



AN IMPROVEMENT OF VOLTAGE QUALITY IN LOW VOLTAGE DISTRIBUTION SYSTEM USING DYNAMIC VOLTAGE RESTORER

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ABSTRACT

With the increase use of semiconductor devices (switched mode power supply) and ICT (information communication technology) equipment in homes, offices and the industry's power quality (PQ) are gaining significant interest to both the electric utility and the industry. The absence of power quality causes enormous economic losses all over the world; it is estimated that these problems cost commerce and industry about 100 billion Euros per annum in the European Union. This paper is, therefore, aimed at mitigating power quality problems such as voltage sag, voltage swell, voltage unbalance and harmonic at low voltage distribution system, using a dynamic voltage restorer (DVR). Implementations of DVR have been proposed at both a medium and low voltage levels to protect sensitive loads from power quality problems. The proposed system is designed using Matlab/Simulink Sim Power System tool box. The simulation results verified the capability of the proposed DVR system in mitigating the power quality problems in a low-voltage distribution system.

Keywords: power quality, voltage sag, injected voltage, dynamic voltage restorer (DVR), harmonics, custom power device.

1. INTRODUCTION

Sensitive loads such as factory automations equipments, hospital equipments, ICT (information communication technology) equipments and semiconductor devices like SMPS (switched mode power supply) are vulnerable to power supply disturbances. Consequently, the demand for a supreme high power quality and voltage stability becomes an issues nowadays (Goswami, Gupta *et al.* 2011). Absence of power quality causes enormous economic losses all over the world, it is estimated that PQ problems cost commerce and industry about 100billion Euros per annum in the European Union (De Keulenaer, 2003). Today, both the utilities and the end users of electrical power are becoming increasingly concerned about the quality of power supplied and power consumed respectively. Generally, PQ problems can solve in two perspectives. First is to ensure that process equipment's are less tolerant to disturbances that are likely to occur, that is letting the devices or process equipment to ride through PQ disturbance (Bollen, 2000) or secondly is the use of custom power devices to mitigate the PQ disturbances.

Numerous of custom power devices (CUPS) are commercially available these days for the purpose of solving PQ disturbances. This include uninterruptible power supplies (UPS), static var compensator (SVC),

active power filters (APF), distribution static synchronous compensators (DSTATCOM), thyristor switched capacitors (TSC), battery energy storage systems (BESS), dynamic voltage restorers (DVR), solid state circuit breaker (SSCB), surge arrestors (SA), solid state transfer switches (SSTS), super conducting magnetic energy storage system (SMES), static electronic tap changers (SETC), distribution series capacitors and power factor corrector (PFC) etc.

Research in field of PQ indicates that dynamic voltage restorer (DVR), which is classified as custom Power System (CUPS) have been successfully employed to solve PQ problems, especially voltage dips and swells (Sannino, Svensson *et al.* 2003) and existing research literature reveals that DVR's is as considered as a suitable, economical and effective device to compensate the voltage disturbances (Roncero-Sanchez and Acha 2009). Beside swell and sag compensation in (Brumsickle, Schneider *et al.* 2001; Wahab and Mohd Yusof, 2006; Wang and Venkataramanan, 2007; Omar and Rahim, 2008), DVR has been successfully used to compensate harmonic (Newman, Holmes *et al.* 2003, Jowder 2009, Babaei and Kangarlu 2012) and also to limit down streams fault current (Li, Vilathgamuwa *et al.* 2007).

DVR technology is still not developed and many areas regarding its control and designs are still at study



level. In (Nelson, Legro *et al.* 1996; Stump, Keane *et al.* 1998; Bollen, 2000) DVR design is discussed and treated with emphasis on the sizing of current, voltage and power and ratings, also in the work of (Ghosh and Ledwich 2004) the structure of DVR have been treated and in (Li, B. H., S. S. Choi, and D. M. Vilathgamuwa) the design considerations for DVR line filter is addressed.

In this paper, a simple, cost effective and fast response custom power device called dynamic voltage restorer (DVR) was proposed to solve power quality problems in a low voltage radial network.

2. DYNAMIC VOLTAGE RESTORER

A DVR is a power electronic voltage correction device based (Brumsickle, Schneider *et al.* 2001, Praveen, Muni *et al.* 2004) connected in series with the feeder of sensitive loads between the load buses and the incoming supply (Ghosh and Ledwich, 2004), as shown in Figure-1. DVR was first installed in Westinghouse in 1996 (Rosli Omar, *et al.* 2011). And since then, because of the growing number of sensitive loads worldwide, many installation have been taken place and with a wide spread of research in the control philosophies of DVR (Praveen, Muni *et al.* 2004). Nowadays, commercial DVR solutions are found within the range of MVA and installed in the industries to support the entire plant.

A modern pulse-width modulated (PWM) inverter that is capable of generating accurate high quality voltage waveforms forms the heart of Custom Power devices like DVR. And a proper design of the control scheme enables the DVR to inject three-phase controllable voltages of required phase angles and amplitudes to maintain the load bus voltage in desired waveform during voltage sags, swells, harmonics in the grid voltage (Jurado and Hidalgo, 2002; Babaei and Kangarlu, 2012).

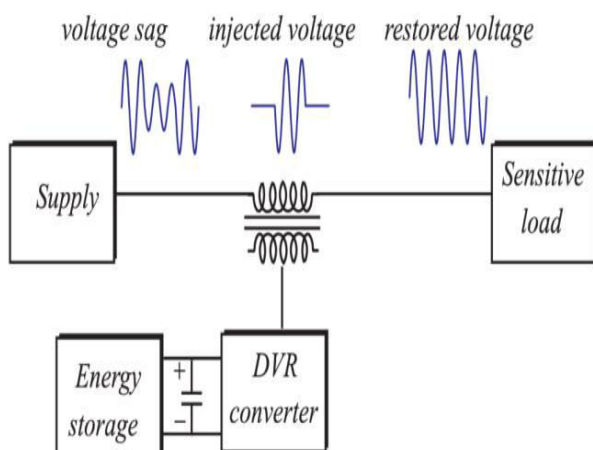


Figure-1. Schematic diagram of a dynamic voltage restorer (DVR) (Nielsen and Blaabjerg 2005).

The power circuit of the DVR consists of five parts as shown in Figure-2. Namely, Voltage injection transformer, line filter, energy storage device, voltage source inverter, bypass switch. The functions of each of these parts are described as follows;

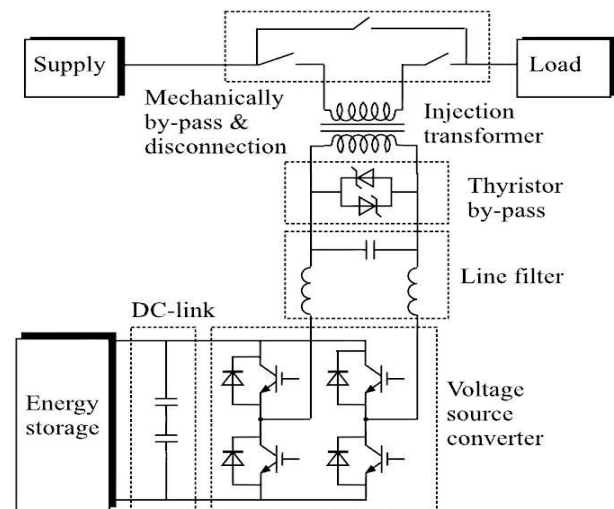


Figure-2. Main configuration of DVR (Nielsen and Blaabjerg, 2005).

2.1 Series voltage injection transformer

A transformer is an important factor that needs to be considered in designing DVR. Because it serve as an interface between the power system network and the DVR and the compensation capability of the DVR totally depend on it rating of the injection transformer (Zhan, Ramachandaramurthy *et al.* 2001).

Basically a transformer consists of the high voltage side and the low voltage side. In systems with DVR, the high voltage side of the transformer is connected in series to the power system network while the low voltage is connected to the power circuit of the DVR. The function of the transformer is to step up the supplied voltage from the output of the filter to the desired level and to isolate the DVR from the power system network. For the DVR to fully compensate the missing voltage, the secondary of the voltage injection transformer must be equal to the main supply voltage (Zhan, Ramachandaramurthy *et al.* 2001).

2.2. Energy storage

During voltage disturbances in the power system network, DVR needs real power to compensate or to mitigate the disturbances. For the DVR with energy storage topology, a storage element or a DC link is required by the voltage source converter to produce an AC voltage which is to be injected into the grid when there is a voltage disturbance in the network (Nielsen, Newman *et al.* 2004).



2.3 Voltage Source Inverter (VSI)

The inverters systems in the DVR are to convert the DC voltage supplied from the storage element to AC voltage source which is to be injected into the system via the injection transformer during voltage disturbances (Kumar and Nagaraju 2007). The rating of the VSI is relatively low in voltage and high in current of the presence of step up injection transformer.

2.4 Bypass switch

In the occurrence of fault in the power system network, fault in the downstream might flow to the inverter circuit of the DVR. To avoid this to happen a bypass switch is incorporated in the inverter circuit to bypass the path for load current during faults, service and overload.

2.5 Line filter

Line filter is included in the DVR system in order to reduce the switching harmonics generated by the PWM VSC. The filtering scheme can be placed either in the inverter side or in the high voltage side. The filtering use in this project is placed in the inverter side. This is because all the higher order harmonics components that is generated by the VSI would be at least eliminated from the system.

3. DVR POWER CIRCUIT

The power circuit of DVR consist of five (5) components as shown in Figure-3, namely: injection transformer, filter, series converter, energy storage and line filter. For each phase of the line, a two winding linear transformer is used, with a voltage ratio of 11/700 kV. The winding of the linear transformer connected to the converter is designated as the secondary while the winding connected to the supply side is designated as the primary.

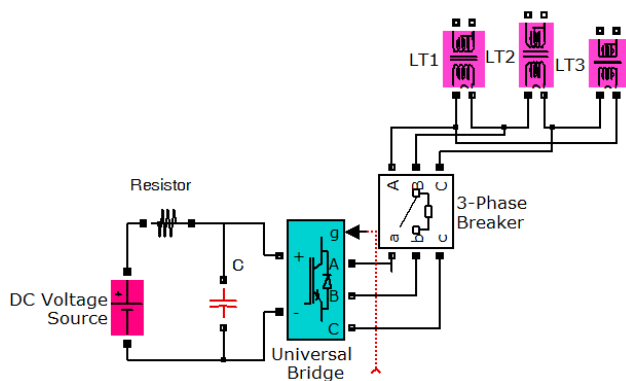


Figure-3. Simulink model of DVR power circuit section.

A regulated constant DC supply source is used as the storage element and a three single phase universal bridge PWM inverters are used in the series converter

circuit as shown in Figure-3.4. The VSI is relatively high in current and low in voltage due to the presence of a step up injection transformer. The parameters of the system is provided in Table-1.

Table-1. System parameters.

S. No.	System quantities	Standards
1	Transmission line parameter	$R=1\Omega$ $L=0.0005E-3$
2	$L1 = L2$	$P=10kW$ $Q_L=100VAR$ $Q_C=100VAR$
3	Specification of inverter	3arms IGBT based, 6 pulse, Sample time= $5\mu s$, Carrier frequency= $1080Hz$
4	PI controller	Sample time = $50\mu s$ $K_p=0.5$ $K_i=50$
5	DC link voltage	100V

4. PROPOSED CONTROL STRATEGY FOR THE DVR

The configuration of the proposed control strategy design is depicted in Figure-4. During voltage disturbance, the DVR detects the power quality disturbances by sensing the load voltage and passed it through a discrete sequence analyser as shown in figure 16. The sequence analyzer now compares the magnitude of the load voltage and the reference voltage (V_{ref}). The errors obtain due to the comparison of the reference voltage and the load voltage is processed by a Proportional Integral (PI) controller, which is just after the sequence analyser.

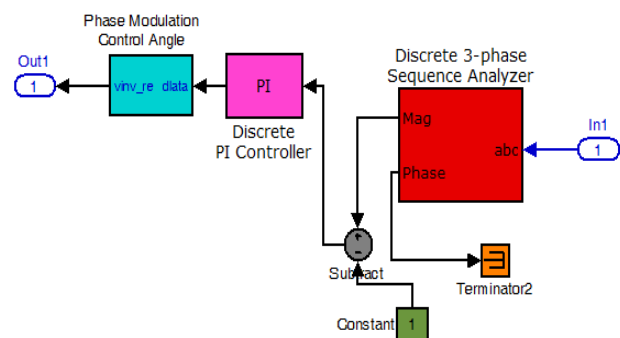


Figure-4. Simulink model of DVR controller.

The PI controller now drives and controlled the plant with the sum of error obtained (difference with the load voltage sensed and the reference voltage) and the



integral value. The input of the PI controller is an actuating which is the error (difference between reference V_{ref} and the terminal voltage). Such kind of error is processed by the PI controller and gives an output of angle δ .

The modulated angle δ from the output of the PI controller is applied to the PWM generators in phase A as presented in equation (1), while the angle of phase B and C are shifted by 120° and 240° as presented in equation (2) and (3), respectively. Therefore, in this PI controller, only voltage the voltage magnitude is taken as a feedback parameter in the control scheme.

$$V_a = \sin(\omega t + \delta) \quad (1)$$

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

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

The sinusoidal signal V_{control} is phase modulated by means of the angle δ as shown in Figure-5. And the modulated three phase voltages are given equation (1), (2) and (3), respectively.

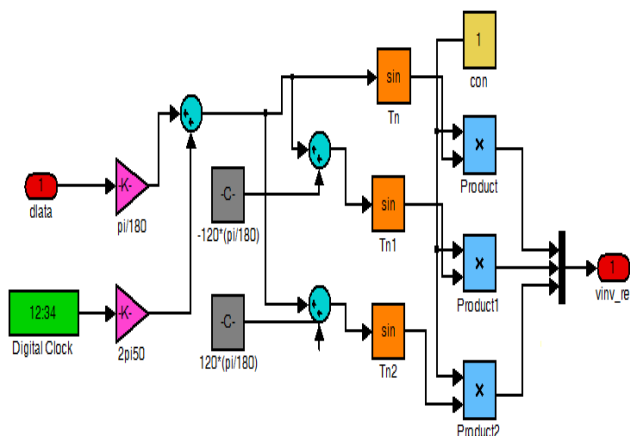


Figure-5. Phase modulation of the control angle δ .

To generate the required switching single for the VSC valve by the PWM generator, the sinusoidal signal V_{control} is then compared against a triangular signal. The frequency modulation index M_f of the carrier signal and the amplitude modulation index M_a are the main parameters required for the sinusoidal PWM scheme. And, in order to obtain the highest fundamental voltage component at the output of the controller, the amplitude modulation index M_a is kept fixed at 1 p.u.

$$Ma = \frac{V_{control}}{V_{tri}} = 1P.U \quad (4)$$

Where;

V_{control} = The peak amplitude of the signal

V_{tri} = The peak amplitude of the triangular signal

5. SIMULATION RESULTS AND DISCUSSIONS

In this section, several simulations are carried out to verify the performance of the DVR system for different types of disturbance and been tested under different load conditions so as to fully investigate it performance.

Simulation is carried out for network with linear load connected and for a network with nonlinear load connected. And all the results obtained are comprehensively discussed in detail. The system runs at 50 Hz frequency and sample time is chosen to be 100 μ s. The total period of simulation in each case is 0.2s.

5.1 Simulation of radial network with linear load connected

The first case presented is the simulation of the three phase radial network in the absence of fault in the system, and in this case, the three phase voltages are in balance condition and the waveform is a pure sinusoidal sine wave as shown in Figure-6 and the DVR system is said to be in a standby mode. Power quality problems are detected by sensing the voltage at the point of common coupling (PPC) during fault period.

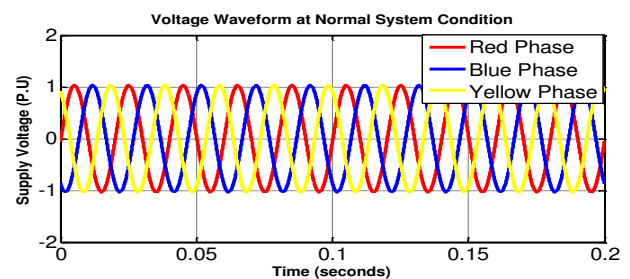


Figure-6. Voltage waveform of the three phase line in the absence of fault.

Simulation is again carried out in the presence of three phase fault, double line to ground fault and single line to ground fault via a fault resistance of 0.8Ω which initiate 75% voltage sag in the supply voltage for all the three types of fault as shown in Figure 7, 8 and 9 respectively.

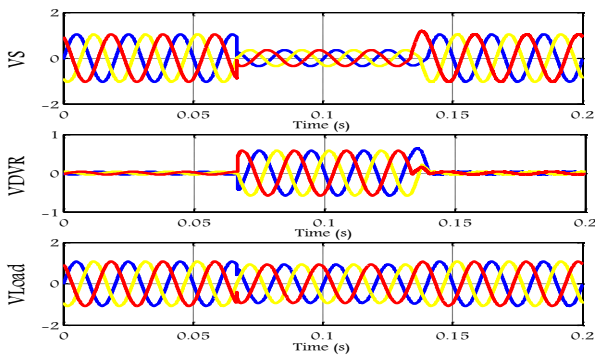


Figure-7. The performance of the DVR in resolving 3phase sag: From top to bottom trace, the Source Voltage waveform without DVR, Injected Voltage and Load waveform with DVR.

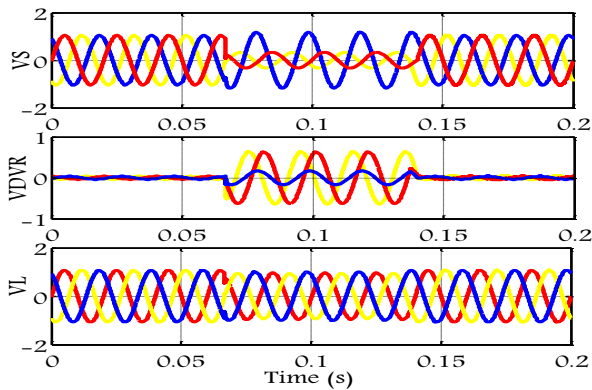


Figure-8. The performance of the DVR in resolving unbalance two phases sag: From top to bottom trace, the Source Voltage waveform without DVR, Injected Voltage and Load Voltage waveform with DVR.

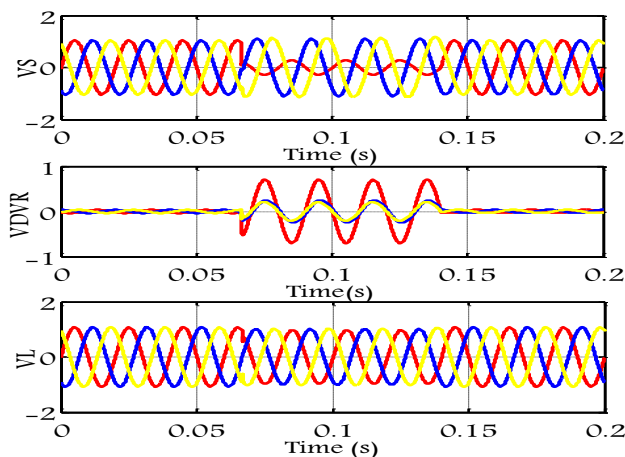


Figure-9. The performance of the DVR in resolving single phase fault: From top to bottom trace, the Source voltage waveform without DVR, Injected Voltage and Load voltage waveform with DVR.

In all the cases shown in Figure 7, 8 and 9, voltage sag was introduced at time 0.065 seconds and it is kept up to time 0.14 seconds with voltage sag duration of 0.075 second. The DVR therefore injects the missing voltage to mitigate the supply voltage (V_s).

Also, it can be noticed that after compensation, the load voltage return to its normal 1 P.U as that of figure 6. This is an indication that the control scheme design for the DVR is good since it can serve the purpose for which it is designed. Nevertheless, the double phase sags and single phase sags shown in Figures 8 and 9 are both classified as unbalanced voltage sags. This occurs when one phase of a three voltage drops down to about 30%, while the other phases remaining swells up as clearly shown in Figures 5 and 6.

It is also important to determine the response of the DC link voltage and current during the starting of the fault to its end. This is very important because the DVR depends solely on the DC voltage, as the injection voltage during sag is obtained from it. The response of the DC-link voltage with respect to the three types of sags namely three phase sags, double phase sags and single phase sags is presented in Figure 10, 11 and 12. As can be seen in all the three sag scenario, before the occurrence of sag, the DC-link voltage is fully charged at rated supply voltage. But at time 0.065s to 0.14s which is the beginning and ending of sag, power is taken solely from the DC-link capacitor. The decay of power in the DC-link voltage is higher during three phase phase and double phase when compared to single phase sag. This is because three phase sags and double phase sags are more severe than single phase sags. For the single phase sag, only a small amount of power is absorbed as shown in Figure-13.

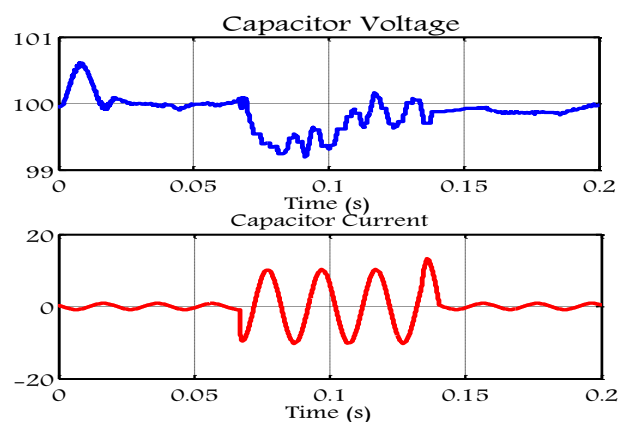


Figure-10. From to bottom trace: DC link voltage and current during three phase sag.

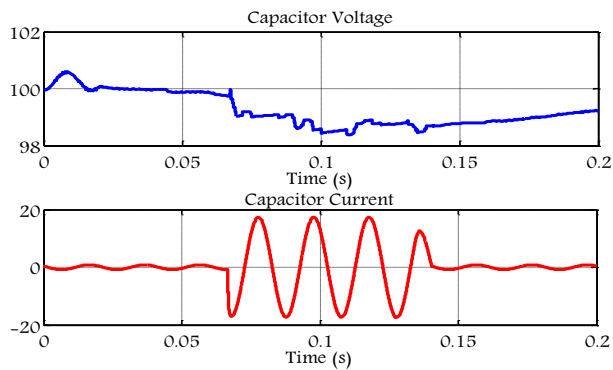


Figure-11. From to bottom: DC link voltage and current during unbalance double phase sag.

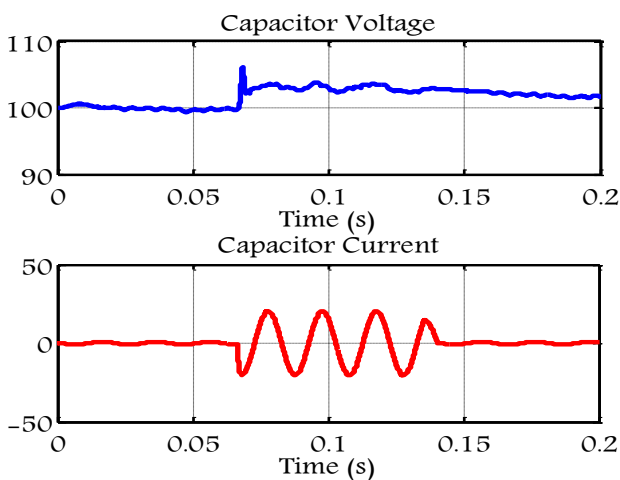


Figure-12. From to bottom trace: DC link voltage and current during unbalance single phase sag.

The capability of the DVR system in resolving interruption (complete loss of supply) is also tested. Figure-13 shows the operation and performance of the DVR during interruption in the system, i.e. that is a complete loss of supply also with duration of 0.075s.

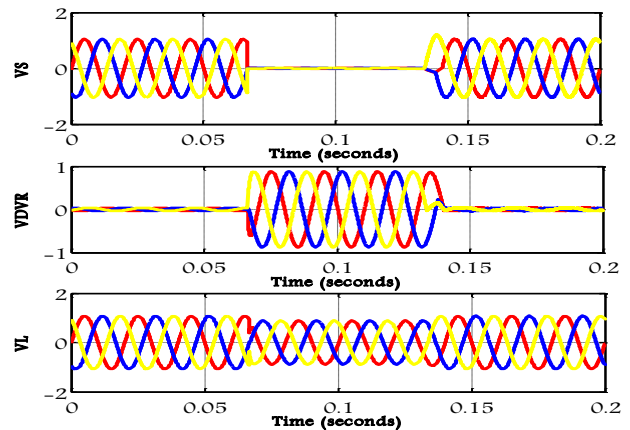


Figure-13. The performance of the DVR in resolving interruption: From top to bottom trace, the Source voltage waveform without DVR, Injected Voltage and Load voltage waveform with DVR.

5.2 Simulation of radial network with non-linear load connected

In this section, the capability of the DVR in resolving harmonics problems is tested and verified. A radial network model with a non-linear load was used in the testing. The non-linear load is used in this case instead of linear load is just create harmonics in the system.

The simulation result obtained shows that the supply voltage (V_s) is not a pure sinusoidal as shown in Figure-14. This is because of the presence of a nonlinear load connected which causes harmonic and distort the supply voltage.

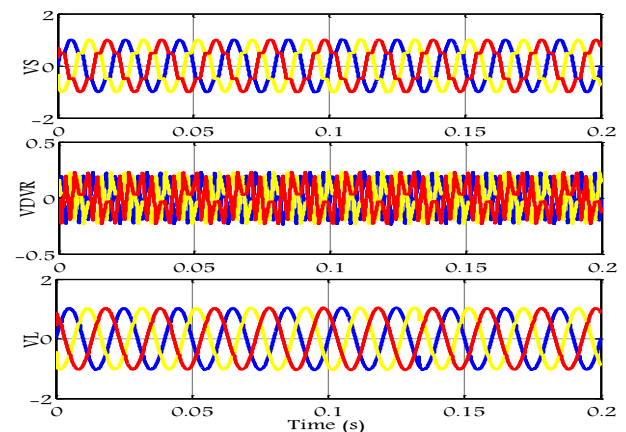


Figure-14. The performance of the DVR in resolving harmonics: From top to bottom trace, the Source Voltage waveform without DVR, Injected Voltage and Load Voltage waveform with DVR.

Fast Fourier Transform (FFT) analysis of the output voltage at the connected load had been done



without and with a capacitor as shown in Figure 15(a) and 15(b).

Total Harmonic Distortion (THD) for the voltage for the above waveform before mitigation was 15.78%.

But mitigation the THD value decreases to 2.06%. Thus, as can be seen, the harmonic is significantly reduced.

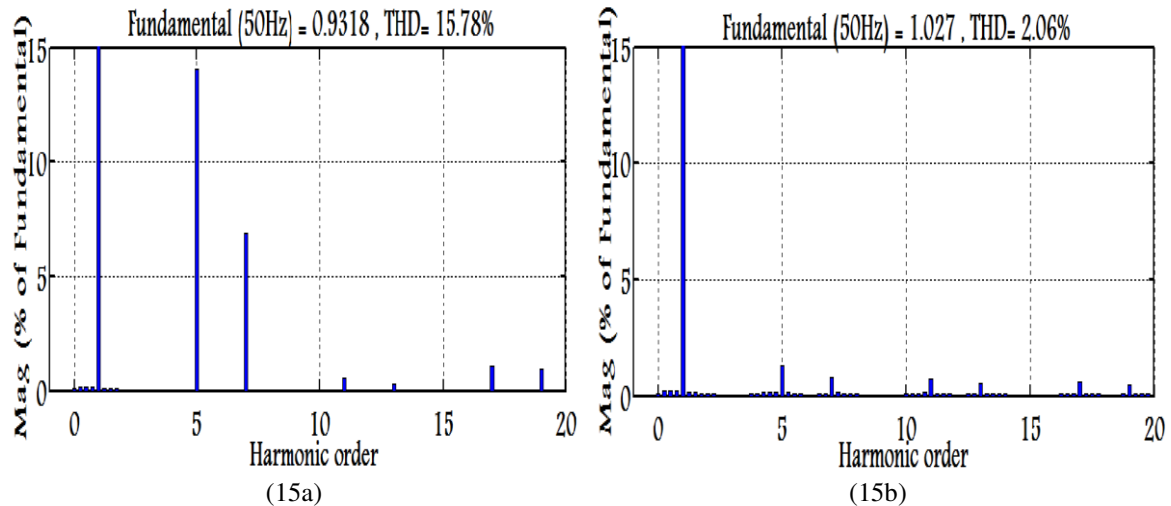


Figure-15. Fast Fourier Transform (FFT) of the source voltage and load voltage (i.e. before and after mitigation).

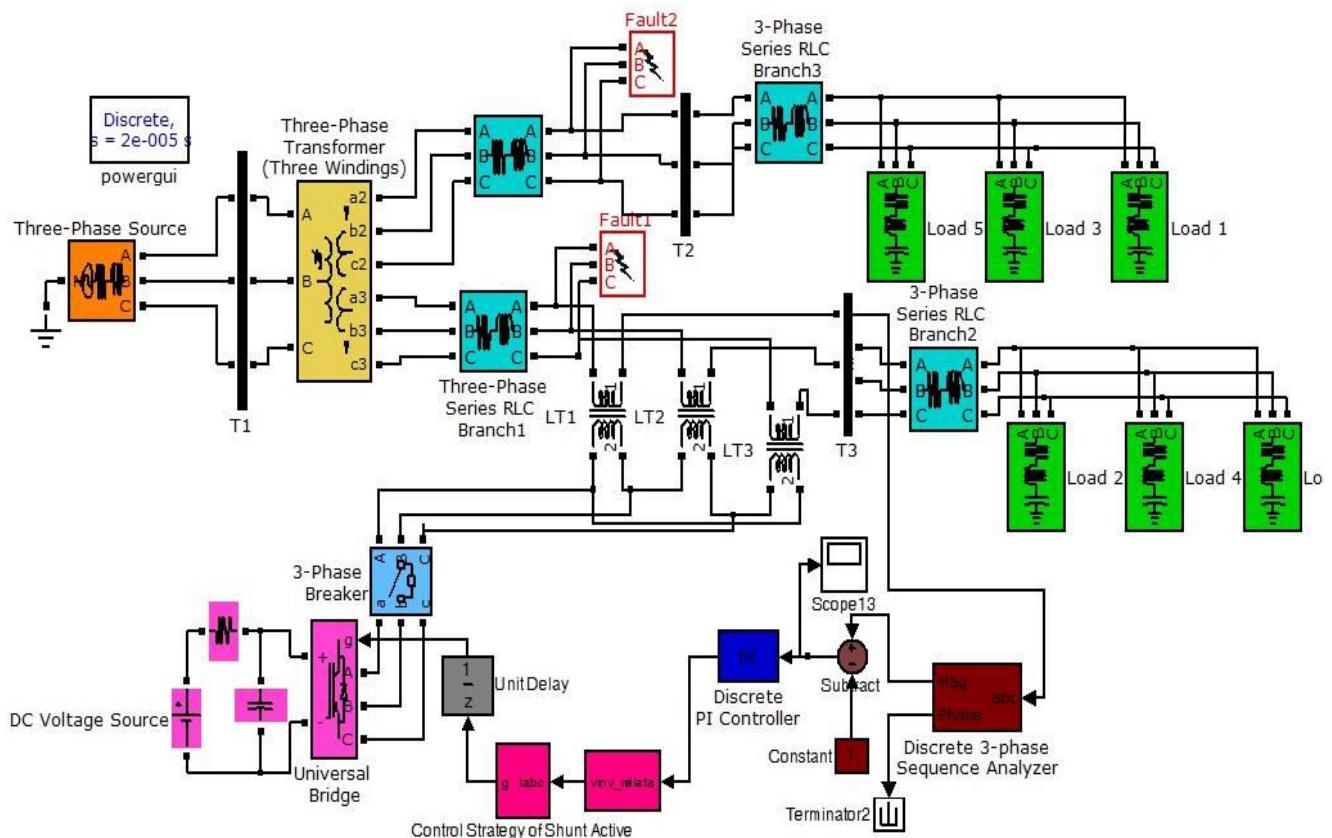


Figure-16. Matlab/Simulink configuration of the proposed DVR system.



6. CONCLUSIONS

A simple, cost effective and fast response custom power device called dynamic voltage restorer (DVR) was proposed to solve power quality problems in a low voltage radial network. The DVR was modelled and simulated using Matlab/Simulink SimPower System Tool Box. The DVR was designed to improve voltage disturbances in a radial network. And from the results obtained, it can be concluded that DVR is a multipurpose device, since it has the capability of mitigating various types of disturbances unlike other power conditioning devices. In addition to that, it can effectively handle both balanced and unbalanced fault conditions without having any difficulties in injecting the appropriate missing component to correct supply voltage so as to keep the load voltage constant. Another important factor observed is that the capacity for power compensation depend on the rating of the DC storage. Therefore the storage capacity should be carefully selected when designing so as to avoid failure of the DVR system.

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