Chapter 3

Series Active Power Filter

Recently, the use of semiconductor switching equipment, such as diodes and thyristor rectifiers, has sharply increased. Power quality degradation generally results from these and other non-linear loads. The more non-linear loads increase, the more complex steps are required to avoid power quality degradation, such as harmonic increase, power factor degradation etc. Passive filters have traditionally been used to eliminate harmonic currents, which are generated by nonlinear loads. To eliminate the harmonics in broadband, too many passive filters would be required. In addition, the hazard of resonance with the source impedance would become quite difficult to avoid. Studies on active power filters began in the late 1970s to overcome the defects of the passive filter. The active power filter is more expensive than the passive, but the former has an advantage in that it can simultaneously eliminate the broadband harmonic at the source stage. Active power filters are categorized as follows: the parallel active power filter, which injects compensation currents; the series active power filter, which injects compensation voltages through a transformer; and the combined system of parallel passive filters and series active power filter. Generally, if the DC smoothing inductor is sufficiently large, nearly constant DC current flows in the DC link of a rectifier. So this type of load can be called a harmonic current source. The parallel active power filter is suitable for compensating for these harmonic current sources, while the series active power filter is appropriate for compensating for the harmonic voltage source, which has sufficient capacitance component in the DC link of the rectifier. In particular, the solution for a harmonic voltage source is critical because the loads that act as harmonic voltage sources, such as copiers, fax machines, fluorescent lamps, air conditioners etc., have continued to increase. In this chapter, the proposed control algorithm for series active power filters is applicable to harmonic voltage source loads as well as to harmonic current source loads. This control algorithm is applied under the basic concept of the generalized p–q theory. However, this generalized p–q theory is valid for compensating for the harmonics and reactive power using the parallel active power filter in the three-phase power system. To overcome such limits, a revised p–q theory is proposed. This revised algorithm may be effective not only for the three-phase three-wire series active power filter with harmonic current voltage loads, but also for the combined system of parallel passive filters and active filter. Another drawback of the generalized p–q theory is that the compensation voltage will be determined by multiplying the gain, which is dependent on the value of current. To obtain the current, some computational efforts are needed using the instantaneous real power and imaginary power. The proposed control algorithm directly extracts compensation voltage references without multiplying the gain. Therefore, the calculation of the compensation voltage reference will turn out to be simpler than for other control algorithms.

3.1 Basic compensation principle

Series active power filters were introduced by the end of the 1980s and operate mainly as a voltage regulator and as a harmonic isolator between the nonlinear load and the utility system. The series connected filter protects the consumer from an inadequate supply voltage quality. This type of approach is especially recommended for compensation of voltage unbalances and voltage sags from the ac supply and for low power applications and represents economically attractive alternatives to UPS, since no energy storage (battery) is necessary and the overall rating of the components is smaller. The series active filter injects a voltage component in series with the supply voltage and therefore can be regarded as a controlled voltage source, compensating voltage sags and swells on the load side. In many cases, the series active filters work as hybrid topologies with passive LC filters. If passive LC filters are connected in parallel to the load, the series active power filter operates as a harmonic isolator, forcing the load current harmonics to circulate mainly through the passive filter rather than the power distribution system.

The main advantage of this scheme is that the rated power of the series active filter is a small fraction of the load kVA rating, typically 5%. However, the apparent power rating of the series active power filter may increase in case of voltage compensation. Fig 1.3 shows the connection of a series active power filter, and Fig 1.4 shows how the series active filter works to compensate the voltage harmonics on the load side. Series filters can also be useful for fundamental voltage disturbances. The series filter during an occasional supply voltage drop keeps the load voltage almost constant and only small instabilities and oscillations are observed during initial and final edges of disturbance [7].

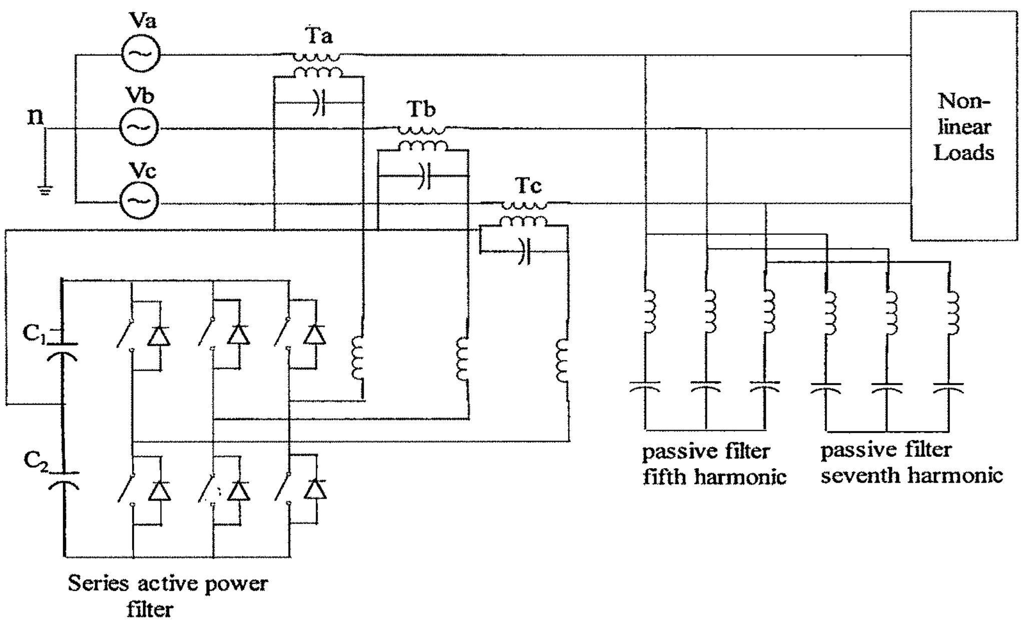

Fig 3.1 Series active power filter topology with shunt passive filters

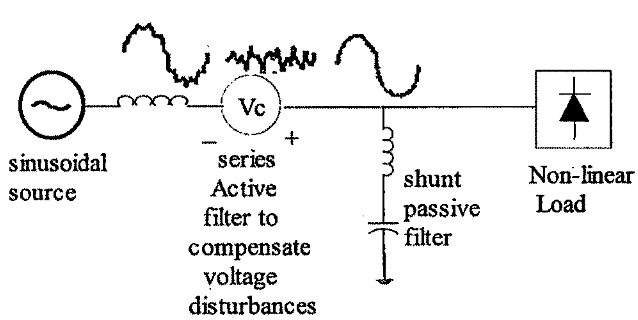

Fig 3.2 Filter voltage generation to compensate voltage disturbances

Fig 3.3 shows the basic compensation principle of series active power filter. A voltage source inverter (VSI) is used as the series active power filter. This is controlled so as to draw or inject a compensating voltage V_c from or to the supply, such that it cancels voltage harmonics on the load side i.e. this active power filter (APF) generates the distortions opposite to the supply harmonics. Fig 3.4 shows the different waveforms i.e.

source voltage, desired load voltage and the compensating voltage injected by the series active power filter which contains all the harmonics, to make the load voltage purely sinusoidal. This is the basic principle of series active power filter to eliminate the supply voltage harmonics [18].

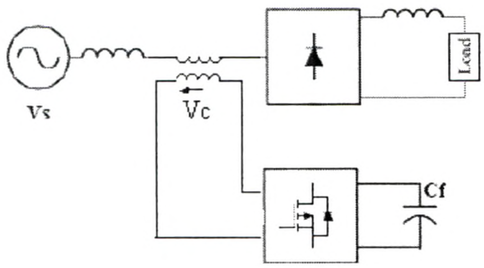

Fig 3.3 Basic compensation principle

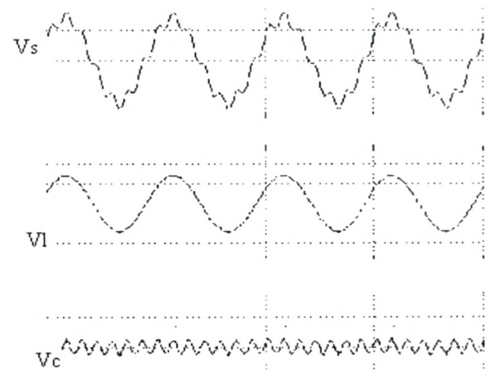

Fig 3.4 Waveforms for the supply voltage, Desired load voltage and the Compensating voltage (filter voltage)

3.2 Design of Reference Voltage and Control Scheme

This Section introduces the control algorithm of the series active power filter, which compensates for harmonics and reactive power. The three-phase voltages v_a, v_b and v_c and currents i_a, i_b and i_c for the three-phase three-wire power distribution system is shown in Fig. 3.5

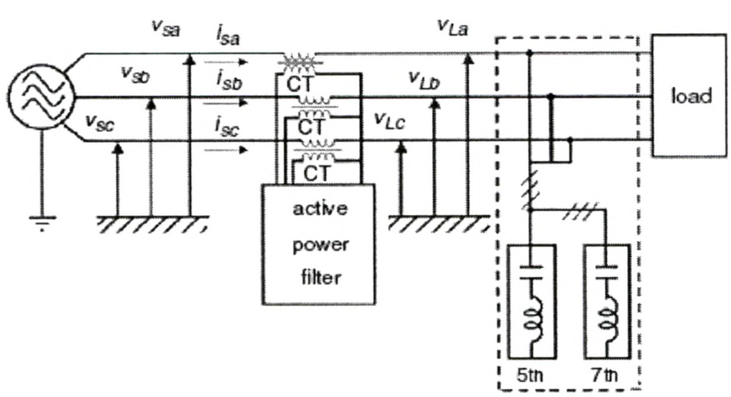

Fig 3.5 Circuit configuration for series active power filter

The three-phase load voltages $v_{L(a,b,c)}$ and the three-phase source currents $i_{s(a,b,c)}$ are represented as:

$$v_{L(a,b,c)} = \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix}, \qquad i_{s(a,b,c)} = \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{3.1}$$

The load voltage vector $v_{L(a,b,c)}$ and the source current vector $i_{s(a,b,c)}$ of (3.1) are transformed into $\alpha\beta 0$ co-ordinates by the substituting (3.3) into (3.2) as

$$v_{L(\alpha,\beta,0)} = \begin{bmatrix} v_{(L\alpha)} \\ v_{(L\beta)} \\ v_{(L0)} \end{bmatrix}, \qquad i_{s(\alpha,\beta,0)} = [T]\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{s0} \end{bmatrix} \tag{3.2}$$

$$[T] = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{3.3}$$

The active power p can be expressed as (3.4) by the inner product of the load voltage vector $v_{L(\alpha,\beta,0)}$ and the source current vector $i_{s(\alpha,\beta,0)}$ of (3.2), where the active power p is the instantaneous active power at the load side of the CT in Fig. 3.2.

$$p = v_{L(\alpha,\beta,0)}\, i_{s(\alpha,\beta,0)} = v_{L\alpha} i_{s\alpha} + v_{L\beta} i_{s\beta} + v_{L0} i_{s0} \tag{3.4}$$

Also, the reactive power $q_{L(\alpha,\beta,0)}$ is represented as (3.5) by the cross product of $v_{L(\alpha,\beta,0)}$ and $i_{s(\alpha,\beta,0)}$

$$q_{L(\alpha,\beta,0)} = v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} = \begin{bmatrix} q_{L\alpha} \\ q_{L\beta} \\ q_{L0} \end{bmatrix} = \begin{bmatrix} \begin{vmatrix} v_{L\beta} & v_{L0} \\ i_{s\beta} & i_{s0} \end{vmatrix} \\ \begin{vmatrix} v_{L0} & v_{L\alpha} \\ i_{s0} & i_{s\alpha} \end{vmatrix} \\ \begin{vmatrix} v_{L\alpha} & v_{L\beta} \\ i_{s\alpha} & i_{s\beta} \end{vmatrix} \end{bmatrix} \tag{3.5}$$

$$q = \left\| q_{L(\alpha,\beta,0)} \right\| = \left\| v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} \right\| \tag{3.6}$$

Where, q is the instantaneous reactive power at the load side of the CT in Fig.3.2.

For a three-phase system without zero sequence voltage and current, i.e. $v_a + v_b + v_c = 0$, and $i_a + i_b + i_c = 0$ ($v_{L0} = \frac{1}{3}(v_a + v_b + v_c) = 0$ and $i_{s0} = \frac{1}{3}(i_a + i_b + i_c) = 0$), (3.4) and (3.5) can be expressed as follows:

$$p = v_{L(\alpha,\beta,0)} \dot{i}_{s(\alpha,\beta,0)} = v_{L\alpha} \dot{i}_{s\alpha} + v_{L\beta} \dot{i}_{s\beta} \tag{3.7}$$

$$q_{L(\alpha,\beta,0)} = v_{L(\alpha,\beta,0)} \times \dot{i}_{s(\alpha,\beta,0)} = \begin{bmatrix} q_{L\alpha} \\ q_{L\beta} \\ q_{L0} \end{bmatrix}$$

$$= \begin{bmatrix} |0| \\ |0| \\ \begin{vmatrix} v_{L\alpha} & v_{L\beta} \\ i_{s\alpha} & i_{s\beta} \end{vmatrix} \end{bmatrix} \tag{3.8}$$

From (3.1)–(3.5), the active voltage vector $v_{p(\alpha,\beta,0)}$ and the reactive voltage vector $v_{q(\alpha,\beta,0)}$ are defined as follows:

$$v_{p(\alpha,\beta,0)} = \frac{p}{\dot{i}_{(\alpha,\beta,0)} \cdot \dot{i}_{(\alpha,\beta,0)}} \dot{i}_{(\alpha,\beta,0)} \tag{3.9}$$

$$v_{q(\alpha,\beta,0)} = \frac{q_{(\alpha,\beta,0)} \times \dot{i}_{(\alpha,\beta,0)}}{\dot{i}_{(\alpha,\beta,0)} \dot{i}_{(\alpha,\beta,0)}} \tag{3.10}$$

The active voltage vector and the reactive voltage vector can be obtained by the vector norm of the three-phase load voltage vector, which is known from (3.9), (3.10). In other words, $v_{p(\alpha,\beta,0)}$ represents the parallel component of the load voltage vector $v_{L(\alpha,\beta,0)}$ to the current vector $i_{s(\alpha,\beta,0)}$; $v_{q(\alpha,\beta,0)}$ represents the perpendicular component of the load voltage vector $v_{L(\alpha,\beta,0)}$ to the current vector $i_{s(\alpha,\beta,0)}$. As a result, the load voltage vector is represented by the sum of the active voltage vector $v_{p(\alpha,\beta,0)}$ and the reactive voltage vector $v_{q(\alpha,\beta,0)}$ as follows:

$$v_{L(\alpha,\beta,0)} = v_{p(\alpha,\beta,0)} + v_{q(\alpha,\beta,0)} \tag{3.11}$$

The active voltage vector $v_{p(\alpha,\beta,0)}$ is induced as follows, using the projection of the load voltage vector $v_{L(\alpha,\beta,0)}$ onto the current vector $i_{s(\alpha,\beta,0)}$:

$$
\begin{aligned}
v_{p(\alpha,\beta,0)} = \mathrm{proj}_{i} v_{L(\alpha,\beta,0)} &= \frac{v_{L(\alpha,\beta,0)} \cdot i_{s(\alpha,\beta,0)}}{\left\| i_{s(\alpha,\beta,0)} \right\|^2} i_{s(\alpha,\beta,0)} \\
&= \frac{v_{L\alpha} i_{s\alpha} + v_{L\beta} i_{s\beta} + v_{L0} i_{s0}}{i_{s\alpha}^2 + i_{s\beta}^2 + i_{s0}^2} i_{s(\alpha,\beta,0)} \\
&= \frac{p}{i_{s\alpha}^2 + i_{s\beta}^2 + i_{s0}^2} i_{s(\alpha,\beta,0)}
\end{aligned} \tag{3.12}
$$

The reactive voltage vector $v_{q(\alpha,\beta,0)}$, which is perpendicular to the active voltage vector $v_{p(\alpha,\beta,0)}$, is also induced through (3.13)–(3.16):

$$
\begin{aligned}
q_{L(\alpha,\beta,0)} &= v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} \\
i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)} &= i_{s(\alpha,\beta,0)} \times \left(v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} \right)
\end{aligned} \tag{3.13}
$$

$$
\begin{aligned}
&= \left(i_{s(\alpha,\beta,0)} \cdot i_{s(\alpha,\beta,0)} \right) v_{L(\alpha,\beta,0)} - \left(i_{s(\alpha,\beta,0)} \cdot v_{L(\alpha,\beta,0)} \right) i_{s(\alpha,\beta,0)} \\
&= \left\| i_{s(\alpha,\beta,0)} \right\|^2 v_{L(\alpha,\beta,0)} - p\, i_{s(\alpha,\beta,0)}
\end{aligned} \tag{3.14}
$$

$$
v_{L(\alpha,\beta,0)} = \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{\left\| i_{s(\alpha,\beta,0)} \right\|^2} + \frac{p}{\left\| i_{s(\alpha,\beta,0)} \right\|^2} i_{s(\alpha,\beta,0)} \tag{3.15}
$$

After taking a cross product on both sides of (3.13), (3.14) is obtained when the right side of (3.13) is unfolded by means of the relations of inner and cross product. After transposing the current vector component of the right-hand side to the left side in (3.14), (3.15) can be obtained. The second term of the right-hand side of (3.15) is the active voltage vector $v_{p(\alpha,\beta,0)}$ and the first term of the right-hand side of (3.15) becomes the reactive voltage vector $v_{q(\alpha,\beta,0)}$:

$$
v_{q(\alpha,\beta,0)} = \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{\left\| i_{s(\alpha,\beta,0)} \right\|^2} = \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{i_{s(\alpha,\beta,0)} \cdot i_{s(\alpha,\beta,0)}} \tag{3.16}
$$

Where $q_{L(\alpha,\beta,0)}$ is equal to the reactive power, which is defined in the instantaneous reactive power theory. The voltage compensation reference of the series active power filter can be represented as (3.17), using $v_{p(\alpha,\beta,0)}$ and $v_{q(\alpha,\beta,0)}$ in (3.9) and (3.10):

$$v^{*}_{C(\alpha,\beta,0)} = \frac{p}{\dot{i}_{s(\alpha,\beta,0)}\dot{i}_{s(\alpha,\beta,0)}}\dot{i}_{s(\alpha,\beta,0)} + \frac{\dot{i}_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{\dot{i}_{s(\alpha,\beta,0)}\dot{i}_{s(\alpha,\beta,0)}} \tag{3.17}$$

The active power and the reactive power can be divided into DC components $\tilde{p}$ and $\tilde{q}$, which are generated from the fundamental components of the load voltages and the source currents, and AC components $\tilde{p}$ and $\tilde{q}$, which are generated from the negative sequence components and the harmonic components of the load voltages and the source currents. If the reactive power q is replaced by the AC component of reactive power $\tilde{q}$, a new voltage compensation reference compensates for the AC component of the active power $\tilde{p}$ and the reactive power $\tilde{q}$.

The compensation voltage reference in $\alpha\beta0$ co-ordinates is obtained from (3.17) and the final compensation voltage reference by transforming this compensation voltage reference in $\alpha\beta0$ co-ordinates into the compensation voltage reference of three-phase co-ordinates. Equation (3.19) is the $\alpha,\beta,0$/three-phase transformation matrix:

$$v^{*}_{C(a,b,c)} = [T]^{-1}\begin{bmatrix} v^{*}_{C\alpha} \\ v^{*}_{C\beta} \\ v^{*}_{C0} \end{bmatrix} = \begin{bmatrix} v^{*}_{Ca} \\ v^{*}_{Cb} \\ v^{*}_{Cc} \end{bmatrix} \tag{3.18}$$

$$[T]^{-1} = \frac{2}{3}\begin{bmatrix} 1 & 0 & 1/2 \\ -1/2 & \sqrt{3}/2 & 1/2 \\ -1/2 & -\sqrt{3}/2 & 1/2 \end{bmatrix} \tag{3.19}$$

The entire algorithm can be explained as: First, three-phase load voltages and source currents are transformed into $\alpha\beta0$ co-ordinates. Then, the active power and the reactive power can be calculated. The AC component of the active power $\tilde{p}$ is extracted by simple filtering. The compensation voltage reference in $\alpha\beta0$ coordinates is calculated by substituting the obtained AC component of the active power, the reactive power and the three-phase currents into (3.17). The final voltage compensation reference for the harmonics and the power factor compensation are obtained by transforming the voltage compensation reference in $\alpha\beta0$ co-ordinates into the voltage compensation reference in three-phase co-ordinates [29].

3.3 Proposed Control block diagram for DVR

The control system employs abc to dqo transformation to dq0 voltages. During normal condition and symmetrical condition, the voltage will be constant and *d*-voltage is unity in p.u. and *q*-voltage is zero in p.u. but during the abnormal conditions it varies [25]. After comparison *d*-voltage and *q*-voltage with the desired voltage error *d* and error *q* is gereted. These error component is converted into *abc* component using *dq0* to *abc* transformation. Phase Locked Loop (PLL) is used to generate unit sinusoidal wave in phase with main voltage. This *abc* components are given to generate three phase Pulses using Pulse Width Modulation (PWM) technique. Proposed control technique block is shown in figure: 3.6 [37].

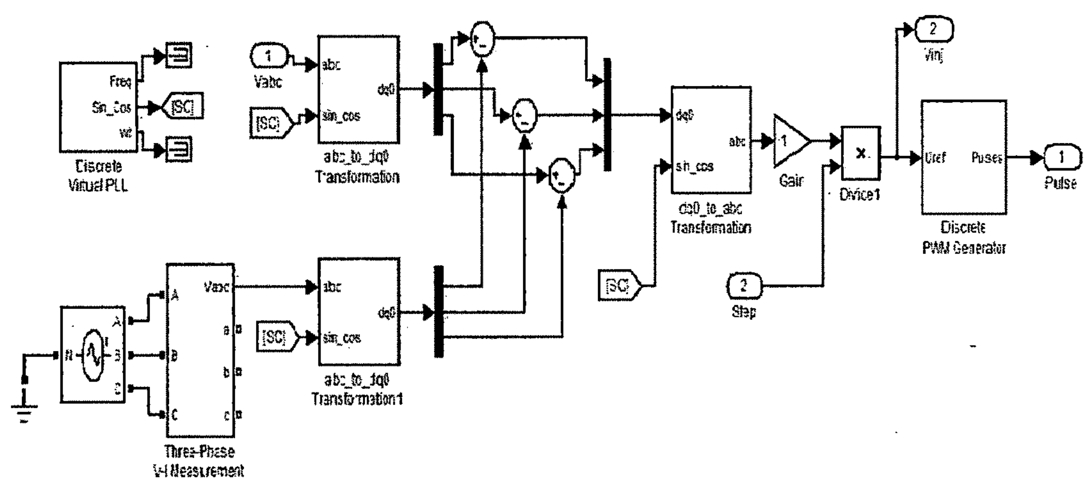

Fig. 3.6 Control block diagram for DVR

3.4 Proposed Simulation Model of Series Active Filter

The model of proposed dynamic voltage restorer is prepared in simulink shown in figure: 3.6 DVR is connecting in series in the distribution system. Programmable voltage source is used as a supply voltage to simulate the voltage sag /swells. This source is responsible to generate the variation in the supply voltage. The primary side of injecting transformer is supplied by voltage sourced converter. The proposed *abc* to *dqo* converter, which is given in figure: 3.6, compares the reference voltage with actual measured voltage of DVR then accordingly generate switching pulse of voltage source converter. A virtual PLL block is used and *sin-cos* is given to *abc* to *dq0* and *dq0* to *abc* converter [38].

The operation of the simulation model shown in chapter 6 of this thesis is described as – first the reference voltages (shown in section 6.3 of chapter 6) are generated and then these reference voltages are compared with the actual load voltages and the error signal is given to the hysteresis controller to generate the firing pulses for the switches of the inverter. The switches are turned on and off in such a way that if the reference voltage is more than the actual load voltage then the lower switch is turned on and the upper switch is turned off and if the reference voltage is less than the actual load voltage then the upper switch of the same leg is turned on and the lower switch is turned off. The output of the series active power filter is fed to the main lines through series transformers so as to make the load voltage purely sinusoidal the harmonic voltage is absorbed or injected by the filter. This has been verified in the simulation results shown in the later chapter of this thesis.

3.5 Conclusion

The DVR restores constant load voltage and voltage wave form by injecting an appropriate voltage. Present novel structure improves power quality by compensating voltage sag and voltage swells. The proposed *abc* to *dqo* converter, compares the reference voltage with actual measured voltage of DVR then accordingly generate switching pulse of voltage source converter. A virtual PLL block is used and *sin-cos* is given to *abc* to *dq0* and *dq0* to *abc* converter. DVR model prepare with help of simulink. The testing of the DVR validates effectiveness of controller