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Design and Simulation of a Novel Self Supported Dynamic Voltage Restorer (DVR) for Power Quality Improvement

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Abstract—Power quality is one of the major concerns in the present era. The problem of voltage sags and swells and its major impact on sensitive loads are well known. To solve this problem, custom power devices are used. One of those devices is the Dynamic Voltage Restorer (DVR), which is one of the most efficient and effective modern custom power devices used in power distribution networks. A new control algorithm for the DVR is proposed in this paper to regulate the load terminal voltage during sag, swell in the voltage at the point of common coupling (PCC).

This new control algorithm is based on synchronous reference frame theory (SRF) along with PI controller is used for the generation of reference voltages for a dynamic voltage restorer (DVR). These voltages, when injected in series with a distribution feeder by a voltage source inverter (VSI) with PWM control, can regulate the voltage at the load terminals against any power quality problem in the source side. It first analyzes the power circuit of the system in order to come up with appropriate control limitations and control targets for the compensation voltage control through the DVR. The control of the DVR is implemented through derived reference load terminal voltages. The proposed control scheme is simple to design. Simulation results carried out by MATLAB with its Simulink and Sim Power System (SPS) toolboxes to verify the performance of the proposed method.

Index Terms— DVR, IGBT, MATLAB/SIMULINK, Power Quality, Synchronous Reference Frame Theory, Voltage sags/swells, VSI,

1 INTRODUCTION

POWER distribution systems, ideally, should provide their customers with an uninterrupted flow of energy at smooth sinusoidal voltage at the contracted magnitude level and frequency [1] however, in practice, power systems, especially the distribution systems, have numerous nonlinear loads, which significantly affect the quality of power supplies. As a result of the nonlinear loads, the purity of the waveform of supplies is lost. This ends up producing many power quality problems. Apart from nonlinear loads, some system events, both usual (e.g. capacitor switching, motor starting) and unusual (e.g. faults) could also inflict power quality problems [2]. Power quality phenomenon or power quality disturbance can be defined as the deviation of the voltage and the current from its ideal waveform. Faults at either the transmission or distribution level may cause voltage sag or swell in the entire system or a large part of it. Also, under heavy load conditions, a significant voltage drop may occur in the system. Voltage sag and swell can cause sensitive equipment to fail, shutdown and create a large current unbalance. These effects can incur a lot of expensive from the customer and causeequipment damage [1]. The voltage dip magnitude is ranged from 10% to 90% of nominal voltage and with duration from half a cycle to 1 min and *swell* is defined as an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. typical magnitudes are between 1.1 and 1.8 p.u [2].

There are many different methods to mitigate voltage sags and swells, but the use of a custom power device is considered to be the most efficient method, e.g. FACTS for transmission systems which improve the power transfer capabilities and stability margins. The term custom power pertains to the use of power electronics controller in a distribution system [10], especially, to deal with various power quality problems. There are different types of Custom Power devices used in electrical network to improve power quality problems. Each of the devices has its own benefits and limitations. A few of these reasons are as follows. The SVC pre-dates the DVR, but the DVR is still preferred because the SVC has no ability to control active power flow [3]. Another reason include that the DVR has a higher energy capacity compared to the SMES and UPS devices. Furthermore, the DVR is smaller in size and cost is less compared to the DSTATCOM and other custom power devices. Based on these reasons, it is no surprise that the DVR is widely considered as an effective custom power device in mitigating voltage sags. In addition to voltage sags swells compensation, DVR can also add other features such as harmonics and Power Factor correction. Compared to the other devices, the DVR is clearly considered to be one of the best economic solutions for its size and capabilities [4].

The voltage injection schemes and design of the self-supported DVR and the different control strategies for the controllers of the DVR have been discussed in [14-16]. E.g, adaline based fundamental extraction have been implemented in [14]. Instantaneous symmetrical component theory [16], space vector modulation, synchronous reference frame theory (SRFT) [15] based control techniques for a DVR are reported in this literature. In this paper, a new control algorithm is

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suggested based on SRF theory which includes P-I Controller for the generation of reference Vd and Vq. Reference load signal generation involves the conversion from three-phase to two-phase and vice versa. Moreover low pass filters are essential part of this algorithm which has slow dynamic response of the compensator.

The organization of the paper is as follows. In section 2, the constructional part of the DVR is briefly described, the operating principle and the voltage injection capabilities of the DVR is discussed in section 3, proposed control algorithm enumerated in section 4 and the detailed description of MATLAB Simulation model along with its performance in electrical network for different power quality problems discussed in section 5 and section 6 respectively.

2 Dynamic Voltage Restorer

A Dynamic Voltage Restorer (DVR) is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and critical load feeder [9]. The basic structure of a DVR is shown in Fig.1.

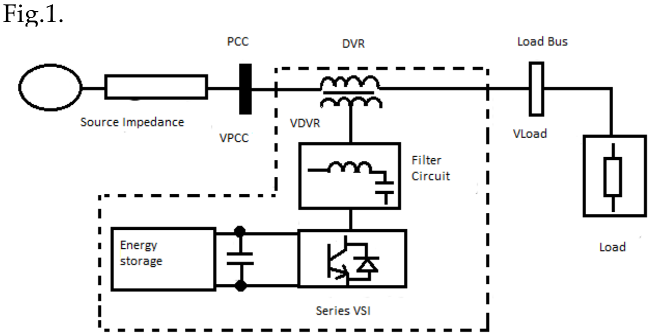

Figure-1: *DVR series connected topology*

It is divided into six categories [9]: (i) *Injection Transformer:* The Injection transformer is a specially designed transformer that attempts to limit the coupling of noise and transforms energy from the primary side to the secondary side. (ii) *Harmonic Filters:* Filters are used to convert the inverted PWM waveform into a sinusoidal waveform by eliminating the unwanted harmonic components generated by VSI action. (iii) *Inverter:* A VSI is a power electronic system which consists of a storage device and switching device, which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle from dc storage. IGBT is a three terminal controllable switch that combines the fast switching times of the MOSFET with the high voltage capabilities of the GTO used as a switching device in VSI. The voltage and current rating of IGBT is 4500 volts and 1200 Amps respectively. [6]. (iv) *Energy Storage Unit:* The purpose is to supply the necessary energy to the VSI via a dc link for the generation of injected voltages (v) *Capacitor:* DVR has alarge DC capacitor to ensure stiff DC voltage input to inverter. (vi) *By-Pass Switch:* If the over current on the load side exceeds a permissible limit due to short circuit on the load or large inrush current, the DVR will be isolated from the system by using the bypass switches and supplying another path for current.

3 Operating Principle of DVR

The schematic diagram of a self-supported DVR is shown in Figure-2[5]. Three phase source voltages (Vsa, Vsb, and Vsc) are connected to the 3-phase critical load through series impedance (Za, Zb, Zc) and an injection transformer in each phase. The terminal voltages (Vta, Vtb, Vtc) have power quality problems and the DVR injects compensating voltages (VCa, VCb, VCc) through an injection transformer to get undistorted and balanced load voltages (VLa, VLb, VLc). The DVR is implemented using a three leg voltage source inverter with IGBTs along with a dc capacitor (Cdc). A ripple filter (Lr, Cr) is used to filter the switching ripple in the injected voltage. The considered load, sensitive to power quality problems is a three-phase balanced lagging power factor load. A self-supported DVR does not need any active power during steady state because the voltage injected is in quadrature with the feeder current.

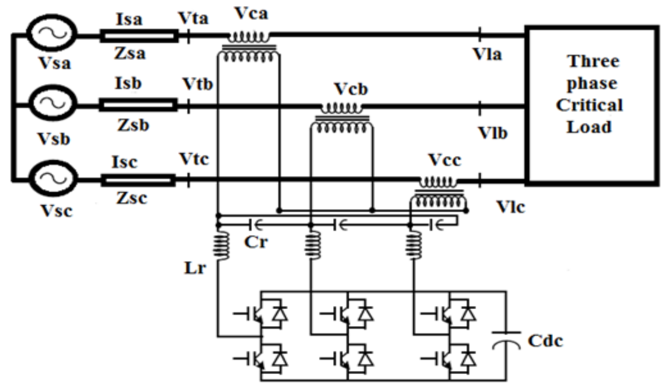

Figure-2: *Schematic diagram of self-supported DVR*

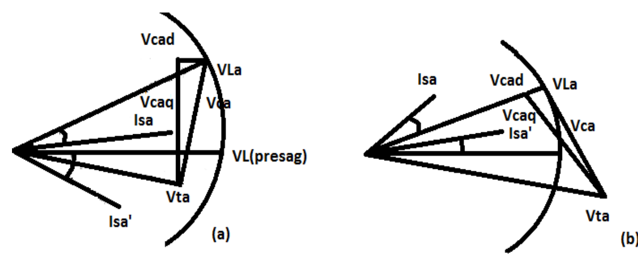

Figure-3: Phasor Diagram for (a) Voltage Sag (b) Voltage Swell

The DVR operation for the compensation of sag, swell in supply voltages is shown in Figure-3. Before sag the load voltages and currents are represented as VL (presag) and Isa′ as shown in Figure-3(a). After the sag event, the terminal voltage (Vta) is gets lower in magnitude and lags the presag voltage by some angle. The DVR injects a compensating voltage (VCa) to maintain the load voltage (VL) at the rated magnitude. VCa has two components, VCad and VCaq. The voltage in-phase with the current (VCad) is required to regulate the dc bus voltage and also to meet the power loss in the VSI of DVR and an injection transformer [5]. The voltage in quadrature with the current (VCaq) is required to regulate the load voltage (VL) at constant magnitude. During swell event, the injected voltage (VCa) is such that the load voltage lies on the locus of the circle as shown in Figure-3(b).

4 Controller of DVR

The basic functions of a controller in a DVR are the detection of voltage sag/swell events in the system; computation of the correcting voltage, generation of trigger pulses to the PWM based DC-AC inverter, correction of any abnormalities in the series voltage injection and termination of the trigger pulses when the event has passed.

The compensation for voltage sags using a DVR can be performed by injecting/absorbing reactive power or real power. When the injected voltage is in quadrature with the current at the fundamental frequency, compensation is achieved by injecting reactive power and the DVR is self-supported with dc bus. But, if the injected voltage is in phase with the current, DVR injects real power and hence a battery is required at the dc side of VSI. The control technique adopted should consider the limitations such as the voltage injection capability (inverter and transformer rating) and optimization of the size of energy storage [4].

Conventional Sag Detection method: The DVR works independently when disturbances occur in the system, provided that the whole system remains connected to the supply grid, i.e. the line breaker does not trip. This open loop control algorithm in Figure-4 based on the comparison between supply side voltages with reference voltage. The voltage sags is detected when the supply drops below 20% of the reference value whereas voltage swells is detected when supply voltage increases up to 25% of the reference value. The error signal is used to generate the commutation pattern for the power switches (IGBT's) constituting the voltage source inverter. Park's transformation [6] is used to control of DVR. The dqo method gives the sag depth and phase shift information with start and end times. The quantities are expressed as the instantaneous space vectors. Firstly convert the voltage from a-b-c reference frame to d-q-o reference. For simplicity zero phase sequence components is ignored. The detection is carried out in each of the three phases.

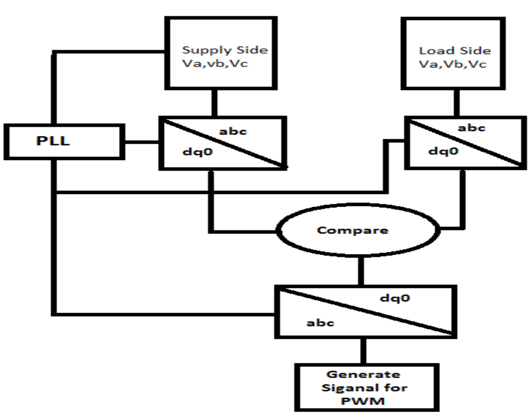

Figure-4: *Control Algorithm for conventional DVR Controller*

Proposed control method: Figure-5 shows the proposed control algorithm based on the comparison between reference load voltage and original load voltage. This is a closed loop system which requires DC link voltage of DVR and amplitude of load voltage to generate direct axis and quadrature axis voltages. When the load voltage drops or increases 10% of its reference load voltage in one or three phases of the system then the error signal generated by the DVR controller to create the PWM waveform for 6-pulse IGBT device.

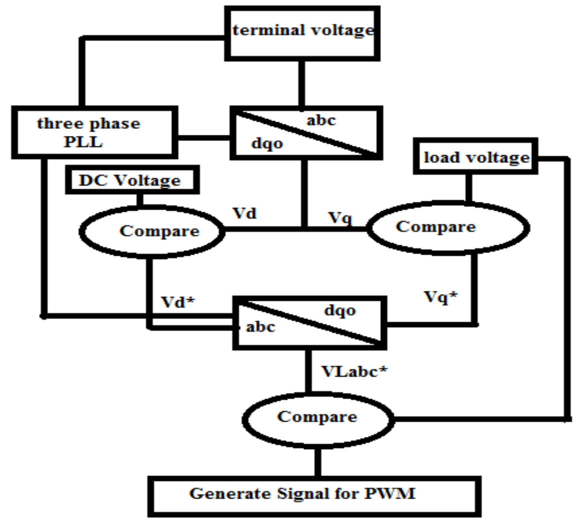

Figure-5: *Proposed Control Algorithm for DVR Controller*

Figure-6 shows the control block of the proposed DVR in which the synchronous reference frame (SRF) theory is used for the control of self-supported DVR. The voltages at PCC (Vt) are converted to the rotating reference frame using the abc-dqo conversion. The harmonics and the oscillatory components of voltages are eliminated using low pass filters (LPF). The components of voltages in d-axis and q-axis are,

$$\mathbf{Vsd = Vsd\ dc + Vsd\ ac}$$
$$\mathbf{Vsq = Vsq\ dc + Vsq\ ac}$$

The compensating strategy for compensation of voltage quality problems considers that the load terminal voltage should be of rated magnitude and undistorted.

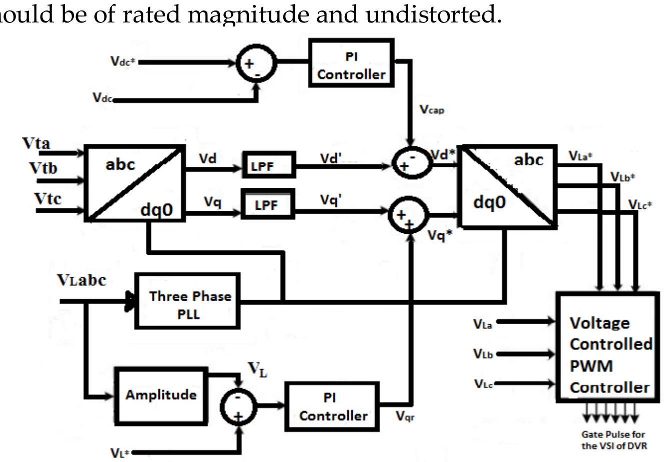

Figure-6: *Control Block of DVR using SRF method of Control*

The sag and swell in terminal voltages are compensated by controlling the DVR and the proposed algorithm inherently provides a self-supporting dc bus for the DVR. Three-phase reference supply voltages (VLa*,VLb*,VLc*) are derived using the sensed load voltages (VLa,VLb,VLc), terminal voltages (Vta, Vtb,Vtc) and dc bus voltage (Vdc) of the DVR as feedback signals. The synchronous reference frame theory based method is used to obtain the direct axis (Vd) and quadrature axis (Vq) components of the load voltage. The load voltages in the three-phases are converted into the d-q-0 frame using the Park's transformation [6]. A three-phase PLL (phase locked loop) is used to synchronize these signals with the terminal voltages (Vta, Vtb, and Vtc). The d-q components are then passed through low pass filters to extract the dc components of Vd` and Vq`. In order to maintain the DC bus voltage of the self-supported DVR, the error between the reference dc capacitor voltage (Vdc*) and the sensed dc bus voltage (Vdc) of DVR is given to a PI controller of which output (Vcad) is considered as the loss component of voltage and is added to the dc component of Vd` to generate Vd*. The reference d-axis load voltage is therefore as,

$$Vld^* = Vsd\ dc - Vloss$$

Similarly, a second PI controller is used to regulate the amplitude of the load voltage (VL). The amplitude of load voltage (VL) at point of common coupling is calculated from the ac voltages (VLa, VLb, VLc) as,

$$VL = \sqrt{\left(\tfrac{2}{3}\right)}\sqrt{VLa^2 + VLb^2 + VLc^{\wedge}2}$$

The amplitude of the load terminal voltage (VL) is employed over the reference amplitude (VL*) and the output of PI controller is considered as the reactive component of voltage (Vqr) for voltage regulation of load terminal voltage added with the dc component of Vq` to generate Vq*.The reference q-axis load voltage is therefore as,

$$Vlq^* = Vsq\ dc + Vqr$$

The resultant voltages (Vd*, Vq*, Vo) are again converted into the reference supply currents using the reverse Park's transformation. Reference supply voltages (VLa*, VLb*, VLc*) and the sensed load voltages (VLa, VLb, VLc) are used in PWM current controller to generate gating pulses for the switches.

5 MATLAB Modelling and Simulation

The DVR is modeled and simulated using the MATLAB and its Simulink and Sim Power System toolboxes. The MATLAB model of the DVR connected system [14] is shown in Figure-7. A three-phase programmable voltage source is connected to the three-phase load through the DVR in order to generate sag, swell and harmonics in supply side. The considered load is a lagging power factor load. DVR consists of a PWM inverter circuit and a DC Voltage source connected at the DC Link of VSI. The IGBT based PWM VSI is modeled using Universal Bridge Block from Power Electronics subset of Power System Block-set. In addition, a ripple filter for filtering the switching ripple in the terminal voltage is connected to the utility supply via wye-open connected series transformer. The dc bus capacitor of DVR is selected based on the transient energy requirement and the dc bus voltage is selected based on the injection voltage level. The dc capacitor decides the ripple content in the dc voltage. The system data are given in Appendix.

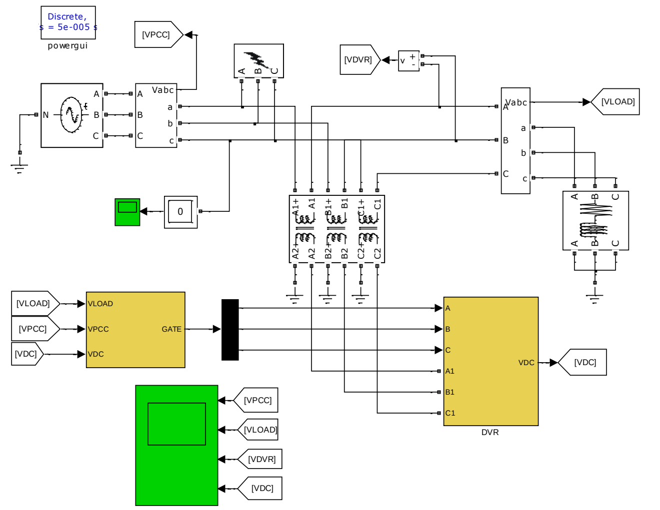

Figure-7: *MATLAB model of DVR connected system*

The control algorithm for the DVR is simulated in MATLAB. The block diagram shown in Figure-6 is modeled for DVR control of Figure-7. The reference load voltages are derived from the sensed terminal voltages, load supply voltages and the dc bus voltage of the DVR. Once a voltage disturbance occurs, with the aid of dqo transformation based control scheme, the inverter output can be steered in phase with the incoming ac source while the load is maintained constant. As for the filtering scheme of the proposed method, output of inverter is installed with capacitors and inductors. A pulse width modulation controller is used over the reference and sensed load voltages to generate gate signals for the IGBT's of the VSI.

6 Performance of the DVR System

The performance of the DVR is demonstrated for different supply voltage disturbances such as sag and swells at terminal voltages [3]. Figure-8(a) shows the transient performance of the system under voltage sag and swells conditions. At 0.12 sec, 50% voltage sag is created in supply side for the duration of 0.13 sec and at 0.3 sec 50% voltage swell is created in terminal voltage side for the duration of 0.1 sec. It is observed that the load voltage is regulated to constant amplitude under both sag and swell conditions. Figure-8(c) shows in the case of voltage sag, which is a condition of a temporary reduction in supply voltage, the DVR injects an equal positive voltage component in all three phases which are in phase with the supply voltage to correct it. On the other hand, for a voltage swell case, which is a condition of a temporary increase in supply voltage, the DVR injects an equal negative voltage in all three phases which are anti-phase with the supply voltage.the in-phase injection of voltage by the DVR. The load voltage is maintained sinusoidal by injecting or absorbing proper compensation voltage by the DVR shown in Figure-8(b). As a result of DVR, the load voltage is kept at 1 p.u. throughout the simulation, including the voltage sag and swell period. It is observed that during normal operation, the DVR is not operational. It quickly injects necessary voltage components to smoothen the load voltage upon detecting voltage sag.

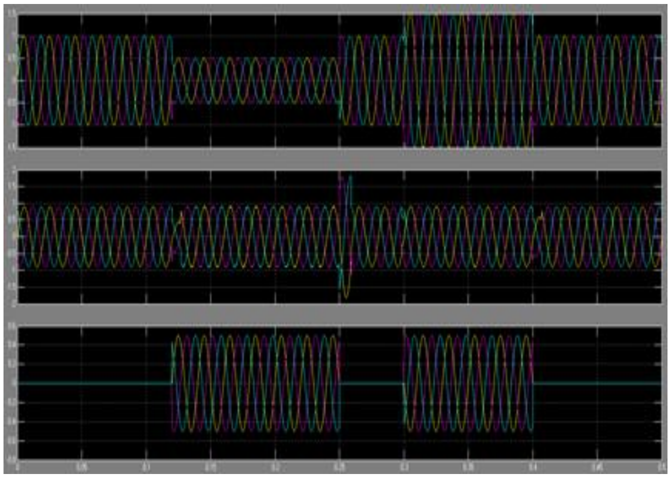

Fig- Voltage Waveforms during 50% voltage Sag and Swell

Figure-9(a) shows the first simulation was done without DVR and a three phase fault is applied to the system at point with fault resistance of 0.66Ω for a time duration of 200 ms. Figure-9(b) shows The second simulation is carried out at the same scenario as above but a DVR is now introduced at the load side to compensate the voltage sag occurred due to the three phase fault applied.

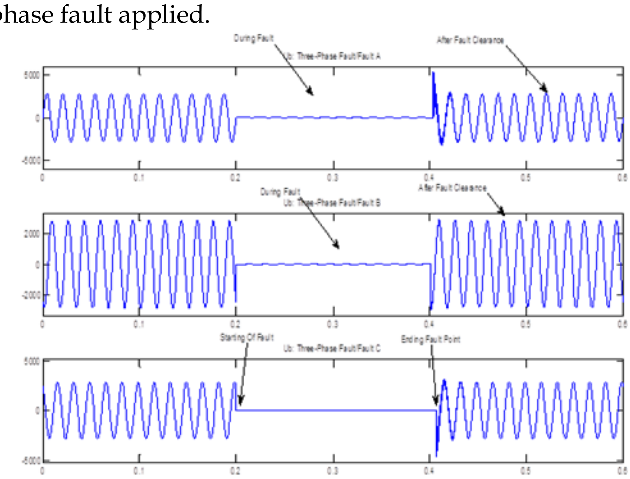

Fig.-9(a) Three phase fault without DVR

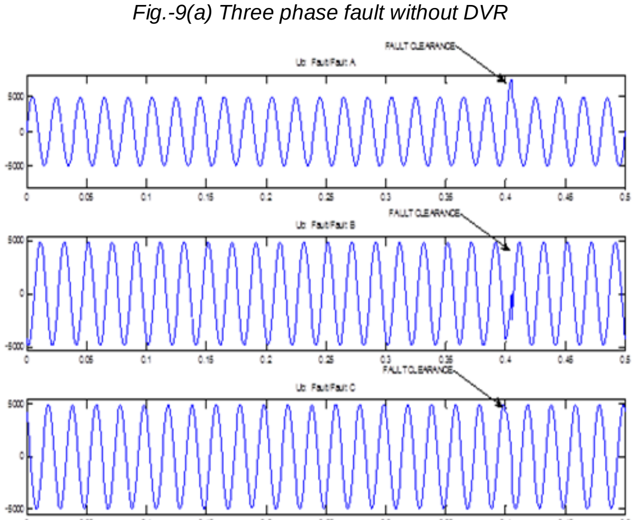

Fig.-9(b): Three phase fault with DVR voltage compensation

The harmonic compensation in load voltage achieved and depicted in Figure-10(a) and 10(b). The terminal voltage is distorted by adding 5th harmonic inversely proportional to their harmonic number. The load voltage is sinusoidal and constant in magnitude due to the injection of opposite harmonic voltage by DVR.

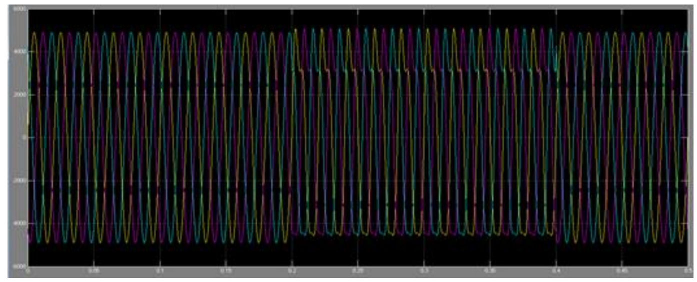

Fig.-10(a) Supply Side Voltage adding with Harmonics

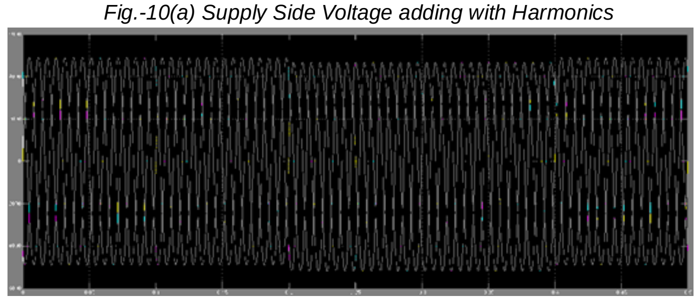

Fig.-10(b) Load Side Voltage after Harmonics Compensation

Table I: Comparison of DVR Rating for different Sag Mitigation

	Conventional Sag Detection Method	Proposed Sag Detection Method
Phase Voltage (V)	100	135
Phase Current (A)	18	18
VA per Phase	1800	2430
KVA (% of Load)	43.25%	58.65%

Table II: THD (Frequency=50 Hz) for different Sag Mitigation Method

	PCC Voltage (V)	THD	Supply Current (A)	THD	Load Voltage (V)	THD
Conventional Method	280.8	7.21	22.15	2.05	380.8	1.55
ProposeMethod	280.8	5.96	20.12	1.18	410.8	0.88

Appendix

AC line voltage: 415 V, 50 Hz
Load: 10KVA, 0.80 pf lag
PI Controller: Kp = 5 Ki = 120
DC voltage of DVR: 300V
Harmonic Filter: Lr = 2.0mH, Cr = 10μF, Rr = 4.8Ω
PWM Switching Frequency: 1080Hz
Injection Transformer: Turns Ratio=1:1
Inverter: IGBT based 3 arms, 6 Pulse, Frequency =1080 Hz, Sample Time= 5 μs
DC Bus Capacitance of DVR: 1000μF

7 Conclusion

The study of DVR is focused on applying a new sag detection method and a new compensating voltage generation method. The conventional sag detection method is unable to detect the voltage sags lower than a definite level. As an instance, a single phase to ground fault resulting voltage sag cannot be determined by this method because the method used the average of the three phase voltage and sees the single phase voltage sag as an average value of three phases. To overcome the disadvantages of the conventional sag detection method, the proposed method is used in this paper. With the proposed method, the controller is able to detect different types of power quality problems without an error and injects the appropriate voltage component to correct immediately any abnormality in the terminal voltage to keep the load voltage balanced and constant at the nominal value. Simulation and experimental results show that, the proposed DVR successfully protects the most critical load against voltage sags. Moreover it has been found that DVR is capable of providing a self-support to its dc bus by taking active power from the ac line.

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