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A Novel Approach to Dynamic Voltage Restorer

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Abstract:
The Dynamic Voltage Restorer (DVR) is one of the most common custom power devices use for the protection of sensitive loads against voltage sag and swell.The main functions of the DVR are the injection of voltage to power line and maintain the pre-sag voltage condition in the load side. Different control strategies are available depending upon the compensation technique. In this paper, emergency control in distribution systems is discussed by using the proposed multifunctional DVR control strategy. Also, the multiloop controllers using the Posicast and P+Resonant controllers is proposed in order to improve the transient response and eliminate the steady-state error in DVR response, respectively. The proposed algorithm is applied to some disturbances in load voltage caused by induction motors starting, and sudden change in load on load side.The innovation here is that the DVR acts as virtual impedance with the main aim of protecting the point of common coupling (PCC) voltage during downstream fault without any problem in real power injection into the DVR. The simulation was carried usingMATLAB/SIMULINK and the results of the simulation show the capability of the DVR to control the emergency of the distribution systems.

Key words: *Custom Power Devices, dynamic voltage restorer (DVR), point of common coupling(PCC), voltage sag, voltage swell*

1. Introduction

The electric power system is considered to be composed of three functional blocks-generation, transmission and distribution. For a reliable power system, the generation unit must produce adequate power supply to meet customer's demand, transmission system must transport bulk power over long distance without overloading system stability and distribution system must deliver power to each customer premises from bulk power systems. Distribution system locates the end of power system and is connected to the customer directly, so the power quality mainly depends on distribution system. In the earlier days, the major focus for power system reliability was on generation and transmission as more capital cost is involved in these. But nowadays distribution system has begun to receive more attention for reliability assessment. The reason behind this is that electrical distribution network failure account for about 90% of the average customer interruptions.

Power distribution systems should provide uninterrupted flow of energy at smooth sinusoidal voltage with constant magnitude level and frequency to their customers. However, in practice, power system, especially the distribution system has numerous nonlinear load which produce power quality problems such as voltage sag/swells, flicker, harmonics distortion, impulse transient and interruptions[1][2]. Among these, two power quality problems such as voltage sag and voltage swell have been identified a major concern to customers. According to IEEE 1959-1995 standard, voltage sag is the decrease of 0.1 to 0.9 p.u. in the rms voltage level at system frequency and with the duration of half a cycle to 1 min.[3]

There are many different methods to mitigate voltage sags and swells, like the introduction of Flexible AC transmission system (FACTS) like static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), interline power flow controller (IPFC), etc. These FACTS devices are designed for the transmission system. But nowadays more attention is on the distribution system for the improvement of power quality, these devices are modified and known as custom power devices. The term custom power pertains to the use of power electronics controller in distribution system specially to deal with various power quality problems. There are many type of custom power device [4]. Some of them are Distributed static compensator (DSTATCOM), Battery Energy Storage System (BESS), Active Power Filter (APF), and Dynamic Voltage Restorer (DVR). Out of these devices Dynamic Voltage Restorer (DVR) is one of the most efficient and effective modern custom power device used in power distribution networks. DVR is the series connected solid state device which compensates the voltage sag/swell at the point of common coupling (PCC) and maintain the load voltage at a desired magnitude and phase[5]. In order to achieve this goal, a DVR injects voltages of suitable magnitude and phase in series with the line. DVR can also add other features like: line voltage harmonics compensation, reduction of transient in voltage and fault current limitation [6] and [7].

2. Dynamic Voltage Restorer

2.1. DVR Components

The basic functions of the DVR are the detection of voltage sag/swell occurred in the power line and injection of balance voltage through injection transformer so as to maintain desired load voltage. This can be achieved either by absorbing or injecting the active and reactive power.It should be noted that when usingthe DVR in real situations, the injection transformer will beconnected in parallel with a bypass switch as shown in Fig. 1. When there is no disturbances in voltage, the injection transformer (hence, the DVR) will be short circuited by this switch to minimize losses and maximize cost effectiveness. A typical DVR-connected distribution system is shown in Fig. 1, where the DVR consists of essentially a series-connected injection transformer, a voltage-source inverter, an inverter output filter, and an energy storage device that is connected to the dc link.

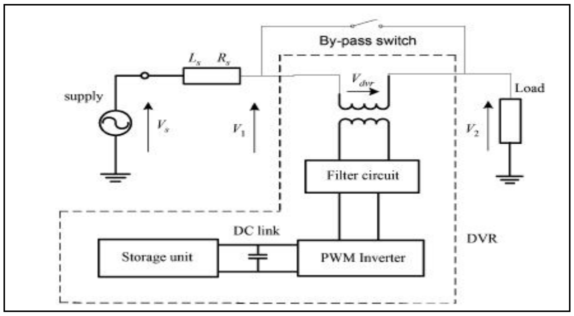


Figure 1: Schematic Diagram of DVR

- Energy Storage Device: This circuit supplies the required energy to the Voltage Source Converter (VSC) via dc link for the generation of injected voltage in the case of sag/swell. Various devices such as Super Conducting Magnetic Energy Storage (SMES), lead acid batteries, flywheels and super capacitors can be used as an energy storage device.
- Voltage Source Converter (VSC): It converts the DC voltage supplied by the energy storage device to a sinusoidal voltage at any required frequency, magnitude and phase angle. There are four main types of switching devices: Metal oxide Semiconductor Field Effect Transistor (MOSFET), Insulated Gate Bipolar Transistor (IGBT) and Integrated Gate Commutated Thyristor(IGCT). Each type has its own benefit and drawbacks. The IGCT is the recent compact device with enhanced performance and consistency that allow building VSC with very large power rating.
- Harmonic Filter: As DVR is a nonlinear device due to VSC switching operation, the possibility of generation of self-harmonics is there. So harmonic filter is also become a part of DVR. It consists of an Inductor and a capacitor. It eliminates the high order harmonic component during DC to AC conversion in VSC which will distort the compensated output voltage.
- Injection Transformer: The primary of the injection transformer is connected in series with the distribution line and the secondary is connected to the DVR power circuit. The primary function of the injection transformer is to increase the voltage supplied by the VSC to a desired level. In addition, the injection transformer also serves the purpose of isolating the DVR circuit to the distribution network.

2.2. Operating Principle of DVR

When the power system of the network is working under normal operating condition i.e. without any fault in the power system, the DVR inject only a small voltage to compensate for the voltage drop of the injection transformer and device losses. However, when voltage sag/swelloccurs in the distributed system, the DVR injects a controlled three phase AC voltage (V_{dvr}) with a certain magnitude and phase angle in series with the AC supply voltage in order to maintain the load voltage as shown in Fig. 2.

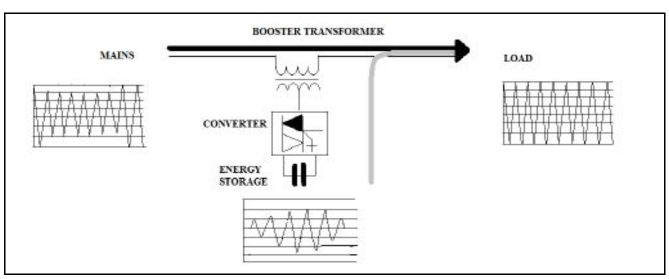


Figure 2: Principal of DVR system

Note that the DVR capable of generating or absorbing reactive power but the active power injection of the device must be provided by an external energy source or energy storage system. The response time of DVR is very short and is limited by the power electronics devices and the voltage sag detection time. The predictable response time is about 2.5 millisecond, and which is much less than some of the traditional methods of voltage correction such as tap-changing transformers [8].

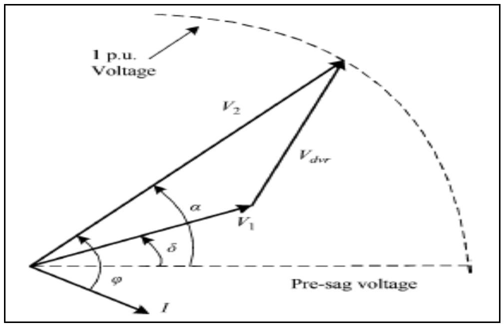


Figure 3: Phasor diagram of the electrical conditions during voltage sag

The phasor diagram in Fig. 3shows the electrical conditions during voltage sag, where, for clarity, only one phase is shown. VoltagesV_1,V_2, andV_{dvr} are the source-side voltage, the load-side voltage, and the DVR injected voltage, respectively. Also, the operators I,φ,δ, andα are the load current, the load power factor angle, the source phase voltage angle, and the voltage phase advance angle, respectively [9]. It should be noted that in addition to the in-phase injection technique, another technique, namely "the phase advance voltage compensation technique" isalso used [9]. One of the advantages of this method over the in-phase method is that less active power should be transferred from the storage unit to the distribution system. This results in compensation for deeper sags or sags with longer durations.

2.3. Equivalent Circuit

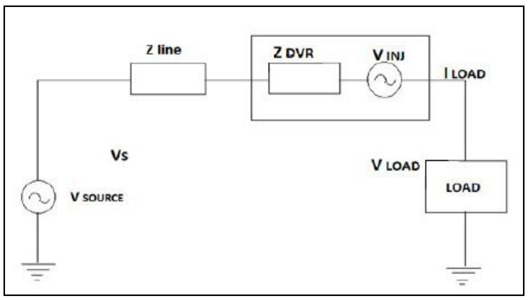


Figure 4: Equivalent circuit diagram of DVR

The Fig 4 shows the Thevenin equivalent circuit of the DVR. Here the impedance Z_{line} depends on the fault level of the load. When the system voltage (V_{source}) drop or reduce from any specific value, the DVR injects a series voltage i.e. V_{dvr} through the injection transformer such that the desired load voltage V_{load} can be maintained. Now the injected voltage of the DVR can be written as

$V_{dvr} = V_{load} + Z_{line} I_{load} - V_{source}$ (1)

Where

V_{load} is thedesired load voltage

Z_{line} is theline impedance

I_{load} is theload current

V_{source} is thesystem voltage during fault condition

If we take I_{load} as I_L, V_{source} as V_{th}, V_{load} as V_L, Z_{line} as Z_{th} then, the load current I_L is given by

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

The load power factor angle θ is given by

$\theta = \tan^{-1}(Q_L / P_L)$ (3)

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

$V_{dvr}\angle\alpha = V_L\angle 0 + I_L Z_{th}\angle(\beta - \emptyset) - V_{th}\angle\delta$ (4)

Where α, β, δ are angles of V_{dvr}, Z_{th}, V_{th} respectively, and $\emptyset$ is load power angle. The complex power injection of the DVR can be written as,

$S_{dvr} = V_{dvr} I_l^*$ (5)

From the above equation, it is clear that when the injected voltage V_{dvr} is in quadrature with I_L, DVR require only reactive power and the DVR itself generate the reactive power. Other phase relationship between V_{dvr} and I_L require active power injection which must be provided by the energy storage of DVR system.

3. DVR Control Scheme

3.1. Existing Sag Compensation Control

The primary existing control structure for a typical DVR sag compensation system is based on a combination of supplyvoltage feed forward and a polarization index (PI) $d-q$ load voltage feedback. A software-based phase-locked loop(PLL) is used to create $d-q$ coordinate sinusoidal referencesfrom the supply, which are used to determine the target phase ofthe output voltages. The phase of these references is controlledto only vary slowly during transients from their presag valuesto minimize phase jump effects. The feed forward control thencalculates the appropriate modulation depth to inject compensatingvoltages between the supply voltages (V_{supply}) and theload voltages (V_{Load}) to restore the load voltages to the targetreferences. However, this does not account for the voltagedrop across the filter inductor and other parameters such asthe transformer, and, hence, closed loop load voltage feedbackcontrol is then added in the $d-q$ frame to minimize any steady state error in the fundamental component.

When the grid voltage is normal, the DVR system is held ina null state to lower its losses. When voltage sag is detected,the DVR switches into active mode to react as fast as possibleto inject the required alternating current (ac) voltages betweenthe grid and the load. The sag detection strategy is based on theroot mean square (rms) of the error vector, which allows for thedetection of symmetrical and nonsymmetrical sags as well as anyassociated phase jump.

3.2. Proposed Compensation Control

The basic functions of a controller in a DVR are (i) detection of voltage sag/swell events in the system (ii) computation of correcting voltage and (iii) generation of trigger pulses to the sinusoidal PWM based DC-AC inverter. In this paper, a multifunctional control system is proposed in which the DVR protects the load voltage using Posicastand P+Resonant controller. The Posicast controller is a kind of step function with two parts and is used to improve the damping of the transient oscillations initiated at the start instant from the voltage sag. The P+Resonant controller consists of a proportional function plus a resonant function and it eliminates the steady-state voltage tracking error [10].

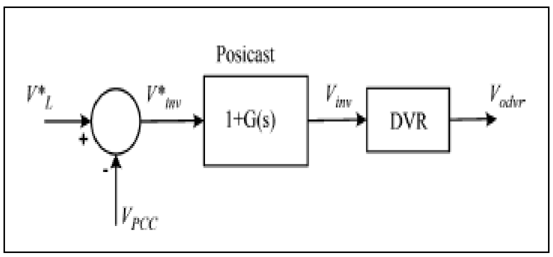


Figure 5: Open loop control using the Posicast controller

The Posicast controller is used in order to improve the transient response. Fig. 5 shows a typical control block diagram ofthe DVR. Note that because in real situations, we are dealing with multiple feeders connected to a common bus, namely “the Point of Common Coupling (PCC)”. As shown in the figure, in the open-loop control, the voltage on the source side of the DVR (V_{pcc}) is compared with a load-side reference voltage (V_L^*) so that the necessary injection voltage (V_{inv}^*) is derived. A simple method to continue is to feed the error signal into the PWM inverter of the DVR. But the problem with this is that the transient oscillations initiated at the start instant from the voltage sag could not be damped sufficiently. To improve the damping, as shown in Fig. 5, the Posicast controller can be used just before transferring the signal to the PWM inverter of the DVR. The transfer function of the controller can be described as follows:

$$1+G(s) = 1+\frac{\delta}{1+\delta}(e^{-sTd/2} \; -1) \qquad (6)$$

where δ and Td are the step response overshoot and the period of damped response signal, respectively as shown clearly in Fig. 6**.**

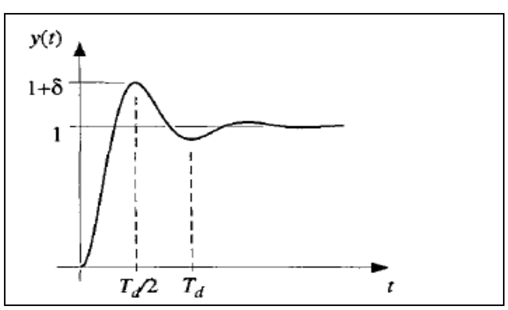


Figure 6: Step response of a damped system

It should be noted that the Posicast controller has limited high-frequency gain; hence, low sensitivity to noise. The Posicast controller works by pole elimination and proper regulation of its parameters is necessary. For this reason, it is sensitive to inaccurate information of the system damping resonance frequency. To decrease this sensitivity, as is shown in Fig. 7, the open-loop controller can be converted to a closed-loop controller by adding a multiloop feedback path parallel to the existing feed forward path. Inclusion of a feed forward and a feedback path is commonly referred to as two-degrees-of-freedom (2-DOF) control in the literature.To eliminate the steady-state voltage tracking error (V_L-V_L^*), a computationally less intensive P+Resonant compensator is added to the outer voltage loop. The ideal P+Resonant compensator can be mathematically expressed as

$G_R(s)=k_p+\frac{2k_i s}{s^2+w_o^2}$ (7)

where k_p and k_i are gain constants and w_o=2π*50 rad/sec is the controller resonant frequency.The ideal resonant controller, however, acts like a network with an infinite quality factor, which is not realizable in practice. A more practical (non-ideal) compensator is therefore used here, and is expressed as

$G_R(s)=k_p+\frac{2k_i w_{cut} s}{s^2+w_o^2+2w_{cut} s}$ (8)

where w_{cut} is the compensator cutoff frequency

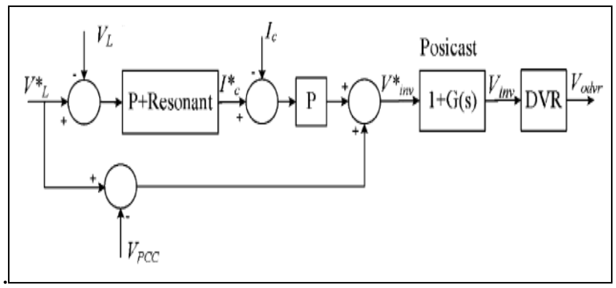


Figure 7: Multiloop control using Posicast and P+Resonant controllers

In order to mitigate the simulated voltage sag/swell a Discrete PWM-based control scheme is implemented. This control system only measures the rms voltage at the load point and exerts voltage angle control as follows: an error signal is obtained by comparing the reference voltage with the rms voltage measured at the load point. The Posicastand P+Resonant controller processes the error signal and generate the required angle δ to drive the error to zero. In the PWM Generators, the sinusoidal voltage,$V_{control}$, is compared against a triangular signal (carrier) in order to generate the switching signals of the VSC valves. The modulating angle δ or delta is applied to the PWM generators in phase A, whereas the angles for phase B and C are shifted by 240^0 or -120^0 and 120^0 respectively.

$V_a = \sin(wt+\delta)$ (9)

$V_b = \sin(wt+\delta-2\pi/3)$ (10)

$V_c = \sin(wt+\delta+2\pi/3)$ (11)

Since the custom power is relatively low power application, PWM methods offer a more flexible option than the fundamental frequency switching (FFS) methods favored in FACTS application.

4. Simulation Results

Fig. 8 depicts a single line diagram of the power system which is used to evaluate the performance of the proposed DVR control system under different fault scenarios, using the MATLAB/SIMULINK software environment. Parameters of the simulated power system and the DVR are given in Appendix. In this paper, two different loads are considered. One is the resistive-inductive(R-L) load as sudden change in load is one of the reasons of voltage sag/swell. The second one is Induction Motor as during the starting of the induction motor, it draws current up to 10-15 times the rated current.

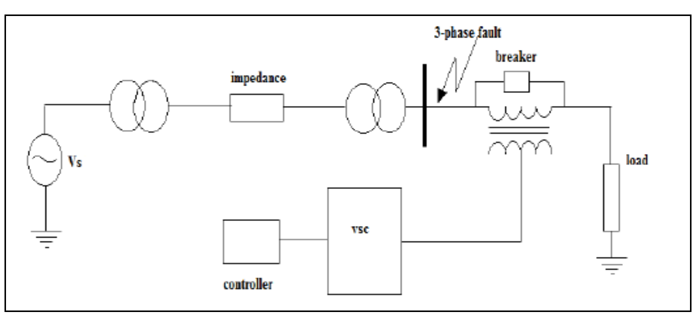


Figure 8: Single line diagram of the system used for simulation studies

4.1. Resistive-Inductive Load (R-L load)

The sudden change in the Resistive-Inductive load (R-L load) is one of the causes of voltage sag. Fig. 9 and Fig. 11 show the output of the load voltage before and after connecting of the Dynamic Voltage Restorer whereas Fig. 10 shows the voltage injected by the DVR. The source side voltage is 240 volt phase-phase. The three phase voltage sag is simulated for 0.3s to 0.9s.

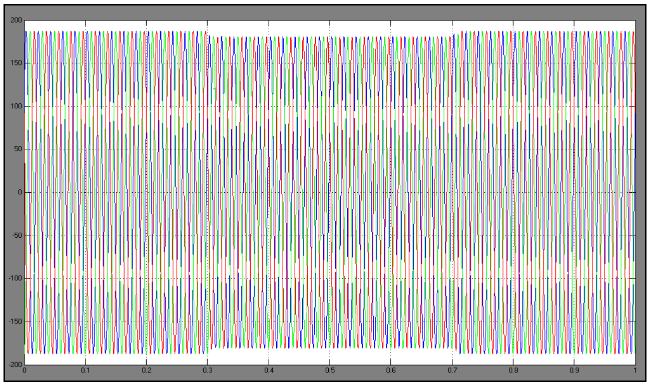


Figure 9: Three phase voltage sag

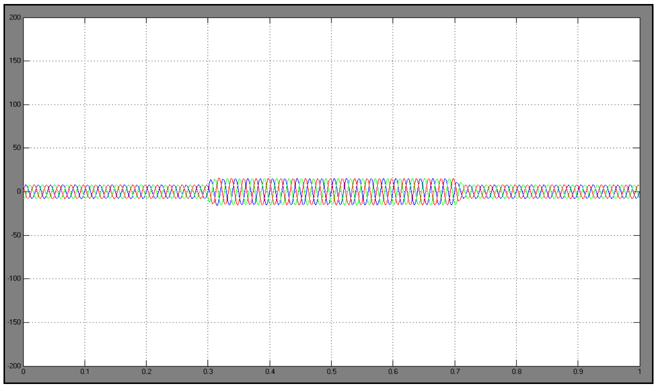


Figure 10: Voltage injected by DVR

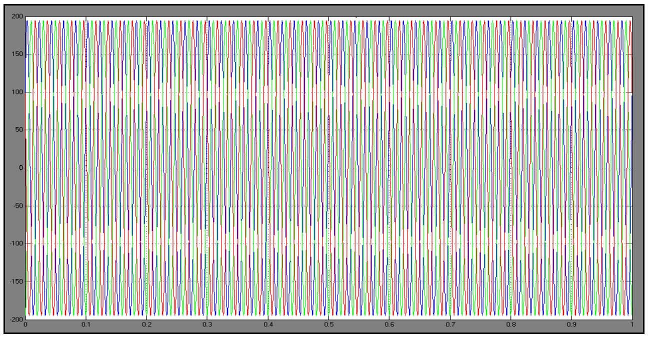
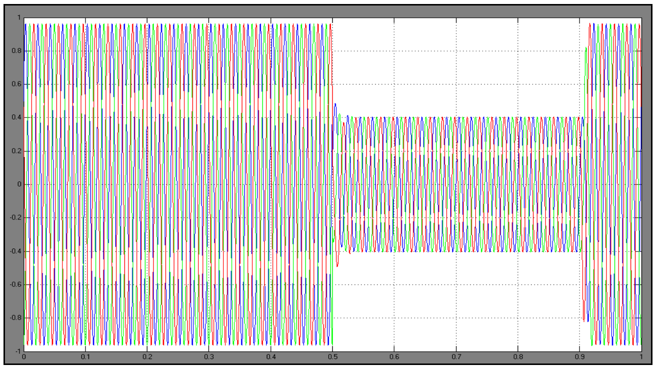


Figure 11: Load voltage after connecting DVR

As from the definition of voltage sag, it is defined as "the reduction in rms voltage to a value which is between 0.1 and 0.9 p.u and lasting for duration 0.5 cycle to 1 minute". So between the per unit value of 0.1 to 0.9, DVR is capable to compensate the voltage sag. The proposed algorithm is applied to two different kind of sagged voltage of magnitude of 0.4 and 0.585 per unit. The Fig. 12, Fig. 15 and Fig. 14, Fig. 17show the voltage before and after connecting the DVR, whereas the Fig. 13 and Fig. 16 show the voltage injected by DVR. The time duration for the magnitude of 0.4 p.u voltage sag is 0.5s to 0.9s, whereas for 0.585 p.u voltage sag, it is 0.5s to 0.6s.



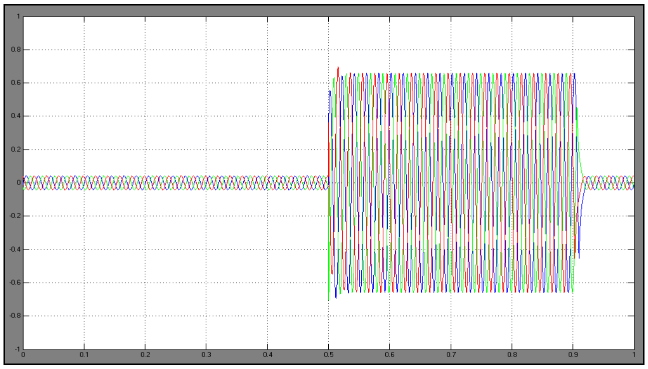


Figure 12: Voltage sag with the magnitude of 0.4 p.u

Figure 13: Voltage injected by DVR

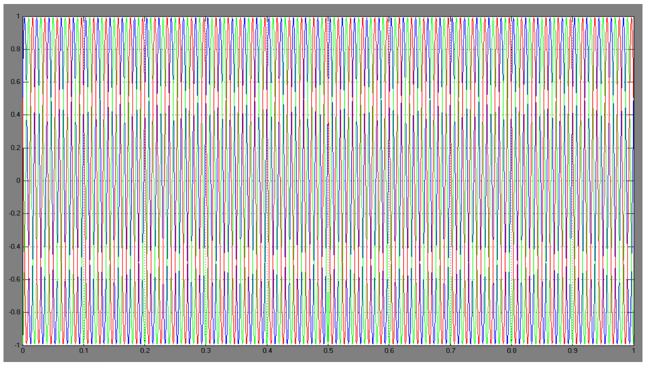
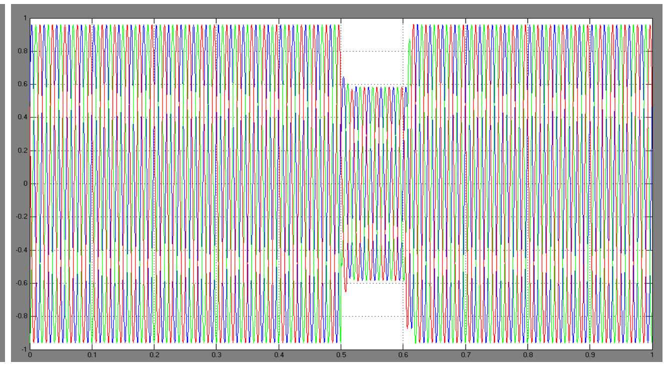



Figure 14: Load voltage after connecting DVR

Figure 15: Load voltage with sag magnitude of 0.585 p.u before connecting DVR

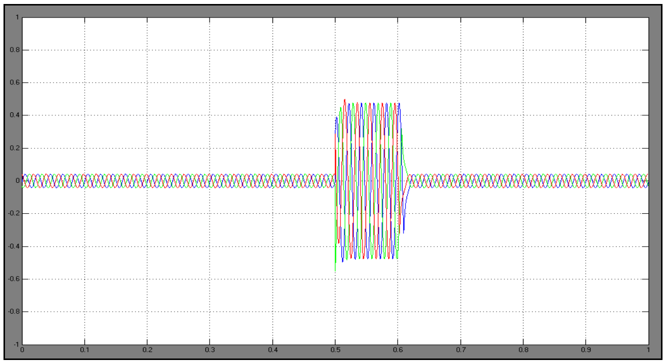


Figure 16: Voltage injected by DVR

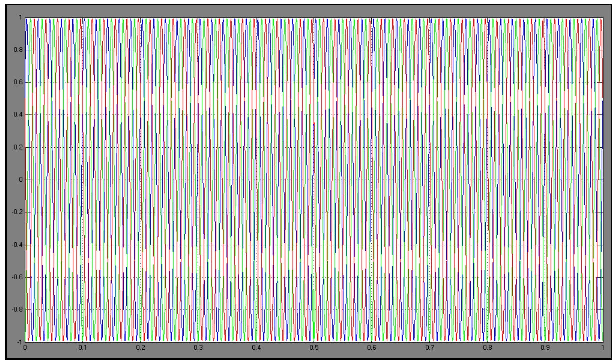


Figure 17: Output voltage after DVR injecion

4.2. Three phase Induction Motor

As an induction motor draw huge amount of current at the starting period,usually 10-15 times the rated current,so it is one of the major cause of voltage sag in distribution system. The Fig. 18 and Fig. 20 show the output voltage of the three phase induction motor before and after connecting DVR whereas Fig. 19 show the compensated output after connecting DVR.

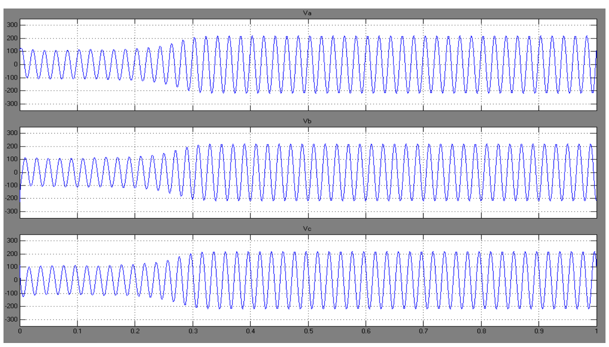
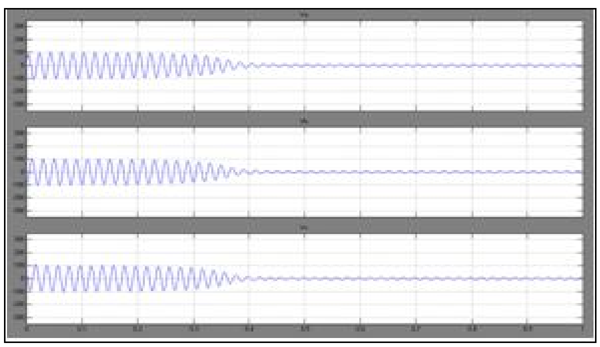



Figure 18: Individual phase representaton of load voltage of induction motor without connecting DVR

Figure 19: Voltage injected by DVR for each phase representation

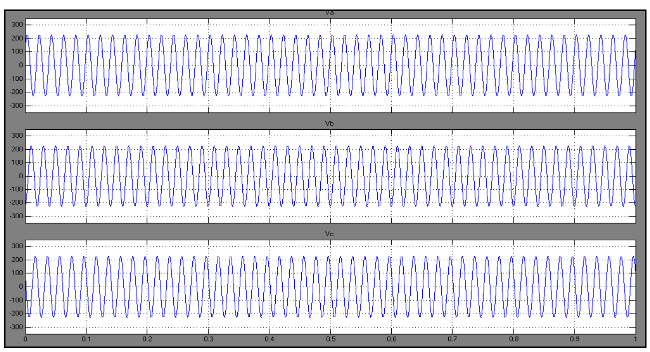


Figure 20: Load Voltage of each phase of induction motor after connecting DVR

5. Conclusion

In this paper, a fast and cost effective Dynamic Voltage Restorer (DVR) is proposed for mitigating the problem of voltage sag or dip in distribution system, and a closed-loop system is used for its control to improve the damping of the DVR response. Also, for further improving the transient response and eliminating the steady state error, the Posicast and P+Resonant controllers are used. The simulation results using MATLAB/SIMLINK verify the effectiveness and capability of the proposed DVR in compensating the voltage sag caused by nonlinear resistive-inductive(R-L) load and the large induction motor starting load.

6. Appendix

Sr. no.	System quantities	Standards
1	Source	3 phase, 240 V(ph-ph), 50 Hz
2	Inverter parameters	IGBT based,3 arms, 6 pulse Switching frequency=5KHz
3	Controller parameters	δ=1,T_d=41.6μs,K_p=1,K_i=100, w_o=314 rad/s,w_{cut}=1.0 rad/s
4	Transmission side Transformer	240/240e3(Yn-Yn)
5	Distribution transformer	240e3/240(Δ-Yg)

Table 1: System Parameters

Load 1 Change in Resistive-Inductive (R-L) Load	Case1 R=6,L=60e-3 to R=12,L=120e-3 Case 2 R=1,L=60e-3 to R=2,L=60e-12 Case 3 R=0.5,L=60e-3 to R=1,L=60e-12
Load 2 Induction Motor as a load	Rated Power=20HP(15KW) Rated Voltage=400v Rated Frequency=50Hz Rated Speed=1460 Rpm

Table 2: Load Parameter

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