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Dvr Based Power Quality Improvement In Distribution System

Priyanka R[1], Selvamathi R[2]
Electrical and Electronics Engineering, VTU, BELAGAVI

ABSTRACT: *In this paper, the dynamic voltage restorer (DVR) with reduced rating VSC is used to improve the power quality by eliminating the harmonics to reduce voltage sags and swells observed in the distribution system. Also different voltage injection schemes is been discussed. A new control technique to ensure power quality is being proposed here by controlling the capacitor supported DVR. Unit vectors are used to estimate the load voltage. Synchronous reference frame theory is used to convert the voltages from the rotating vectors to the stationary frame. Also the DVR with battery energy storage system is also demonstrated to eliminate the power quality problems stated above.*

INDEX TERMS: *Dynamic voltage restorer (DVR), voltage sag, voltage swell, voltage harmonics, unit vector, voltage source converter (VSC), PI controller, Park's transformation.*

I. INTRODUCTION

Power quality became the major concern in power systems since 1990s. Here we are concentrating on distribution system. Power quality problems such as voltage sags, swells, transients, harmonics and interruptions are observed in the supply voltage. These problems are caused due to the use of sensitive and critical equipments such as communication networks, process industries precise manufacturing industries and other modern loads in distribution side. And also affect the sensitive loads due to the variations in supply voltage. In order to avoid this kind of power quality problems in distribution side we are using custom power devices. Custom power devices are of three categories viz., series connected compensators, shut connected compensators and series and shunt connected compensators.

Here, in this paper we are using a series connected compensator called DVR (Dynamic Voltage Restorer). DVR is a series connected compensator with the capability of regulating the voltage from problems such as sags, swells and harmonics. So to enhance the quality of power on distribution side we prefer to use DVR and ensure that, DVR will protect the loads from tripping and avoids losses due to it.

DVR is one of the most effective and efficient custom power devices [2,3,4] with the advantages of fast response, lower cost and smaller in size. It consists of a control unit to calculate the amount of voltage to be added or removed in order to maintain the constant voltage. The controlling of DVR is done by a Proportional Integral (PI) Controller and a PWM Generator. PI controller is a type of feedback controller which operates the system to be controlled with a weighted sum of error. It generates the desired signal for the PWM generator to trigger the PWM inverter. The Phase lock loop (PLL) and dq0 transformation are also the basic components of DVR. Synchronous reference frame theory is used for the conversion of voltages from rotating vectors to stationary frame.

This paper, investigates the performance of DVR in improving the quality of power under three phase faults at two different time periods. Also, the reduced rating VSC is used to improve the power quality with improved efficiency compared to the reference base paper [1].

II. OPERATION OF DVR

The schematic representation of DVR connected system is as shown in Fig. 1(a). The supply voltage V_s will be varying and distorted due to the disturbances in the system. So the injected voltage V_{inj} is inserted to the system by DVR to maintain the load voltage V_{load} constant in its magnitude and undistorted. The phasor diagram of different voltage injection scheme for DVR is shown in Fig. 1(b). $V_{L(pre\text{-}sag)}$ is the voltage across the critical load prior to the voltage sag condition. During the voltage sag, the voltage is reduced to V_s with a phase lag angle of θ. Now, the DVR injects a voltage such that the load voltage magnitude is maintained at the pre-sag condition. According to the phase angle of the load voltage, the injection of voltages can be in four ways [9].

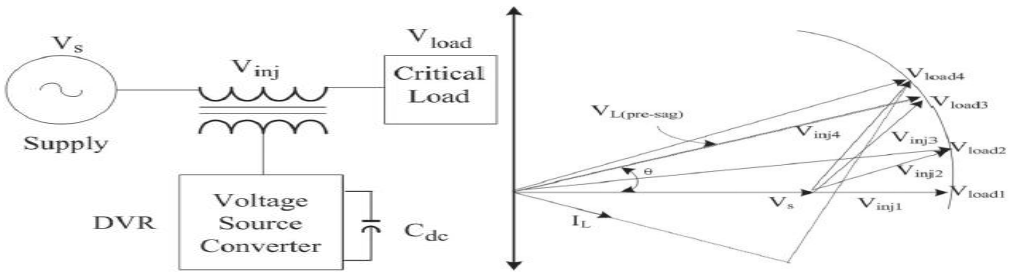

Fig. 1(a): schematic representation of DVR connected system. (b) Phasor diagram of different voltage injection schemes of DVR.

V_{inj1} represents the voltage injected in phase with the supply voltage. With the injection of V_{inj2}, the load magnitude remains same but it leads $V_s$by a small angle. In V_{inj3}, the load voltage retains the same phases that of the pre sag condition, which may be an optimum angle considering the energy source[10]. V_{inj4} is the condition where the injected voltage is in quadrature with the current and this case is suitable for a capacitor supported DVR as this injection involves no active power[7]. However, a minimum possible rating of the converter is achieved by V_{inj1}. The DVR is operated in this scheme with a battery energy storage system(BESS) and also a capacitor supported DVR is operated.

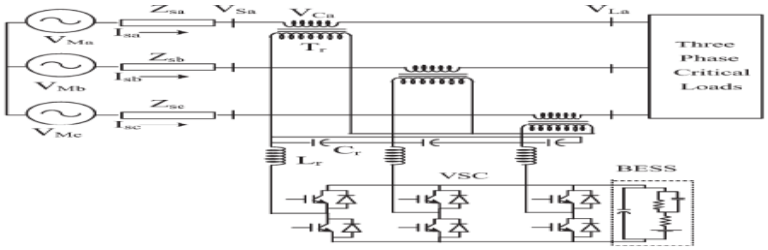

Fig.2 (a) Schematic diagram of a DVR connected system with BESS.

Fig.2 (a) shows the schematic of a three phase DVR connected to restore the voltage of a three-phase critical load. A three phase supply is connected to a critical load with the help of a three phase series injection transformer. The equivalent voltages of the supply for phase A is V_{Ma} and is connected to the point of common coupling(PCC), V_{Sa}through short-circuit impedance Z_{Sa}. The DVR injects the voltage V_{Ca}in phase A, such that the load voltage V_{La} is maintained at rated magnitude and is undistorted. A three-phase DVR is connected to the line in series using three single phase transformers Tr to inject a voltage. L_r and $C_r$represent the filter components. These are used to filter the ripples in the injected voltage. A three leg VSC with 6 insulated gate bipolar transistors (IGBTs) is used as a DVR, along which a BESS is connected to its DC bus.

III. CONTROL OF DVR SYSTEM

The compensation of power quality problems like voltage sag using a DVR can be done by injecting the real power or reactive power [7]. When the injected voltage is in quadrature with the current at the fundamental frequency, the compensation is made by injecting reactive power; the DVR is with a self-supported dc bus[3,4]. And when the injected voltage is in phase with the current, the DVR injects real power. Hence a battery is required to store the backup power at the DC bus of the VSC. The limitations like voltage injection capability (transformer and converter ratings) and the optimization of energy storage element size are to be considered by the control techniques used for DVR control.

A. Control of DVR with BESS

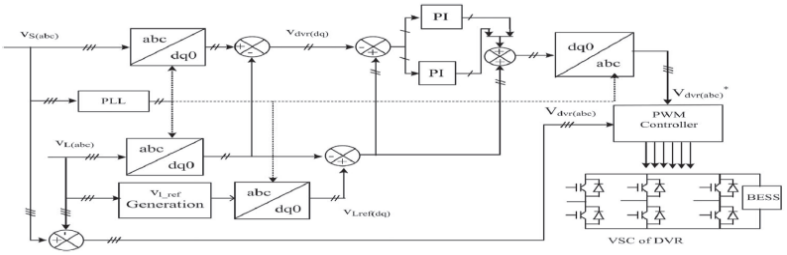

Fig.2. (b) control block of the DVR which uses SRF method of control for BESS

Fig. 2 (b) represents the control block of the DVR with the SRF theory used for the estimation of reference signal. The voltages at the PCC(V_S) and at the load terminal (V_L) are sensed and then the IGBTs' gate signals are drawn. The reference load voltage V_L^* is taken using the derived unit vector [13]. Load voltages (V_{La},V_{Lb},V_{Lc}) are converted to the rotating reference frame using abc-dqo conversion using Park's transformation with unit vectors(sinθ, cosθ) and are derived using a phase locked loop as

$$\begin{bmatrix} v_{Lq} \\ v_{Ld} \\ v_{Lo} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ \sin\theta & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_{Laref} \\ v_{Lbref} \\ v_{Lcref} \end{bmatrix} \quad (1)$$

Similarly, reference load voltages (V_{La}^* V_{Lb}^* V_{Lc}^*) and voltages at PCC V_S are also converted to the rotating reference frame. Then, the DVR voltages are obtained in the rotating reference frame as

$v_{Dd} = v_{Sd} - v_{Ld}$(2)

$v_{Dq} = v_{Sq} - v_{Lq}$ (3)

The reference DVR voltages are obtained in the rotating reference frame as

$v_{Dd}^* = v_{Sd}^* - v_{Ld}$ (4)

$v_{Dq}^* = v_{Sq}^* - v_{Lq}$ (5)

The error between the reference and actual DVR voltages in the rotating reference frame is regulated using two proportional-integral (PI) controllers.

By taking v_{Dd}^* from equation (4), v_{Dq}^* from equation (5) and v_{Do}^* as zero, we obtain reference DVR voltages in the abc frame from a reverse Park's transformation as follows:

$$\begin{bmatrix} v_{dvra}^* \\ v_{dvrb}^* \\ v_{dvrc}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-\frac{2\pi}{3}) & \sin(\theta-\frac{2\pi}{3}) & 1 \\ \cos(\theta+\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} v_{Dq}^* \\ v_{Dd}^* \\ v_{Do}^* \end{bmatrix}$$

Reference DVR voltages($v_{dvra}^*, v_{dvrb}^*, v_{dvrc}^*$) and actual DVR voltages($v_{dvra}, v_{dvrb}, v_{dvrc}$)are used in a pulse width modulated (PWM) controller to generate gating pulses to a VSC of the DVR. The PWM controller is operated with a switching frequency of 10kHz.

B. Control of self-supported DVR (capacitor supported DVR)

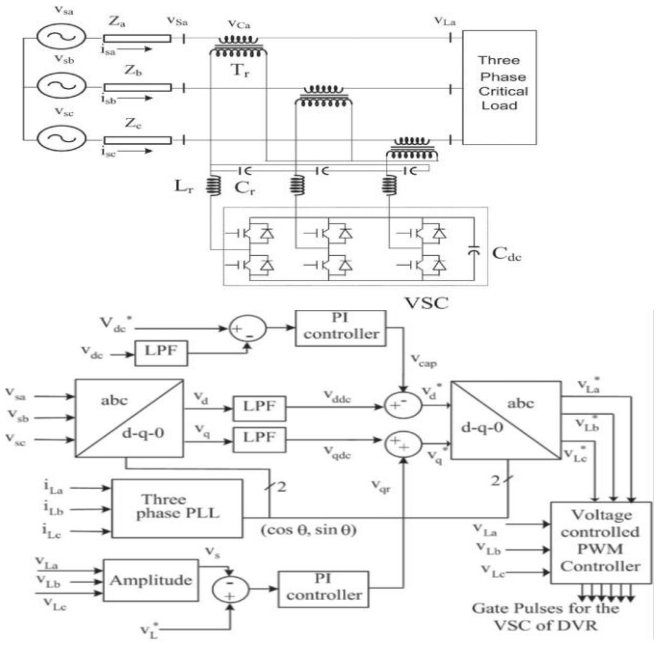

Fig.3. (a) Schematic diagram of a capacitor supported DVR connected system. (b) Control block of the DVR which uses SRF method of control for capacitor connected DVR

The schematic of a capacitor supported DVR connected to three phase critical load is as shown in fig. 3(a) and its control block using SRF theory is shown in fig.3(b). The voltages at the PCC (V_S) are converted to the rotating reference frame using Park's transformation(abc-dqo conversion). The harmonics in the voltage are eliminated using the low pass filters (LPFs) [13]. The components of voltages in the d-axis and q-axis respectively are

$V_d = V_{ddc} + V_{dac}$ (7)

$V_q = V_{qdc} + V_{qac}$ (8)

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

In order to maintain the dc bus voltage of the self-supported capacitor, a PI controller is used at the dc bus voltage of the DVR and the output is considered as a voltage v_{cap} for meeting its losses

$v_{cap(n)} = v_{cap(n-1)} + K_{p1}(v_{de(n)} - v_{de(n-1)}) + K_{i1}v_{de(n)}$(9)

Where $v_{de(n)} = v_{dc}^{*} - v_{dc(n)}$ is the error between the reference v_{dc}^{*} and sensed dc voltage v_{dc} at the n^{th} sampling instant.K_{p1}andK_{i1} are the proportional and the integral gains of the dc bus voltage PI controller.

The reference d-axis load voltage is therefore expressed as follows:

$v_d^{*} = v_{ddc} - v_{cap}$(10)

The amplitude of load terminal voltage V_L is controlled to its reference voltage v_L^{*} using another PI controller. The output of the PI controller is considered as the reactive component of voltage v_{qr} for voltage regulation of the load terminal voltage. The amplitude of load voltage V_L at the PCC is calculated from the ac voltages (v_{La}, v_{Lb}, v_{Lc}) as $V_L = (2/3)^{1/2}(v_{La}^2 + v_{Lb}^2 + v_{Lc}^2)^{1/2}$ (11)

Then, a PI controller is used to regulate this to a reference value as

$v_{qr(n)} = v_{qr(n-1)} + K_{p2}(v_{te(n)} - v_{te(n-1)}) + K_{i2}v_{te(n)}$(12)

Where $v_{te(n)} = v_L^{*} - v_{L(n)}$ denotes the error between the reference v_L^{*} and the actual $v_{L(n)}$ load terminal voltage amplitudes at the n^{th} sampling instant.K_{p2}andK_{i2} are the proportional and integral gains of the dc bus voltage PI controller.

The reference load quadrature axis voltage is expressed as follows:

$v_q^{*} = v_{qdc} - v_{qr}$ (13)

Reference load voltages $(v_{La}^{*}, v_{Lb}^{*}, v_{Lc}^{*})$ in the abc frame are obtained from a reverse Park's ransformation as in (6). The error between the sensed load voltages (v_{La}, v_{Lb}, v_{Lc}) and reference load voltage is used over a controller to generate gating pulses to the VSC of the DVR.

IV. MODELING AND SIMULATION

The DVR connected system consisting of a three-phase supply,three phase critical loads [11], and the series injection transformers shown in fig.2 (a) i.e., with BESS is modelled in MATLAB/Simulink environment.The sim power system toolbox is used in modelling this system. The simulated model of fig.2 (a) without controls for DVR is shown in fig.4 (a) and the resulting voltages without compensations for voltage sag is shown in fig. 4(b) and that for swell is shown in fig. 4(c)and the outputs with controls using SRF theory for themcompensating the sags and swells respectively is shown in figs 5 (a)and 5 (b) respectively. Similarly, the capacitor supported DVR system in fig. 3(a) is simulated as per controls shown in fig. 3(b) and its results for sag and swell compensationare respectively as shown in fig. 6(a) and fig. 6(b). An equivalent load considered is 10kVA, 0.8-pf lag linear load. The parameters of the considered system for the simulation study are given in the appendix. The reference DVR voltages are derived from sensed PCC voltages (v_{Sa}, v_{Sb}, v_{Sc}) and load voltages (v_{La}, v_{Lb}, v_{Lc}). A PWM controller is used over the reference and sensed DVR voltages to generate the gating signals for the IGBTs of the VSC of the DVR.

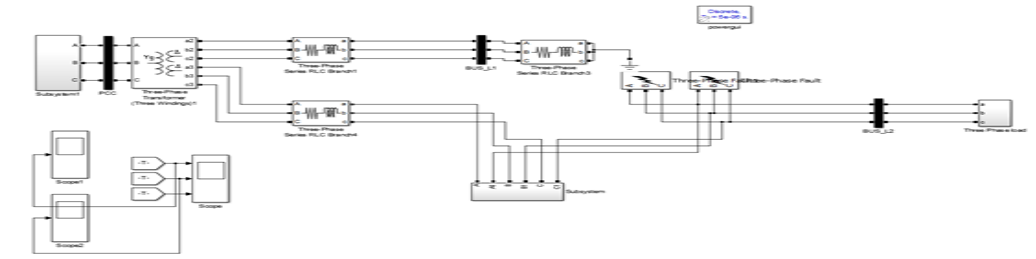

Fig. 4(a) simulated model of DVR connected system with BESS without controls.

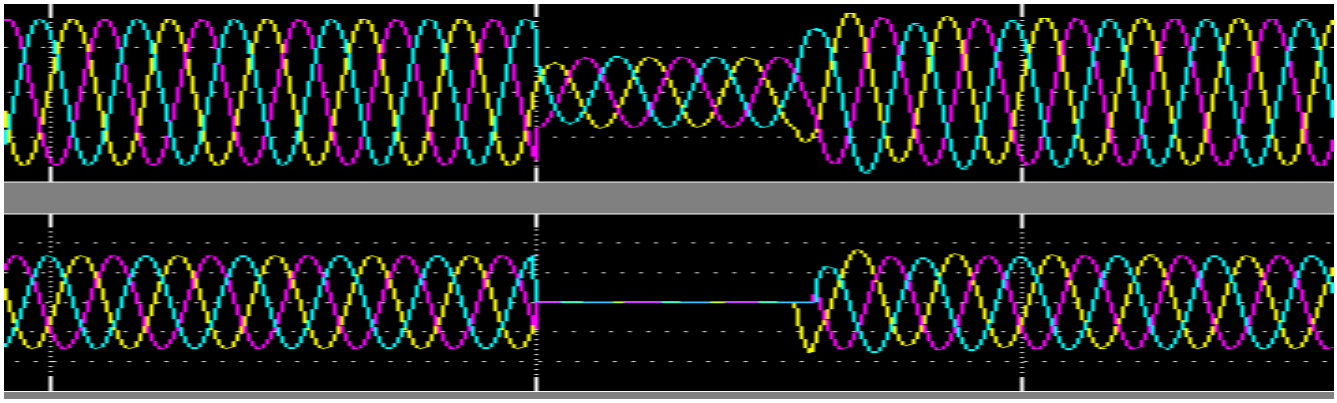

fig. 4(b) voltage sags observed at PCC voltage and load voltage

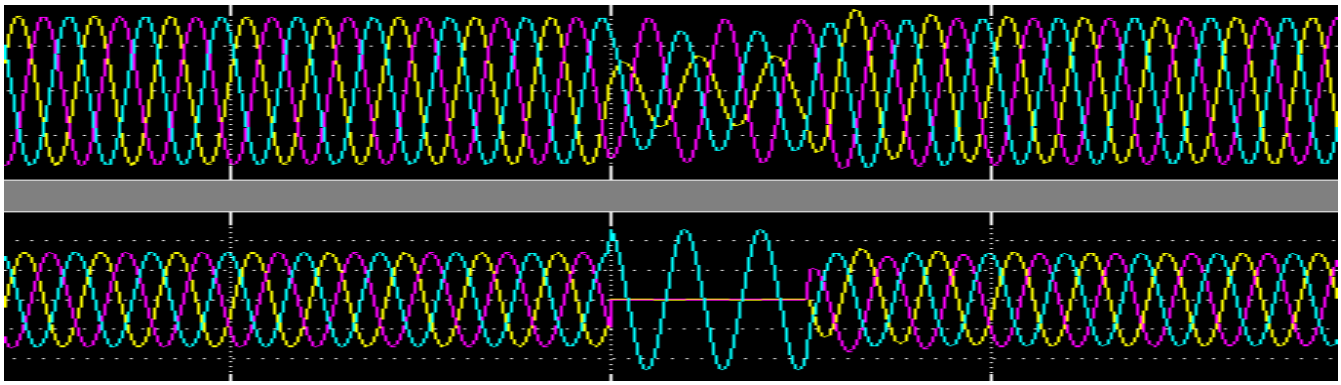

fig. 4(c) voltage swells observed at PCC voltage and load voltage

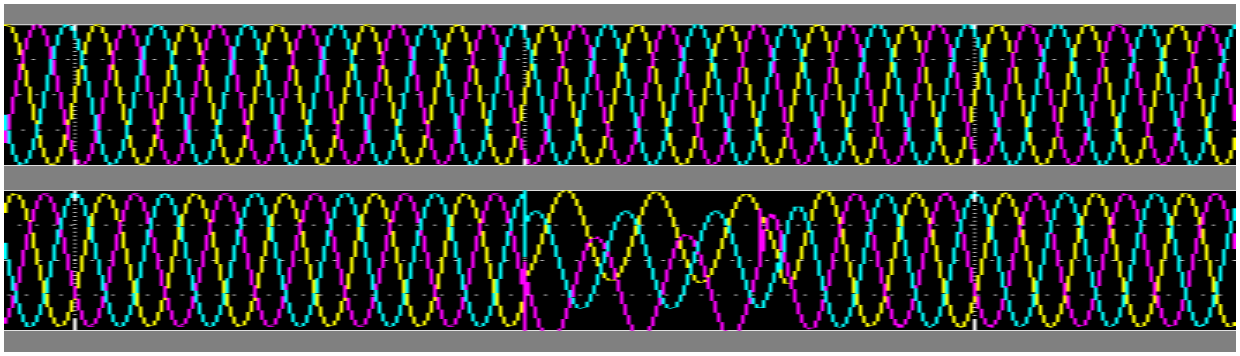

fig. 5(a) voltage sags compensated at PCC voltage andload voltage

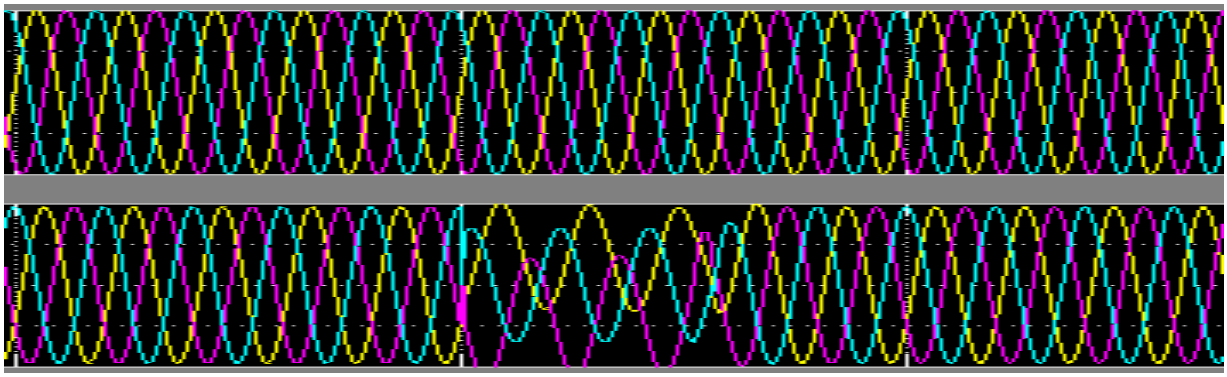

fig. 5(b) voltage swells compensated at PCC voltage and load voltage

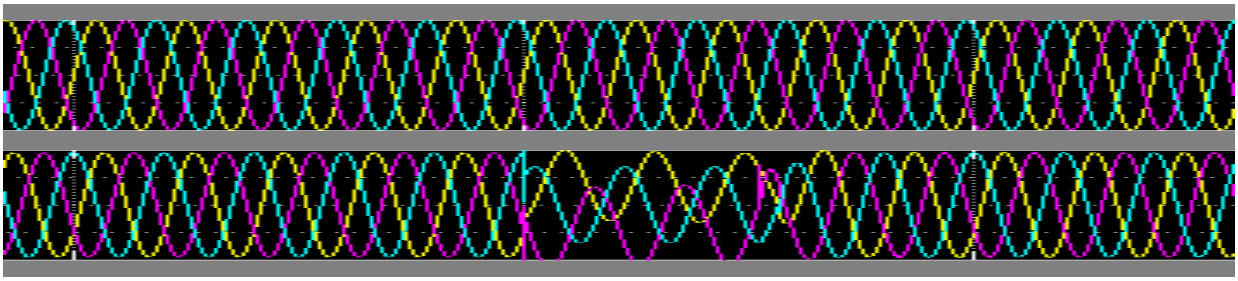

fig. 6(a) voltage sags compensated at PCC voltage and load voltage

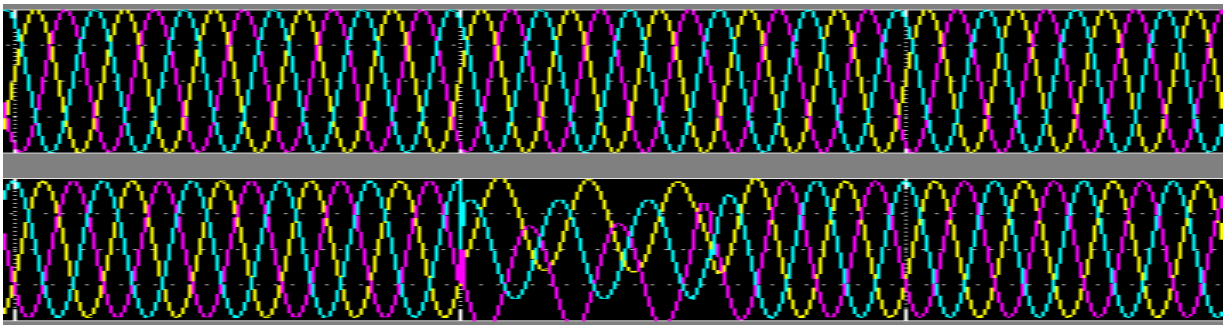

fig. 6(b) voltage swells compensated at PCC voltage and load voltage

V. PERFORMANCE OF THE DVR SYSTEM

The performance of the DVR is demonstrated for different supply voltage disturbances such as voltage sag and swell in [1.] Fig. 5(a) to 6(c) shows the transient performance of the system under voltage sag and swell conditions as explained in modelling part. At 0.2s-0.25s, a sag in supply voltage is created for six cycles, and at 0.6s-0.65s, a swell in the supply voltages is created for 1cycles. It is observed that the load voltage is regulated to maintain constant amplitude under both sag and swell conditions. PCC voltages v_s , load voltages v_L, DVR voltages v_C, amplitude of load voltage V_L and PCC voltage V_s, source currents i_S, reference load voltages and dc bus voltage are also shown in output results obtained in fig.5 and fig.6. The total harmonic distortions (THDs) of the voltage at the load voltage for BESS and capacitor supported systems are shown in fig 7(a) and (b) respectively.

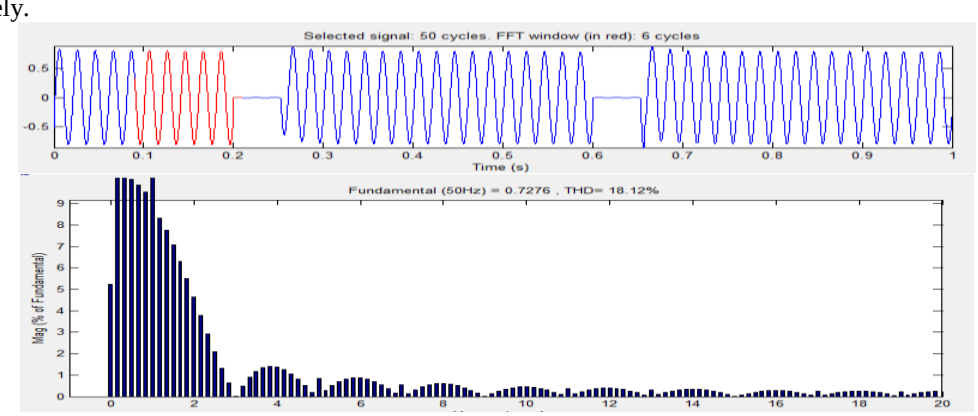

Fig 7(a).input signal and its THD analysis for DVR connected system with BESS without control

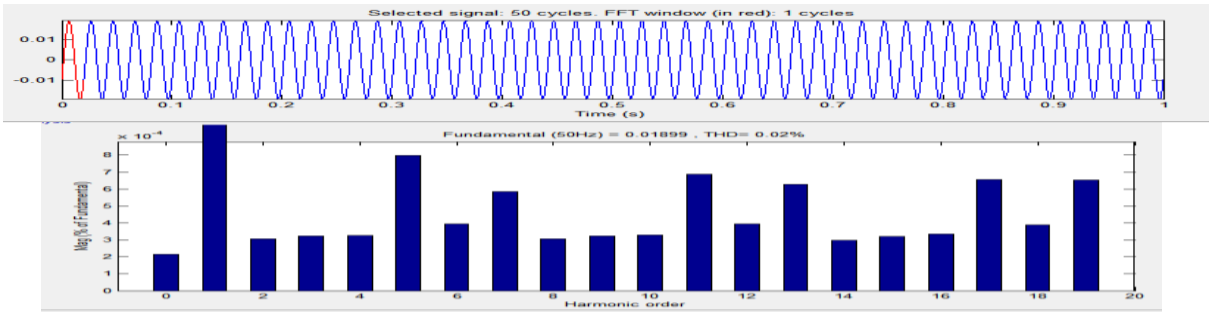

Fig 7(b).input signal and its THD analysis for DVR connected system with BESS

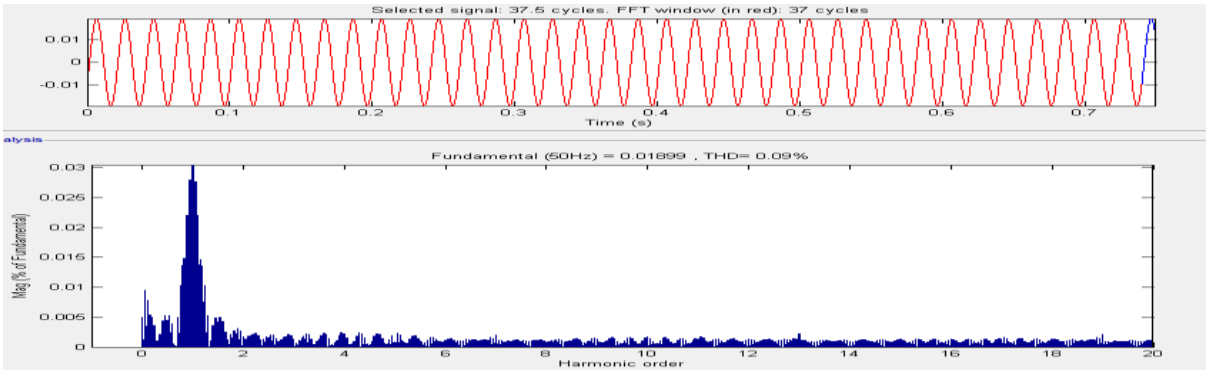

Fig 7(c).input signal and its THD analysis for capacitor supported DVR connected system

It is observed that the load voltage THD is reduced to a level of 0.02% from the PCC voltage of 18.12%.in BESS system. and is reduced to a level of 0.09% in capacitor supported DVR system. so we can notice the improved efficiency compared with the performance of system in[1].

The magnitudes of the voltage injected by the DVR for mitigating the same kinds of sag in the supply with different angles of injection are observedin[1].The injected voltage, series current and kVA ratings of the DVR for the four injection schemes are given in table-1. In scheme-1 in table-1, the in-phase injected voltage is V_{inj1} in the phasor diagram in fig.1 and only this scheme is executed with the improved efficiency in this paper. In scheme-2, a DVR voltage is injection at a small angle of 30degree, and in scheme-3, the DVR voltage is injected at an angle of 45deg. The injection of voltage in quadrature with the line current is in scheme-4. The required rating of compensation of the same using scheme-1 is much less than that of scheme-4. Hence, only scheme-1 is used in improving the efficiency.

TABLE-1: SELECTING DVR RATINGS FOR MITIGATING THE SAG

	Scheme -1	Scheme -2	Scheme -3	Scheme -4
Phase voltage	90	100	121	135
Phase current	13	13	13	13
VA per phase	1170	1300	1573	1755
kVA (% of load)	37.5%	41.67%	50.42%	56.25%

VI. CONCLUSION

The operation of a DVR has been demonstrated with a new control technique using various methods for voltage injection scheme-1 of table-1. A comparison of the performance of the DVR with scheme-1for existing one in [1] and one performed with areduced- rating VSC for BESS and capacitor-supported DVR shows that the efficiency is higher in this paper compared to that in [1]. The reference load voltage has been estimated using the method of unit vectors and the control of DVR has been achieved as per the controls in [1], with improved efficiency for both BESS and capacitor supported DVR. The same SRF theory has been used for estimating the reference DVR voltages as in[1]. It is concluded that the voltage injection in-phase with the PCC voltage results in minimum rating of DVR but at the cost of an energy source at its dc bus along with better efficiency in mitigating the power quality problems.

APPENDIX

AC line voltage: 415V, 50Hz
Line impedance: L_s= 3.0mH, R_s= 0.01Ω
Linear loads: 10-kVA 0.80-pf lag
Ripple filter: C_f = 10μF, R_f= 4.8Ω
Series transformers: three phase transformer of rating 10kVA, 200V/300V

DVR with BESS:
Dc voltage of DVR: 200V
Ac inductor: 0.005H
Gains of the d-axis PI controller:kp=0.63 kd=0.0504

Gains of the q-axis PI controller:kp=0.63 kd=0.0504
PWM switching frequency:10kHz

DVR with capacitor:

Dc voltage of DVR: 200V
Ac inductor: 0.005H
Gains of the d-axis PI controller:kp=0.63 kd=0.0504
Gains of the q-axis PI controller:kp=0.63 kd=0.0504
PWM switching frequency:10kHz

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