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# Review of Dynamic Voltage Restorer Application for Compensation of Voltage Harmonics in Power Systems

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***Abstract***
*Power distribution networks are considered the main link between power industry and consumers and they are exposed to public judgment and evaluation more than any other section. Thus, it is essential to study power quality in distribution section. On the other hand, power distribution networks have always been exposed to traditional factors such as voltage sag, voltage swell, harmonics and capacitor switching which destruct sinusoidal waveforms and decrease power quality as well as network reliability. One of the methods by which power quality problems might be addressed is to apply power electronic devices in the form of custom power devices. One of such devices is Dynamic Voltage Restorer (DVR) which is connected in series to distribution networks. At the same time, through injection of voltage to the network it is able to control voltage amplitude and phase. It is adopted lend to compensate for voltage sags through injecting series and synchronous three phase voltage.This paper reviews on the application of DVRfor Voltage Compensation in recent years and gives sets of information for each control ofthe DVR in distribution networks.*

***Keywords**: Power Quality, Control Systems, Dynamic Voltage Restorer (DVR), Distribution Networks*



## 1. Introduction

Distribution section is found to be the major link between power industry and consumers; for this, it frequently is evaluated and appraised by people. Hence, essential to deal with power quality on distribution section is essential. On the other hand, distribution networks are exposed to traditional disturbances for sinusoid waveforms such as dynamic voltage sag and swell, harmonics and capacitive switching in turn damage power quality and network reliability to large extent. Such foregoing disturbances are incurred by some consumers and affect other consumers and network equipment. Additionally, given some accidents network might impose disturbances on susceptible consumers. Hence, distribution companies are responsible for offering reliable and high quality power for their consumers. This necessitates application of power quality controller devices in the networks. This might be done using power electronic devices called custom power devices, improving disturbances. An example of such devices is found to be Dynamic Voltage Restorer which is modeled and simulated here. At the same time, its impacts on disturbances in distribution networks is investigated. Having been necessity of using DVRs dealt with, its structure, operation principles and control method are explicated. To the best of our knowledge, there are several control strategies for DVRs such as sinusoid current control, line current in terms of instantaneous power theory and synchronous reference frame. Of these, instantaneous power theory with new modifications was selected as it properly offset all harmonic components, negative and zero sequences of line current and other disturbances of load current among others. To shed lights on 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. According to simulation results, DVR serves as a powerful compensator for three phase current unbalance, reactive power compensation, voltage sag and voltage oscillations [1,2,3,5].

## 2. Operation Principles of DVR System

The major fundamental of DVR operation is to detect voltage sag and to inject lost voltage to the network. A divider model can be utilized to specify voltage sag quantity in radial

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distribution systems. It is illustrated in Figure 1. This approach assumes that fault current is much greater than loads current 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 is characterized with phase angle jump. [11-12], [16].

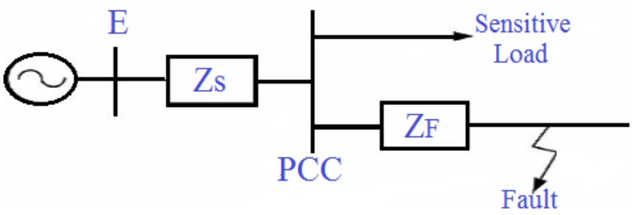


Figure 1. Voltage Divider Model for Voltage Sag

As per Figure 1, to calculate voltage in PCC and phase angle following equations are considered:

$$Vsag = \frac{Zf}{Zs+Zf} E = \frac{Zf}{Zs+Zf} \tag{1}$$

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

Where, Zs = Rs + jX represents source impedance in PCC; Zf = Rf + JXf denotes impedance between PCC and fault location; and E is source voltage which equals to 1pu. Figure 4 shows DVR power circuit. It is consisted of four parts: inverter (VSI), injection transformer, passive filter and energy storage and also Figure 2 and Figure 3 *shows placement* of *DVR's* in distribution networks. [59-62].

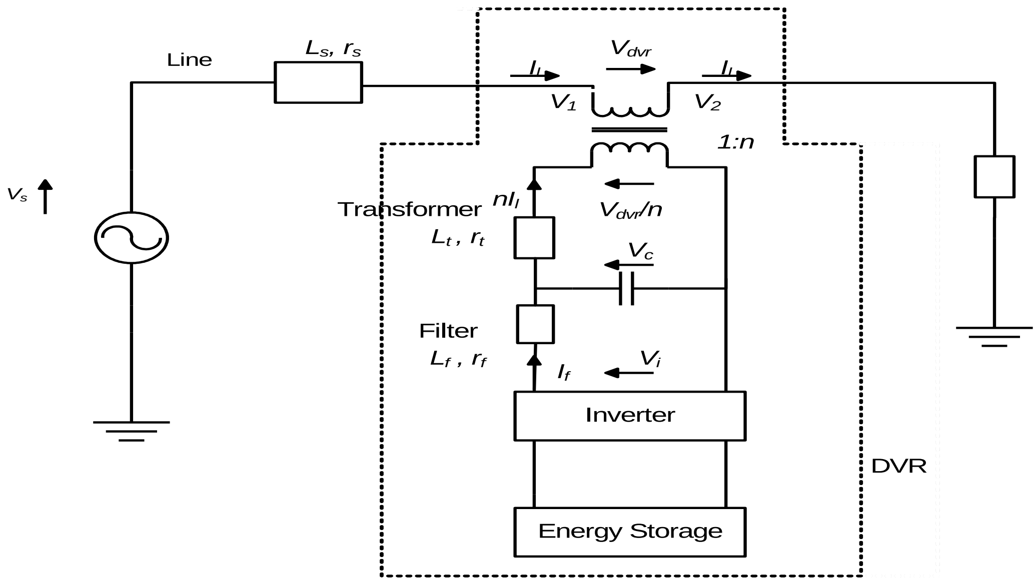


Figure 2. Distribution System with DVR

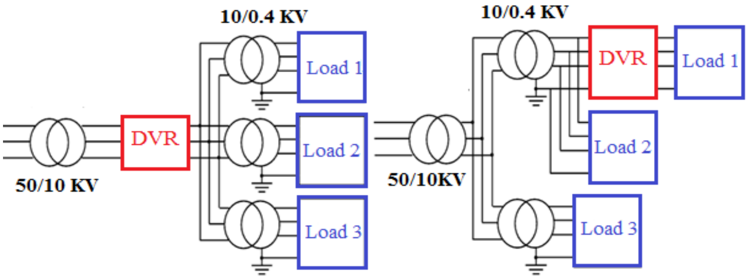


Figure 3. Placement of DVR's in Distribution Networks

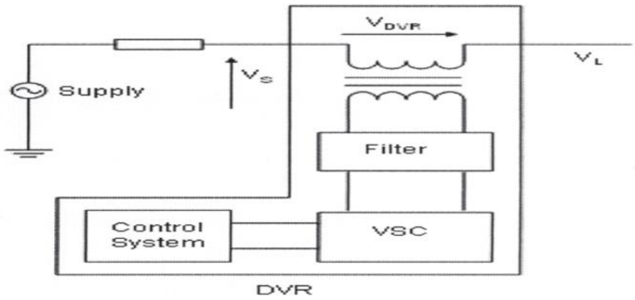


Figure 4. Actual Schemes of a DVR

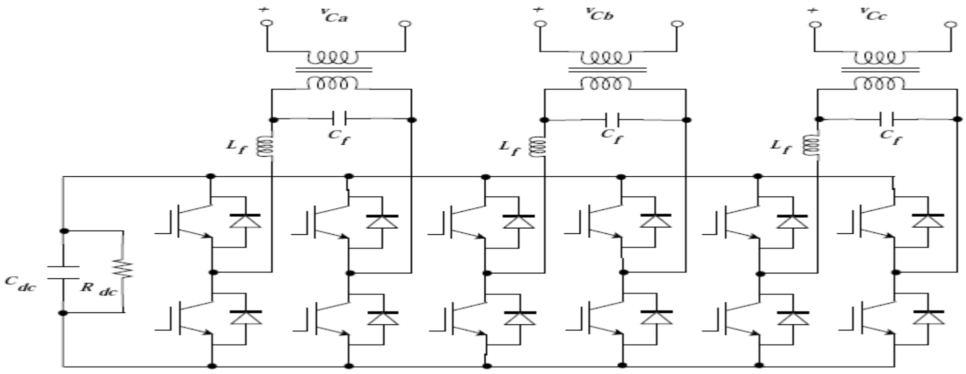


Figure 5. Structure and Configuration of DVR

DVR may need to increase active powerin order to correct larger faults. To satisfy this end, an energy storage system should be utilized. Recently, capacitive banks have been applied in DVR system design. Once fault is corrected and system turns back to normal circumstance, DVR receives the consumed energy from the network and stores it. Given energy storage capabilities capacitive banks classification relies on system factors including load and predicted voltage sag. The DVR is connected in series within distribution lines by an injection transformer. Indeed, three phase transformer in primary side should be designed so that it could bear all line current. Initial voltage rate is defined as maximum voltage which through DVR might be injected to circuit. Pulse Width Modulation switching will generate output voltage waveforms. In case voltage sag reaches to its lowest voltage level, energy storage system embedded in DVR is used to voltage modification. By Ideal restoration its means that load voltage does not subject to any change. In fact, once DVR compensates for large voltage disturbances, from DVR to distribution system active power should be transferred. In case there is an infinite energy storage capacity DVR, line voltage tends to be unchanged while throughout all types of faults.

However, presumably, when DC link capacity is limited, energy stored n DVR will be constrained. For instanced DVR cannot keep load voltage constant when DC link voltage decreases and the stored energy is lost in severe voltage sags. Therefore, losses of injected energy is essential for DVR. To inject DVR reduced voltage to distribution system some methods can be found in literature [10-12], [18]. Figure 5 shows structure and configuration of DVR.

## 3. Voltage SAG Compensation Methods

So far, the most widely used methods to compensate the voltage are as follows: application of underground cables instead of aboveground ones, increasing the equipment insulation area, to feed susceptible loads from two or more points, to install error current limiter reactors, to isolate susceptible loads by separate lines, to reduce shortage durations by rapid protection equipment, to install voltage sag compensators among many others. The first six options entails for network management, human resources, and current repair and maintenance costs, and on the other side they are exclusively exert on voltage shortage matter, and could not be developed. In contrast, once it was put forwarded in topic power quality by *Hingorani* as 1998, advanced compensators in the distribution networks so called custom power devices was recommended to improve power quality and meet consumer's demands. Factors including DVR power, various load types and various types of voltage sags constraint DVR compensation capability various. Some loads are very susceptible to phase jump. Hence, control strategy reliesrelies on load features. DVR injects voltage in three various methods given type and load sensitivity to amplitude and phase variations. [10, 14, 20, 62].

### 3.1. in-phase Compensation Method (IPC)

As for IPC method the injected voltage can be posited as in-phase characterized with voltage sag. So, while compensation, load voltage would be in-phase with source voltage. In case supply voltage subjects to a phase jump while voltage sag, load voltage will subjects to the same jump. Under such circumstance just voltage magnitude remains constant as it is illustrated by Phasor diagram in Figure 6. [62, 63].

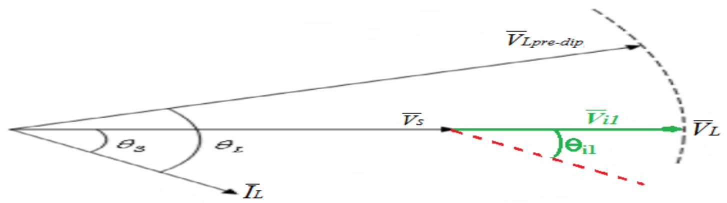


Figure 6. Phasors Diagram of the IPC method

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

$$Si1 = IL\,Vi = IL(VL - VS) \tag{3}$$

$$Pi1 = IL\,Vi\cos\theta s = IL(VL - Vs)\cos\theta s \tag{4}$$

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

### 3.2. Pre-Dip Compensation Method (DPC)

Some loads are also susceptible to phase jump. So, as well asvoltage magnitude, voltage phase should converted to an in-phase nature with the voltage before voltage sag. As a consequence, DVR should inject a voltage equals to difference between load voltage before SAG (which is the same as voltage after sag) and network voltage while sag. PDC methods demonstrated in Figure 7 can explains it [30-32], [62].

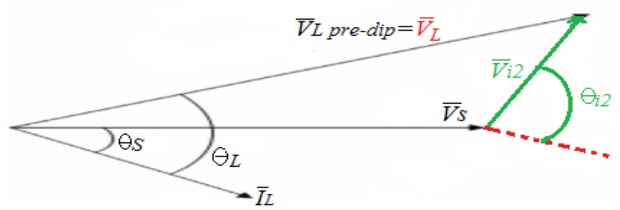


Figure 7. Phasors Diagram of the PDC Method

From power quality viewpoint such method outperforms as it keep both amplitude and phase of load voltage. Injected apparent and active power as well as amplitude and phase of injected voltage might be obtained through following equations:

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

$$Pi2 = IL(VL\cos\theta L - Vs\cos\theta s) \tag{6}$$

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

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

**3.3. Phase Advanced Compensation Method (PAC)**

In this approach to attenuate injected energy, the injected voltage should transferred in comparison with source voltage. Taking equation for Pi2 in to account, it can be inferred that inject power is zero once $\theta_s = 0$ i.e. VL and IL will be in-phase. This scheme seeks to minimize DVR injected power while compensation. As figure 8 shows, the load voltage phasor fluctuates around a circle with radius represented by VL [60- 62].

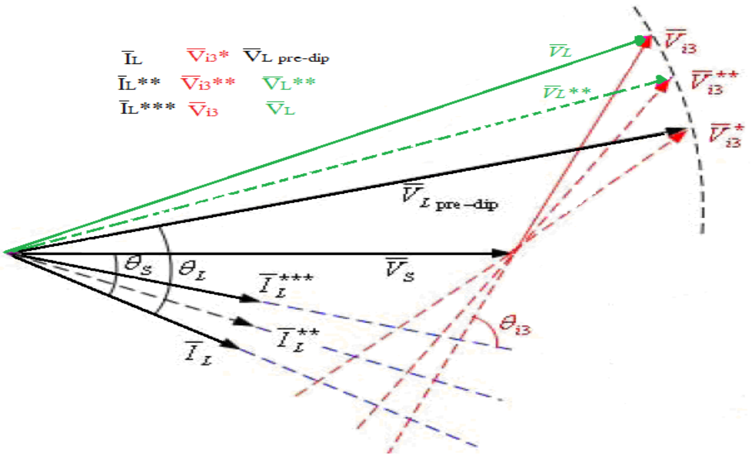


Figure 8. Phasors Diagram of PAC Method

It is worthy to note that foregoing method is not lend for those loads susceptible to phase shift. Another drawback as for this method is great amplitude of injected voltage. Under such condition injected apparent and active powers can be derived. Additionally, injected voltage phase and magnitude could be calculated by following formula.

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

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

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

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

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

The foregoing equations prove that when VL.Cosθ>VS DVR should take VS and IL in phase upon injecting voltage; but, in case VL.Cosθ<VS Pi3 is negative and active power should be set to zero without adjusting $\theta_s$to zero. In other words, voltage sag is offset by reactive power. Given this, injected voltage is vertical to load current. Its value for zero power flow is derived using Pi3 equation [7, 9].

## 4. Different Types of DVR

DVRs are divided into two groups In terms of energy supply: 1) DVR with energy storage system, 2) DVR without energy storage system. (Figure 9) In the former, energy is supplied by capacitive bank or batteries; whereas, in the latter energy is provided using the network connected to load or supply [22, 23].

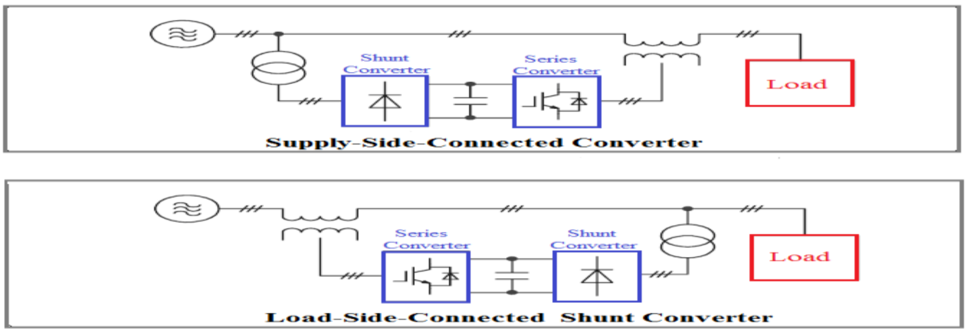


Figure 9. Topologies for DVRs without Energy Storage

## 5. Strategy of Control

Control system design is of great importance in DVR structure as this section specifies response time and ways of voltage sag compensation. To infer control signal parameters such as amplitude, frequency, phase shift and so control circuits are utilized on which are injected by DVR. The injected voltage is generated by present inverters considering control signals. Control schemes for DVR either closed loop or open loop can be used. Closed loop approach outperforms while is more complicated and non-cost-effective. Here, open loop scheme is explicated. Three phase voltage of the source similar to SPLL is transformed to two phase; then, values are obtained in synchronous reference frame ($V_q$, $V_d$) where values are DC and constant. These values get smaller While voltage sag and the difference between their values before sag and while voltage sag will generate an error signal ($V_{qerror}$,$V_{d\ error}$). The required pulses for switching of inverter are obtained Using inverse of the mentioned transforms and the same angle estimated by SPLL, obtained. In fact, information about voltage supply phase and amplitude are essential for DVR. SPLL is adopted to evaluate phase of voltage supply. In case of occurring single phase to ground short circuit fault, positive, negative and zero sequences will be generated in voltage, in turn, results in errors in phase measurement. Figure 10 shows control strategy of DVR [44-46], [62].

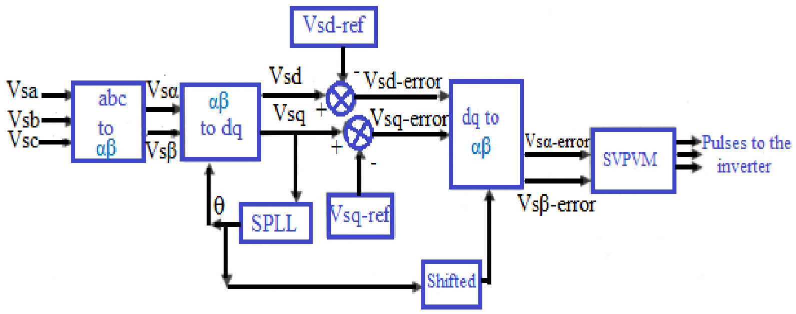


Figure 10. Block Diagram of Control System

It should be noted that to eliminate the shifting effect of injection transformer shift block is applied. As simulation results showed, DVR can appropriately compensate for three phase and single phase short circuit faults as well.

### 5.1. A Three Phase DVR and its Control

In the present section, a straightforward three phase DVR is discussed. it can protects balanced load voltage constant amplitude against fluctuations, harmonics, voltage sag unbalanced condition and so on. A three phase inverter is made of three single phase inverters connected to primary side of a transformer using star connection. There is a series connection between secondary side and series to lines. Three phase transformer is characterized with nominal value of is 10kVA with 1:5 conversion ratio. It implies that the inverter can inject 20% of nominal voltage. Inverter adopts sinusoid PWM (single pole switching) under switching frequency of 20 kHz. Inverters transform stored DC voltage of energy storage system to a suitable injection voltage. The resultant voltage is filtered and subsequently injected in series by injection transformer.

Figure 11 shows block diagram of control strategy for a DVR [40-41], 62, 65].

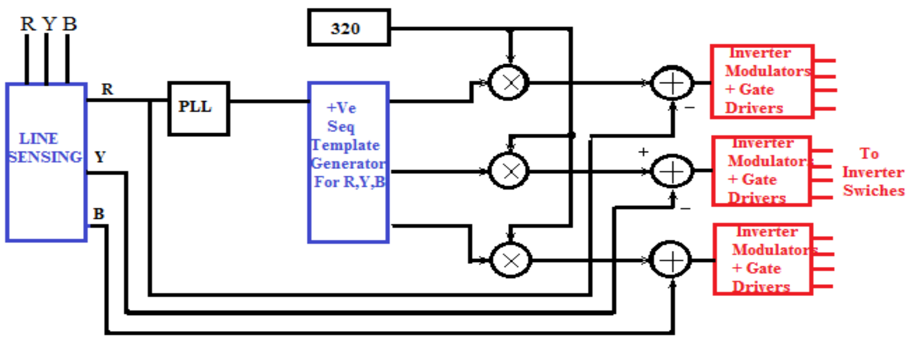


Figure 11. Block Diagram of Control Strategy for a DVR

By PTs and a PLL locked in R phase load voltage attenuates step by step. Synchronized with R, net sinusoid wave phase is fed into a positive sequence generator (in terms of all pass filter). As it can be seen, it generates positive sequence waves with unity amplitude. Such paradigms are amplified by a desired amplitude (320V for load voltage). Actual load voltage generated by sensor circuits is lowered under these patterns such that reference signals for inverter modulators could be generated. DC section serves as a power source link or a converter. Figure 12 illustrates SIMULINK simulation diagram for the system [62-64].

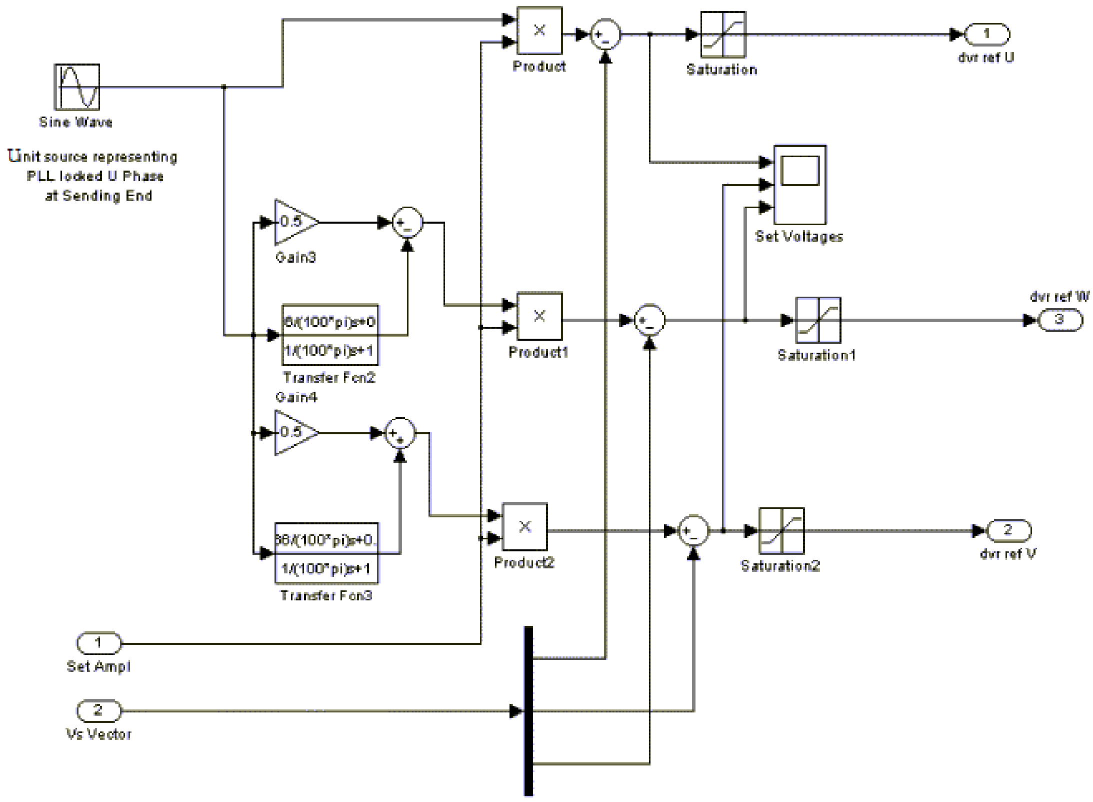


Figure 12. Reference Block of Inverter

In the present subsystem, saturation block is set at ± 65 Volts to represents overmodulation inverter limit. The former models inverter as an ideal voltage controlled align with voltage source and can be used just to clarify concepts. The latter 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 accounts for inverter losses. The former one will leads to very optimistic and promising results under dynamic conditions – for instance it will proved that output voltage is not even aware of a sudden phase variations at input. In practice this will not be case. The various un-modelled lags along with inverter filter response time will really transfers sudden variations in the input voltages at least partially to the output side. The first model performance simply does not relies on load current, as this model has no impedance anywhere. But practically output voltage will get influenced by load harmonics and can be attributed to two reasons the inverter output filter will entails for harmonic drops once harmonic load currents flow through it and in absence of feedback control the system does not correct to the inverter right. Secondly inverter finite bandwidth of (because of a finite switching frequency) will fail to generate high frequency content generated at the source bus characterized with high frequency component of load currents flowing in source impedance (which in the first simulink model is taken as zero). When sag rate, swell or flicker or harmonic content is excessive the inverter will saturated and clip its output less than others. To the result will be distortion in output voltage. However simulation reveal that such distortion even for sags which take source voltage to 100V peak stay under 10%. All of three models manifest clipping effect. The DVR controlof is not a very complicated problem and in fact field experience accounts for feed forward control. However the main drawback is to provide a suitable DC Side energy source to handle long periods of sag or swell or flicker throughout the day (like arc furnace). In case it is a battery it requires a charger. Some researchers have presented drawing charging power from the line using the same inverter while periods which sag or swell is little and can be handled by 90-degree voltage injection. But that makes the control complicated to some extent. If it is an AC-DC Diode Rectifier the DVR can handle just sags and not swells as while 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 subsequently 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 13 shows simple schematic of a DVR in distribution network. The most popular application for DVR is to compensate voltage sags and voltage swells in distribution systems [30-32, 62]. The power circuit of DVR in Figure 14 is shown.

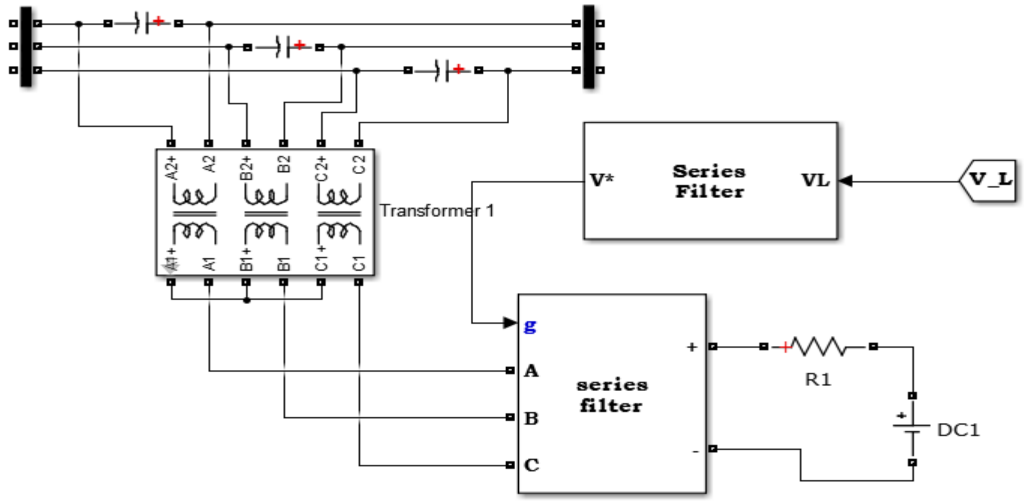


Figure 13. Schematics of a Simulated DVR and its Performance

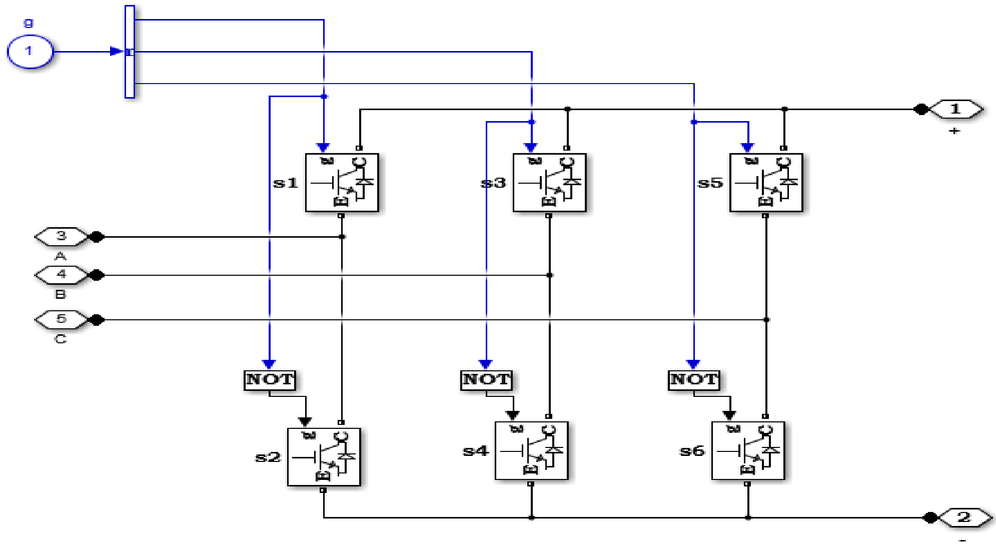


Figure 14. Power Circuit of DVR

## 6. Simulation Results

Here, a DVR's efficiency in a sample distribution network is investigated. Figure 15 and Figure 16 shed lights on voltage of one of the phases' loadwith and without DVR. As it can be observed DVR is successful in compensation resulting in power quality improvement in the distribution network.

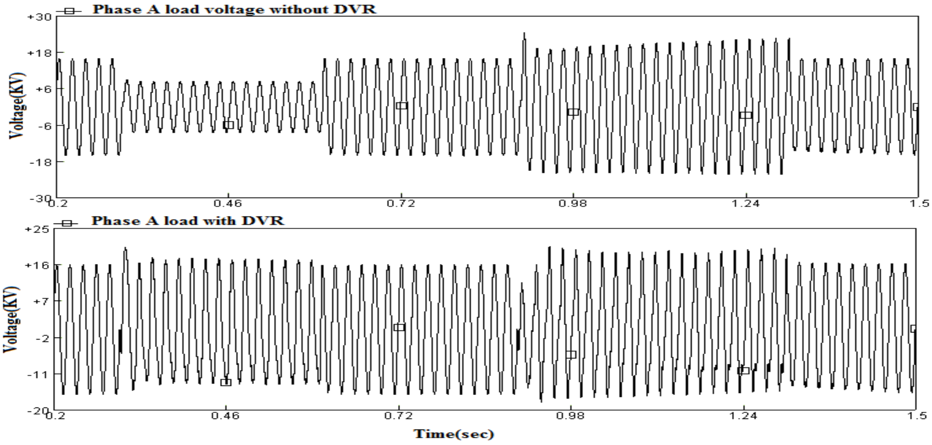


Figure 15. Voltage of one of the phases' load (A) with and without DVR

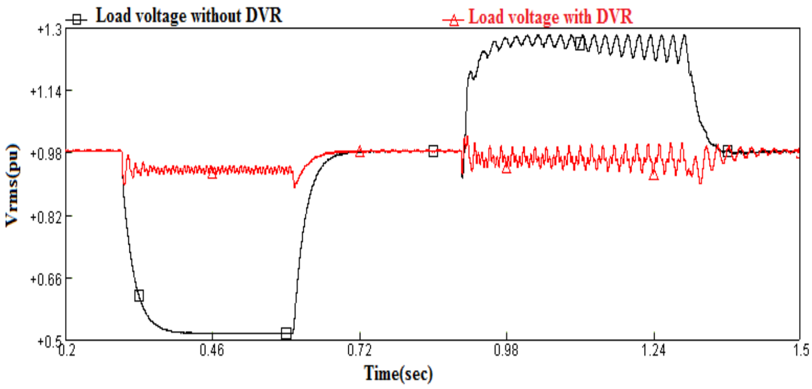


Figure 16. Voltage (pu) of one of the phases' load (A) with and without DVR

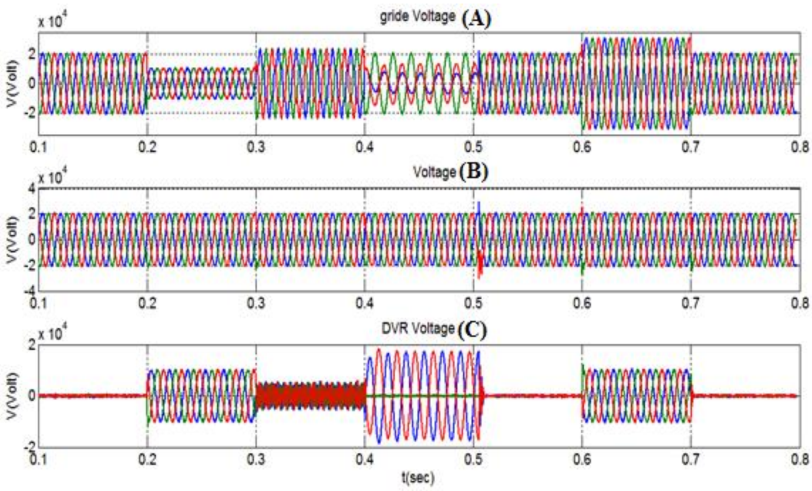


Figure 17. Grid voltage (A), compensated voltage by DVR (B), injected voltage by DVR (C)

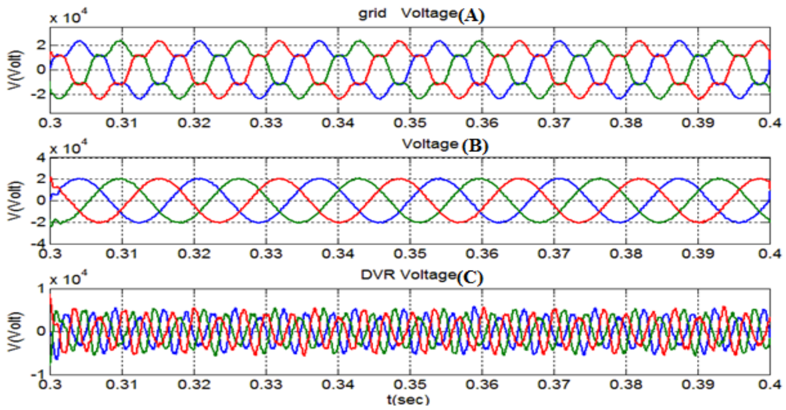


Figure 18. Compensation ofvoltage harmonics by DVR, grid voltagecontains harmonics of 5, 7(A), compensated voltage by DVR (B), injected voltage by DVR (C)

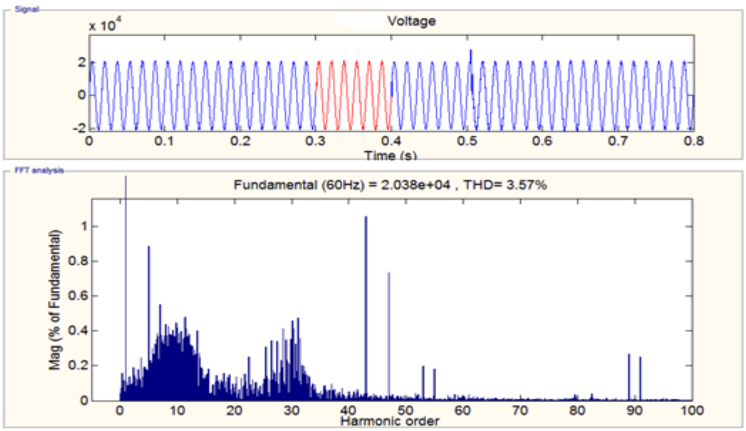


Figure 19. Grid voltage and Its harmonic distribution after compensation by DVR

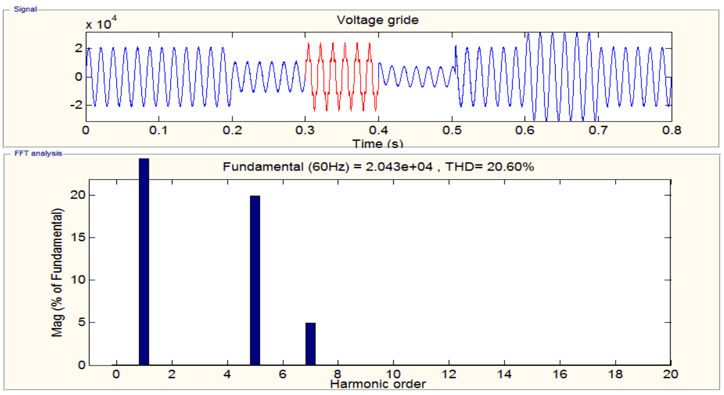


Figure 20. Grid voltage and Its harmonic distribution before compensation by DVR

## 7. Conclusions

As mentioned before, the existence of sensitive loads in the network needs to challenge with the voltage disturbances and doing this is necessary. This article introduces the structure of the DVRs as a fundamental solution for challenge with voltage disturbances and also deals with important quantities in power quality as per IEC and IEEE standards. At the same time, DVR contribution in enhancing such factors was mentioned. As simulation showed, in a distribution network DVR can offer proper compensation for active power, voltage harmonic distortion, voltage unbalanced condition, voltage sag and finally voltage swell.

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