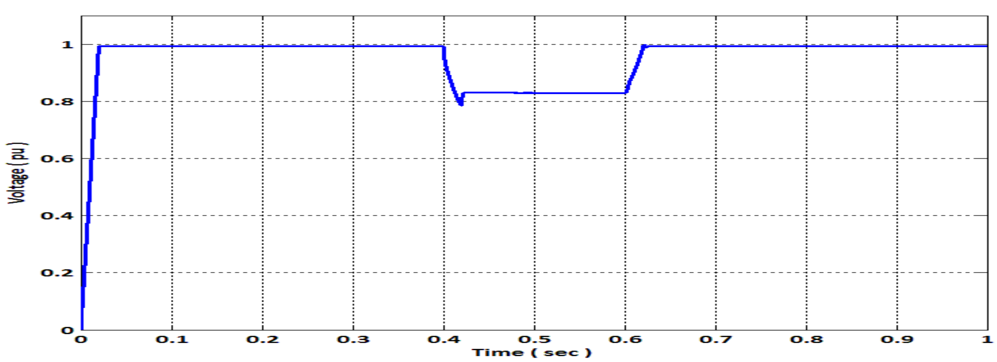

Figure22: Voltage p.u .at the Load Point: with DVR Energy Storage of 1Kv

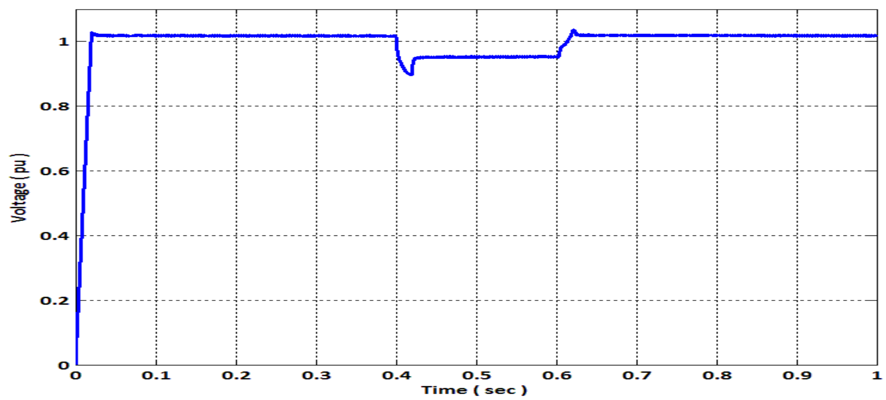

Figure23: Voltage p.u .at the Load Point: with DVR Energy Storage of 4KV.

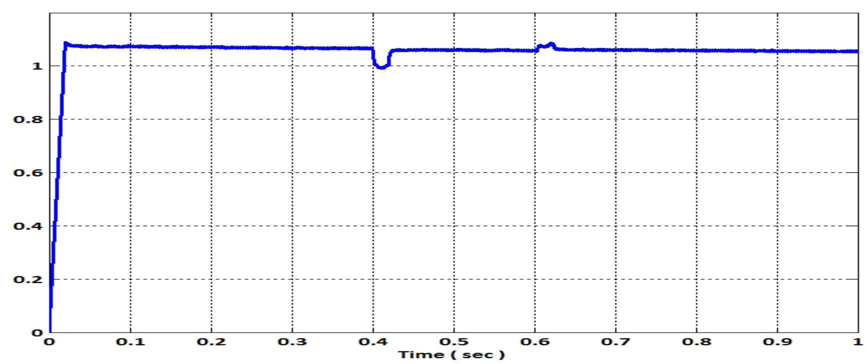

Figure 24: Voltage p.u .at the Load Point: with DVR Energy Storage of 6Kv.

Table 1: Voltage Required 11 kV at Load Terminal DC Voltage

DC Voltage Supply	Voltage (p.u.)	Voltage sag
1 Kv	0.83	17%
4 Kv	0.88	12%
6 Kv	1.09	9% swell

9. CONCLUSIONS

In this paper the important quantities in power quality according to IEC and IEEE standards were discussed. Moreover, the role of DVR in improving these factors was mentioned. The simulation results revealed that in a distribution network DVR may provide proper compensation for active power, voltage harmonic distortion, voltage unbalanced condition, voltage sag and voltage swell.

APPENDIX A

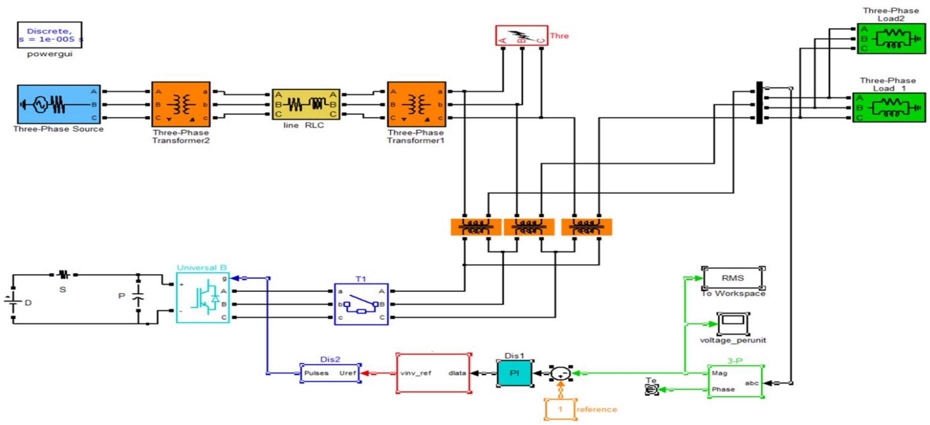

Figure 15: Simulation Model of DVR Test System

APPENDIX B

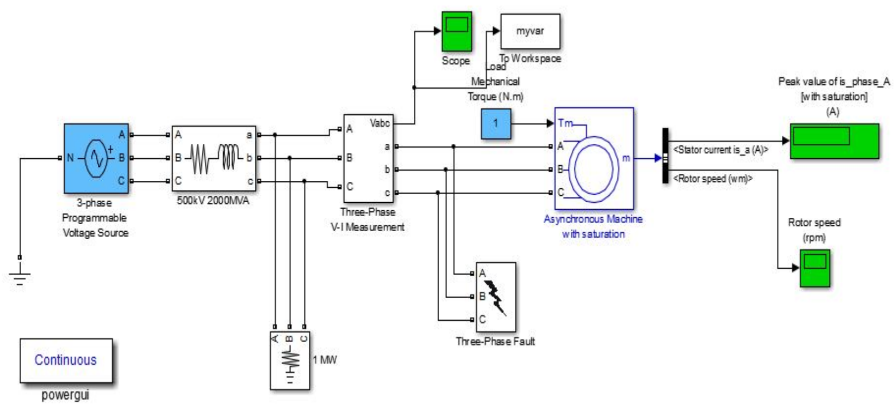

Figure 25: Block diagram of Asynchronous Motor in distribution network

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