Dynamic Voltage Restorer for Power Quality Improvement with D-Q Reference Frame

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Abstract- Power Quality problems in the present-day distribution systems are more in these days due to the increased use of sensitive and critical equipment pieces such as communication network, process industries, and precise manufacturing processes. Power quality problems such as transients, sags, swells, and other distortions to the sinusoidal waveform of the supply voltage affect the performance of these equipment pieces. Technologies such as custom power devices are emerged to provide protection against power quality problems. Out of which the series connected type known as DVR can regulate the load voltage from the problems such as sag, swell, and harmonics in the supply voltages in an efficient manner. DVR is controlled by duly employed d-q reference frame strategy. The direct and quadrature axis parameters are set to a standard reference values so as to find if at all there exist any voltage change that may lead to consequences of power quality failure. Unlike the conventional control strategy, a lucid design of direct-quadrature control strategy is used. Hence, it can protect the critical consumer loads from tripping and consequent losses.

Keywords: Dynamic voltage restorer (DVR), power quality, unit vector, voltage harmonics, voltage sag, voltage swell.

I. INTRODUCTION

Power distribution systems, ideally, must give their customers with an uninterrupted flow of power at smooth sinusoidal voltage at the constant magnitude and frequency. However, in practice, power systems, particularly the distribution systems, have different nonlinear loads, which widely modify the quality of power supplies. As a result of the nonlinear loads, the purity of the sine waveform is lost. This will produces the several power quality issues. 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 whole power system and also, under heavy load conditions, a significant voltage drop could occur in the system. Voltage sag and swell can cause sensitive equipment to fail, blackout and produce a large current unbalance. These effects can acquire a lot of expensive from the customer and cause equipment damage. The voltage sag is defined as an decrease in rms voltage from 10% to 90% of nominal voltage with duration from half a cycle to 1 minute and voltage swell is defined as an increase in rms voltage or current from 90% to 110% of the nominal voltage at the power frequency for durations from 0.5 cycles to 1 minute. Typical magnitudes are between 1.1 and 1.8 p.u.

There are several different methods to compensate voltage sags and voltage 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. To improve power quality problems in electrical system, different types of custom power devices are used. Depending upon the type of connection made the custom power devices are classified. Each of the devices has its own advantages and limitations. The SVC pre-dates the DVR, but the DVR is still preferred because the SVC has no ability to control active power flow. Furthermore, the advantageous facts are that the DVR is smaller in size and cost is less compared to the DSTATCOM and other custom power devices. Based on these reasons, DVR is widely considered as an effective custom power device to mitigate voltage sags. In addition to voltage sags and swells compensation, DVR can also reduces the harmonics and improves the Power Factor.

DVR is clearly considered to be one of the best economic solutions for its size and capabilities when compared to the other devices. Many solutions and their problems using DVRs are reported, such as the voltages in a three-phase system are balanced and an energy-optimized control of DVR is discussed in [10]. Industrial examples of DVRs are given in [11], and different control methods are analyzed for different types of voltage sags in [12]–[15]. A comparison of different topologies and control methods is presented for a DVR in [17]. The design of a capacitor-supported DVR that protects sag, swell, distortion, or unbalance in the supply voltages is discussed in [19]. The performance of a DVR with the high frequency-link transformer is discussed in [20]. In this paper, the control and performance of a DVR are demonstrated with a lucid control technique using d-q parameters as the main criteria for the control of the DVR.

II. DYNAMIC VOLTAGE RESTORER (DVR)

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Dynamic Voltage Restorer is a series compensating device which is used to reduce the supply side disturbances.DVR is a Custom Power Device used to eliminate supply side voltage disturbances. DVR can reduce the voltage sags, voltage swells and harmonics to keep the load voltage constant at a desired magnitude and phase angle. DVR can reduce these power quality problems which are existing at the point of common coupling (PCC). The series connected custom power device with filters and PWM inverter is shown in Fig1.

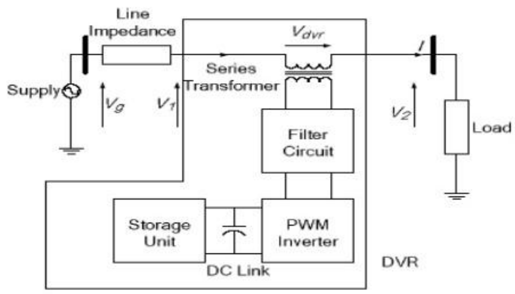
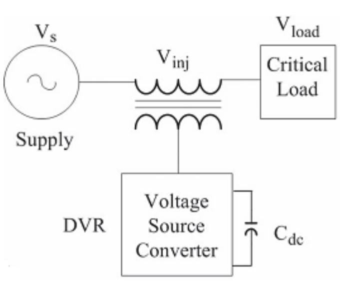


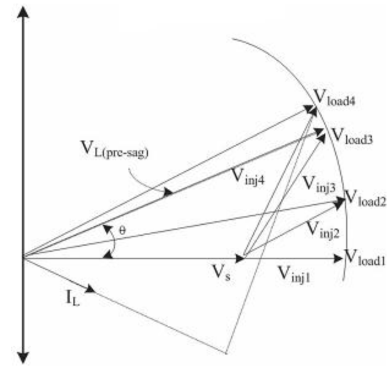
Fig. 1.Basic diagram of DVR system.

III. OPERATION OF DVR

Figure 2(a) shows the simplified diagram of a DVR system. Even though the supply voltage is not constant in magnitude, the injected voltage (Vinj) is inserted such that the load voltage (Vload) is constant and undistorted. The phasor diagram of different DVR voltage injection schemes is shown in figure 2(b). Prior to the voltage sag, VL (pre-sag) is a voltage across the sensitive load. The voltage is reduced to supply voltage (Vs) with a phase angle of θ during the voltage sag condition. Then the DVR injects the missing voltage such that the load voltage is kept constant. The voltage injection schemes can be divided into four ways [19] according to the phase angle of the load voltage. The injected voltage is in-phase with the supply voltage is represented by Vinj1. Vinj2 represents the load voltage leads the supply voltage by a small phase angle but the magnitude of load voltage is same. Vinj3 represents the voltage injected by an optimum angle but the load voltage remains same.



(a)



(b)

Fig. 2. (a) Basic circuit of DVR. (b) Phasor diagram of the DVR voltage injection schemes.

The schematic diagram of a three-phase DVR connected system is shown in Figure3. A three phase series injection transformer is connected between the three phase supply and critical load. In the figure3, phase A equivalent voltage i.e VMa which is connected to the point of common coupling (PCC) VSa through Zsa i.e short circuit impedance. VCa is the injected voltage in phase A which is injected by the DVR such that the load voltage VLa is undistorted. Three single-phase transformers Tr are connected in series with the distribution line which is used to inject a voltage in series with the system. The filter components Lr and Cr which are used to filter out the ripples in the injected voltage.. A three-leg Voltage Source Converter (VSC) with insulated-gate bipolar transistors (IGBTs) is used as a Dynamic Voltage Restorer and a Battery Energy Storage System (BESS) is connected to its bus.

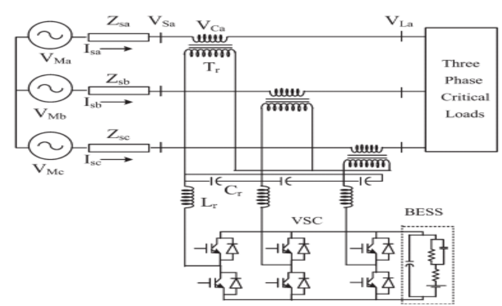


Fig. 3. Schematic of the DVR-connected system

IV. CONTROL OF DVR

The compensation for voltage sags using a DVR can be performed by injecting or absorbing the reactive power or the real power [17]. When the injected voltage is in quadrature with the current at the fundamental frequency, the compensation is made by injecting reactive power and the DVR is with the compensated amount of voltage. However, if the injected voltage is in phase with the current, DVR injects real power. The control technique adopted should consider the limitations such as the voltage injection capability (converter and transformer rating) and optimization of the size of energy storage.

A. Control of DVR with d-q values as reference for Voltage Sag, Swell, and Harmonics Compensation

Fig. 4 shows a control block of the DVR in which the SRF theory is used for reference signal estimation. The voltages at the PCC V_S and at the load terminal V_L are sensed for deriving the IGBTs' gate signals. The reference load voltage $V*L$ is extracted using the derived. 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(sin,θ,cos,θ) derived using a phase-locked loop as

$$\begin{bmatrix} v_{Lq} \\ v_{Ld} \\ v_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_{La\text{ref}} \\ v_{Lb\text{ref}} \\ v_{Lc\text{ref}} \end{bmatrix} \quad (1)$$

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

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

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

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

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

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

The error between the reference and actual DVR voltages in the rotating reference frame is regulated using two proportional–integral (PI) controllers. Reference DVR voltages in the abc frame are obtained from a reverse Park's transformation taking V^*_{Dd} from (4), V^*_{Dq} from (5), V^*_{D0} as zero as

$$\begin{bmatrix} v_{\text{dvra}}^* \\ v_{\text{dvrb}}^* \\ v_{\text{dvrc}}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} v_{Dq}^* \\ v_{Dd}^* \\ v_{D0}^* \end{bmatrix} \quad (6)$$

Reference DVR voltages $(v_{\text{dvra}}^*, v_{\text{dvrb}}^*, v_{\text{dvrc}}^*)$ and actual DVR voltages $(v_{\text{dvra}}, v_{\text{dvrb}}, v_{\text{dvrc}})$ 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 10 kHz.

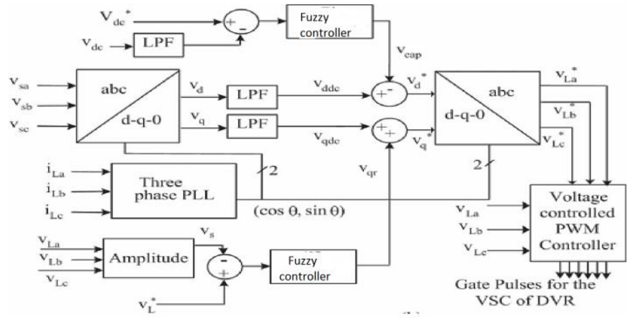


Fig. 4.Control block of the DVR that uses the SRF method of control

Fig 4. Shows a schematic of a capacitor-supported DVR connected to three-phase critical loads, and Fig 4 shows a control block of the DVR in which the SRF theory is use for the control of self-supported DVR. Voltages at the PCC VS are converted to the rotating reference frame using abc−dqo conversion using Park's transformation. The harmonics and the oscillatory components of the voltage are eliminated using low pass filters (LPFs). The components of voltages in the d- and q-axes are

$$v_d = v_{d\text{dc}} + v_{d\text{ac}} \quad (7)$$

$$v_q = v_{q\text{dc}} + v_{q\text{ac}}. \quad (8)$$

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

The referenced-axis load voltage is therefore expressed as follows: $v_d^* = v_{d\text{dc}} - v_{\text{cap}}.$ (9)

The amplitude of load terminal voltage V_L is controlled to its reference voltage V_a^* 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

$$V_L = (2/3)^{1/2}\left(v_{La}^2 + v_{Lb}^2 + v_{Lc}^2\right)^{1/2}. \quad (10)$$

The reference load quadrature axis voltage is expressed as follows:

$$v_q^* = v_{q\text{dc}} + v_{qr}. \quad (11)$$

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

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V. Synchronous Reference Frame Method (d-q Method)

The in the control of the DVR makes the main intension of this per unit d-q reference parameters usage is for the compensation of the sag and swell of the voltages and to overcome the distortions in the sine wave in a lucid way. A description of the well-known (conventional) srf and d-q methods is presented, which is followed by description of the d-q theory method.

Unlike the conventional control the introduction of the per unit system of control of the DVR will help in the easy comparison of the faulty voltage and help in taking measures that help in overcoming the loss or excess amount of voltage causes due to the usage of sensitive loads in the present day system. The flow chart would duly demonstrate the control technique involved in the DVR.

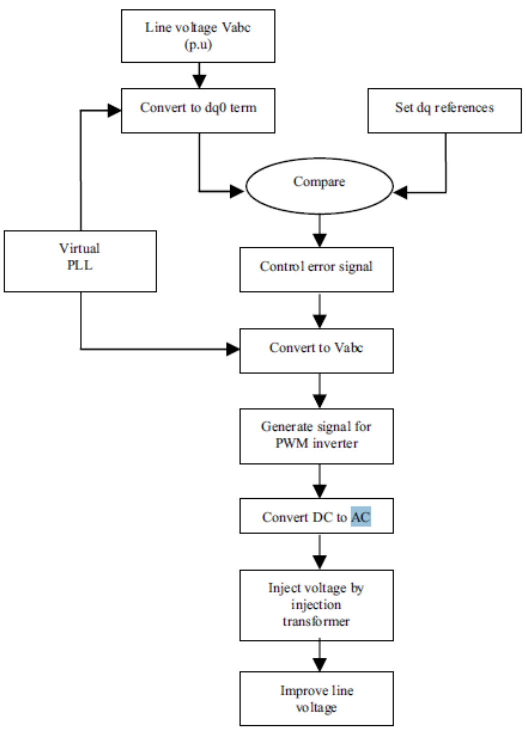


Figure 2. Flow chart of DVR operation

Fig. 5.Flow chart of d-q method of control

Instantaneous Active Power Theory (p-q Theory)
The instantaneous and reactive power method, remains one of the most popular APF control schemes which are mainly concentrating on the variation of the voltage in minute level. These per unit equations would help in overcoming the lengthy process of solving the typical equations.

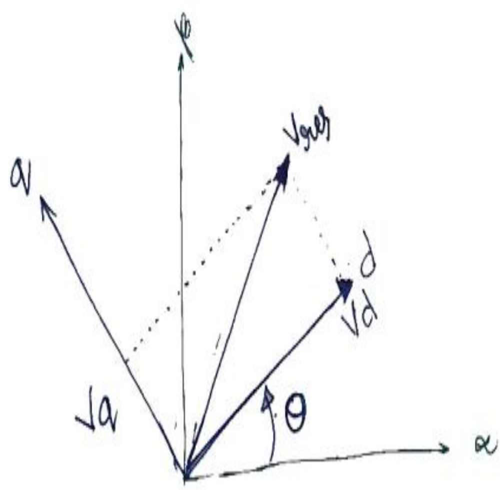
$$\begin{bmatrix} V\alpha \\ V\beta \\ V0 \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix}$$

$$\begin{bmatrix} i\alpha \\ i\beta \\ i0 \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} ia \\ ib \\ ic \end{bmatrix}$$

$$P\alpha\beta = V\alpha i\alpha + V\beta i\beta$$

$$Q\alpha\beta = V\alpha i\beta - V\beta i\alpha$$

$$\overline{\overline{P}} = \widetilde{P} + \vec{P}, \overline{\overline{Q}} = \widetilde{Q} + \vec{Q}$$



d-q theory

Fig. 6.Grphical representation of d-q control

The d-q method is the most studied and the load currents are transformed into the d-q components in order to separate the fundamental and harmonics components of instantaneous currents (id, iq).

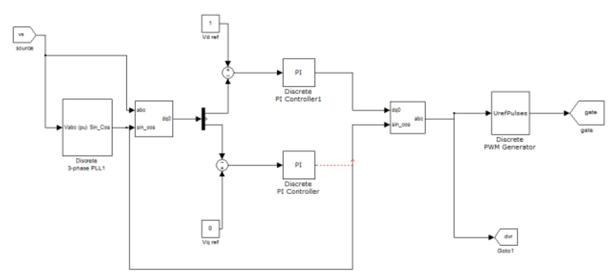


Fig. 7. Block diagram of d-q control method

The block diagram which is designed in the matlab would help understanding of the control of the DVR. The d and q parameters are set to a standard reference values of 1 and 0 to which they are supposed to get compared with the source voltage which is set to a less magnitude of 0.5 per unit (step) which in turn create a dip in the voltage

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resulting a sag. So, which this particular voltage is tried to match with the se parameters by an virtual PLL, there is a necessity of ther voltage mount that ought to be created to overcome the faulty value.So, this is the time of action of the series ly connected DVR..Similarly a swell in the value of voltage is set by an increase in the step magnitude to 1.5, where the process of control is eventually the same.

VI.MATLAB/SIMULINK RESULTS

Here simulation is carried out for 2 cases,
1) Voltage Sag Compensation by using DVR,
2) Voltage Swell Compensation by using DVR
with d-q frame theory

Voltage Sag/Swell Compensation by using Proposed DVR with D-Q frame theory is done with the simulink diagram shown in Fig 8.

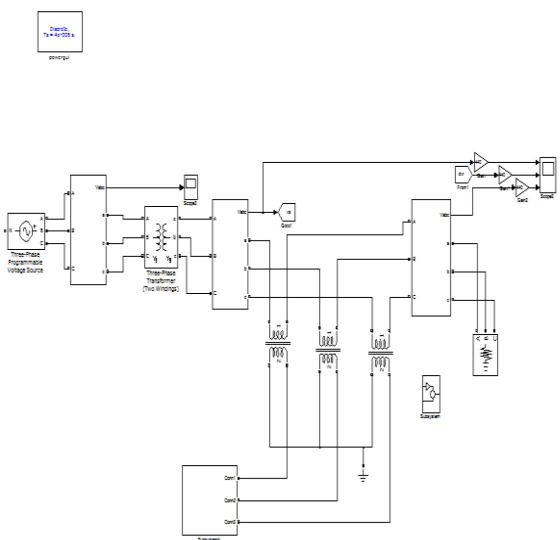

Fig.8 Matlab/Simulink Modelling of Proposed DVR under Voltage Sag/Swell Issues using Hysteresis Voltage Controller

Fig.8 shows the Matlab/Simulink Modelling of Proposed DVR under Voltage Sag/Swell Issues with D-Q frame theory with the help of computer simulation tool.

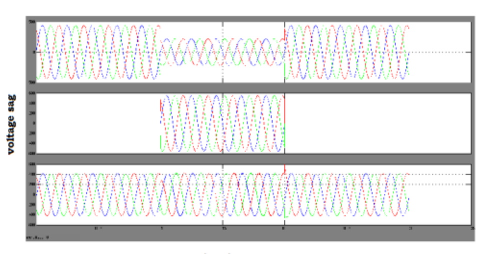

Fig.9 Source Voltage, DVR Injected Voltage, Load Voltage of Proposed DVR under Voltage Sag Issues

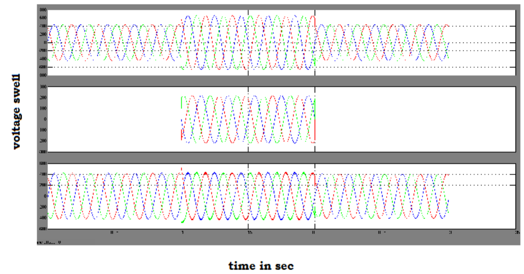

Fig.10 Source Voltage, DVR Injected Voltage, Load Voltage of Proposed DVR under Voltage Swell Issues

Fig 9 and 10 represent the resulting wave forms of the designed simulink diagram for the control of the DVR. The wave forms include the mitigagation of the sag and swell voltages and bringing back the original form o the voltage waveform.

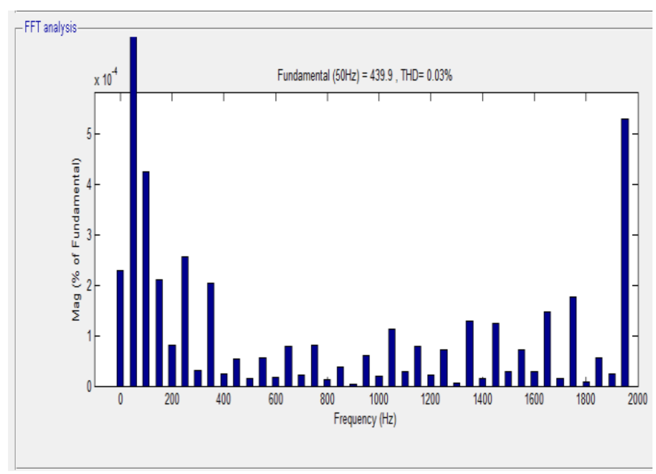

Fig 11.THD Analysis of Supply voltage

The harmonic voltage of the supply voltage would rather imply that the total harmonic distortion of the value0.03 is considerably a good amount of reaching a sustained value of voltage control level.

VII. CONCLUSION

The operation of a DVR has been demonstrated with a new control technique using various voltage injection schemes. The control of DVR using the d-q parameters has made it so simple to overcome the faulty voltage which results in various issues of the system. The control of voltages would inturn help in the improvement of the power quality of the entire system. Which gives a better scope for the study in the upcoming inventions in the power quality designs. The reference load voltage has been estimated using the method of unit vectors and the control of DVR has been achieved, which minimizes the error of voltage injection. It is concluded that the voltage

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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. The hysteresis voltage controller offers better characteristics and also improves the performance with d-q frame theory

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