Power Control and Quality Management in DG Grid Interfaced Systems

B. Raghava Rao¹, N. Ram Mohan²

¹ PG Student, Dept. of EEE, V.R. Siddhartha Engineering College, A.P. (state), India.
² Associate Professor, Dept. of EEE, V.R. Siddhartha Engineering College, A.P. (state), India.

ABSTRACT

Renewable energy resources (RES) are being increasingly connected in distribution systems utilizing power electronic converters. This thesis presents a control strategy for achieving maximum benefits from these grid-interfacing inverters when installed in 3-phase 3-wire distribution systems. The inverter is controlled to perform as a multi-function device by incorporating active power filter functionality. The inverter can thus be utilized as a power converter to inject power generated from RES to the grid. The instantaneous reactive power theory (IRP), also known as p–q theory based a new control is proposed for 3-phase three wire and 3-leg shunt active power filter (APF) to suppress harmonic currents, compensate reactive power and neutral line current and balance the line currents under unbalanced non-linear load. The APF is composed from 3-leg voltage source inverter (VSI) with a common DC-link capacitor and hysteresis-band PWM current controller. All of these functions may be accomplished either individually or simultaneously. With such a control, the combination of grid-interfacing inverter and the 3-phase 3-wire non-linear unbalanced load at point of common coupling appears as balanced linear load to the grid. In this thesis instantaneous p-q theory by Clark’s transformation by using PI controller is implemented. A MATLAB/Simulink model has been developed to simulate the system operation.

Keywords: Active filter (APF), Distribution Generation(DG),grid interconnection, power quality , instantaneous p-q theory, PI controller

1. INTRODUCTION

Recently, nonlinear loads are dominantly used in consuming electric energy. Such loads result in power quality degradation. Active power filtering is alternative way to compensate for harmonics produced by these nonlinear loads. For current-type harmonic producing loads, an active power filter must be installed in parallel to inject currents with the same magnitude but the opposite polarity as the undesired currents in order to minimize the harmonic contents at the source side. Under function as a current compensator, a shunt active power filter must be able to make sinusoidal source currents regardless the main voltage conditions therefore the power generated at source side will also contain the ac component.

Renewable energy source (RES) integrated at distribution level is termed as distributed generation (DG). The utility is concerned due to the high penetration level of intermittent RES in distribution systems as it may pose a threat to network in terms of stability, voltage regulation and power-quality (PQ) issues. Therefore, the DG systems are required to comply with strict technical and regulatory frameworks to ensure safe, reliable and efficient operation of overall network. With the advancement in power electronics and digital control technology, the DG systems can now be actively controlled to enhance the system operation with improved PQ at PCC. The harmonic currents and voltages produced by balanced 3-phase non-linear loads such as motor drivers, silicon controlled rectifiers (SCR), large uninterruptible power supplies (UPS) are positive-sequence harmonics (7th, 13th, etc.) and negative-sequence harmonics (5th, 11th, etc.). However, harmonic currents and voltages produced by single phase non-linear loads such as switch-mode power supplies in computer equipment which are connected phase to neutral in a 3-phase 4-wire system are third order zero-sequence harmonics (triplet harmonics—3rd, 9th, 15th, 21st, etc.).

These triplet harmonic currents unlike positive and negative-sequence harmonic currents do not cancel but add up arithmetically at the neutral bus. This can result in neutral current that can reach magnitudes as high as 1.73 times the phase current. In addition to the hazard of cables and transformers overheating the third harmonic can reduce energy efficiency. In this paper that the grid-interfacing inverter can effectively be utilized to perform following important functions: 1) transfer of active power harvested from the renewable resources (wind, solar, etc.); 2) load reactive power demand support; 3) current harmonics compensation at PCC; and 4) current unbalance and neutral current compensation in case of 3-phase 3-wire system. Moreover, with adequate control of grid-interfacing inverter, all the four objectives can be accomplished either individually or simultaneously. The PQ constraints at the PCC can therefore be strictly maintained within the utility standards without additional hardware cost.

2. SYSTEM MODEL
A. TOPOLOGY: Active power filters are power electronic devices that cancel out unwanted harmonic currents by injecting a compensation current which cancels harmonics in the line current. Shunt active power filters compensate load current harmonics by injecting equal-but-opposite harmonic compensating current. Generally, three-wire APFs have been conceived using three leg converters. In this paper, it is shown that using an adequate control strategy, even with a three phase three-wire system, the topology of the investigated APF and its interconnection with the grid is presented in Fig. 1. It consists of a three-leg three-wire voltage source inverter. In this type of applications, the VSI operates as a current controlled voltage source.

B. VOLTAGE SOURCE CONVERTER (VSC): A Voltage Source Converter (VSC) is a power electronic device that connected in shunt or parallel to the system. It can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. It also converts the DC voltage across storage devices into a set of three phase AC output voltages. It is also capable to generate or absorbs reactive power. If the output voltage of the VSC is greater than AC bus terminal voltages, is said to be in capacitive mode. So, it will compensate the reactive power through AC system. The type of power switch used is an IGBT in anti-parallel with a diode. The three phase three leg VSI is modeled in Simulink by using IGBT.

3. P-Q THEORY BASED CONTROL STRATEGY
A. CONTROL STRATEGY
This theory, also known as “instantaneous reactive power theory” was proposed in 1983 by Akagi et al. (Hirfumi 1983 and Hirfumi1984) to control active filters. It based on a set of instantaneous powers defined in time domain. No restrictions are imposed on the voltage or current waveforms, and it can be applied to three-phase systems with or without a neutral wire for three-phase generic voltage and current waveforms. Thus, it is valid not only in steady state, but also in transient states.

The $p-q$ Theory first transforms voltages and currents from the $a-b-c$ to $a-\beta-o$ coordinates, and then defines instantaneous power on these coordinates. Hence, this theory always considers the three-phase system as a unit, not a superposition or sum of three single-phase circuits. The $p-q$ Theory uses the $a-\beta-o$ transformation, also known as the Clarke transformation, which consists of a real matrix that transforms three-phase voltages and currents into the $a-\beta-o$ stationary reference frames. The $a-\beta-o$ transformation or the Clarke transformation maps the three-phase instantaneous voltages and currents in the $a-b-c$ phases into the instantaneous voltages and currents on the $a-\beta-o$ axes.
The Clarke Transformation (Hirfumi 1999) of three-phase generic voltages and load currents are given by

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
\frac{1}{\sqrt{3}} & 1 & \frac{1}{\sqrt{3}} \\
0 & 1 & 0 \\
\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}}
\end{bmatrix} \begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]  
(1)

\[
\begin{bmatrix}
i_{a0} \\
i_{b0} \\
i_{c0}
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
\frac{1}{\sqrt{3}} & 1 & \frac{1}{\sqrt{3}} \\
0 & 1 & 0 \\
\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}}
\end{bmatrix} \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]  
(2)

Form the Eqs. (1) and (2), the \(p-q\) theory consist of an algebraic transformation (Clarke transformation) of the measured 3-phase source voltages \((V_a, V_b, V_c)\) and load currents \((i_a, i_b, i_c)\) in the \(a-b-c\) coordinates to the \(a-\beta-0\) coordinates, followed by the calculation of the instantaneous power components \((p, q, p_0)\). One advantage of applying the \(a-\beta-0\) transformation is to separate zero-sequence component from the \(a-b-c\) phase components. The \(\alpha\) and \(\beta\) axes make no contribution to zero-sequence components. According to The \(p-q\) theory, the instantaneous power components on the load side are defined as:

Instantaneous real power \((p)\), imaginary power \((q)\) and zero sequence power \((p0)\) are calculated as Eq.

\[
\begin{bmatrix}
p \\
q
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
V_a & 0 & V_b \\
0 & V_a & V_b \\
0 & V_b & V\alpha
\end{bmatrix} \begin{bmatrix}
i_a \\
i_b \\
i_\alpha
\end{bmatrix}
\]  
(3)

The total instantaneous power \((p3)\) in 3-phase 3-wire system is calculated as sum of instantaneous real and zero-sequence power.

\[
p_3 = p + p_0 = v_a i_a + v_b i_b + v_c i_c = i_a + i_b + i_c
\]  
(4)

The instantaneous real and imaginary powers include AC and DC values and can be expressed as follows:

\[
p = \hat{p} + p = \hat{p} + p_{2o} + p_h
\]

\[
q = \hat{q} + q = \hat{q} + q_{2o} + q_h
\]  
(5)

DC values \((\hat{p}, \hat{q})\) of the \(p\) and \(q\) are the average active and reactive power originating from the positive-sequence component of the load current. AC values \((\hat{p}, \hat{q})\) of the \(p\) and \(q\) are the ripple active and reactive power originating from harmonic \((ph, qh)\) and negative sequence component \((p2o, q2o)\) of the load current. For harmonic, reactive power compensation and balancing of unbalanced 3-phase load currents, all of the imaginary power \((\hat{q}\) and \(\hat{q}\) components) and harmonic component \(\hat{q}\) of the real power is selected as compensation power references and compensation current reference is calculated as Eq.
\[
\begin{bmatrix}
i_{C\alpha}^n \\
i_{C\beta}^n
\end{bmatrix} = \frac{1}{v_{c}^2 + v_{\beta}^2} \begin{bmatrix}
v_{\alpha} & -v_{\beta} \\
v_{\beta} & v_{c}
\end{bmatrix} \begin{bmatrix}
-p + \Delta p \\
-q
\end{bmatrix}
\]  
(6)

Since the zero-sequence current must be compensated, the reference compensation current in the zero coordinate is \(i_0\) itself:

\[
i_{C0}^* = -i_0
\]  
(7)

The additional average real power (\(\Delta \bar{p}\)) is equal to the sum of \(P_{\text{loss}}\), to cover the VSI losses and \(p0\), to provide energy balance inside the active filter

\[
\Delta \bar{p} = p0 + P_{\text{loss}}
\]  
(8)

The signal \(P_{\text{loss}}\) is used as an average real power and is obtained from the voltage regulator. DC-link voltage regulator is designed to give both good compensation and an excellent transient response. The actual DC-link capacitor voltage is compared by a reference value and the error is processed in a PI controller, which is employed for the voltage control loop since it acts in order to zero the steady-state error of the DC-link voltage.

Equations (6) and (7) represents required compensating current References \(I_{\alpha}^*, I_{\beta}^*, I_{\gamma}^*\) in \(\alpha-\beta-0\) coordinates to match the demanded powers of the load. Eq. (9) is valid to obtain the compensating phase currents \(I_{\alpha}, I_{\beta}, I_{\gamma}\) in the \(a-b-c\) axis in terms of the compensating currents in the \(\alpha-\beta-0\) coordinates:

\[
\begin{bmatrix}
i_{C\alpha}^n \\
i_{C\beta}^n \\
i_{C\gamma}^n
\end{bmatrix} - \sqrt{\frac{2}{3}} \begin{bmatrix}
\frac{1}{2} & 1 & 0 \\
-\frac{1}{2} & \frac{1}{2} & \frac{\sqrt{3}}{2} \\
-\frac{1}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix} \begin{bmatrix}
i_{C\alpha}^n \\
i_{C\beta}^n \\
i_{C\gamma}^n
\end{bmatrix}
\]  
(9)

These load reference currents calculated by the control algorithm equations should be supplied to the power system by switching of the IGBT of the inverter. The method for generation of the switching pattern is achieved by the instantaneous current control of the 3-leg APF currents. The actual 3-leg APF line currents are monitored instantaneously, and then compared to the reference currents generated by the control algorithm. A hysteresis-band PWM current control is implemented to generate the switching pattern of the VSI.

B. PI CONTROLLER

The controller used is the discrete PI controller that takes in the reference voltage and the actual voltage and gives the maximum value of the reference current depending on the error in the reference and the actual values. The difference of this filtered dc-link voltage and reference dc-link voltage (\(V_{dc\*}\)) is given to a discrete-PI regulator to maintain a constant dc-link voltage under varying generation and load conditions.

The mathematical equations for the discrete PI controller are:

The voltage error \(V_{dc\text{err}(n)}\) at the nth sampling instant is given as:

\[
V_{dc\text{err}(n)} = V_{dc\text{err}(n-1)} + K_{PV}V_{dc}(n) - K_{IV}V_{dc\text{err}(n)}
\]  
(10)

The output of discrete-PI regulator at nth sampling instant is expressed as

\[
I_{m(n)} = I_{m(n-1)} + k_{PV}V_{dc\text{err}(n)} + k_{IV}V_{dc\text{err}(n)}
\]  
(11)

Where \(K_{PV} = 0.5\) and \(K_{IV} = 1\) are proportional and integral gains of dc-voltage regulator.

C. HYSTERESIS BASED CURRENT CONTROLLER

The hysteresis control, limit bands are set on either side of a signal representing the desired output waveform. The inverter switches are operated as the generated signals within limits. Hysteresis-band PWM is basically an instantaneous feedback control method of PWM where the actual signal continually tracks the command signal within a hysteresis band. In this controller compare the measured and reference compensating currents and given gate signals to inverter.
**D. SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Phase Supply (r.m.s)</td>
<td>Vg = 400 V, 50 Hz</td>
</tr>
<tr>
<td>3 Phase Rs and Ls</td>
<td>0.001 Ω, 10-5 mH</td>
</tr>
<tr>
<td>3 Phase Line R, L</td>
<td>0.01 Ω, 0.001 mH</td>
</tr>
<tr>
<td>3 Phase Non-linear Load</td>
<td>R=4 Ω, L=10-3 H</td>
</tr>
<tr>
<td>DC-Link Capacitance &amp; voltage</td>
<td>Cdc =800μF, Vdc= 1100V</td>
</tr>
<tr>
<td>Coupling Inductance</td>
<td>Lf=2.0 mH</td>
</tr>
</tbody>
</table>

**SIMULATION DIAGRAM AND RESULTS**

**Fig 4.** Basic principle of hysteresis band control

**Fig 5.** Simulink model for grid interfaced inverter

**Fig 6.** Control circuit for shunt active filter
RESULTS

Fig 7 Grid Voltage, Compensating APF, Neutral current waveform

Fig 8 DC Voltage, Load current, Grid Current waveform

Fig 9 Combination of Compensating and load current waveform
CONCLUSION

This paper presented novel control of an existing grid interfacing inverter to improve the power quality at PCC for a 3 phase 3 wire DG system. The grid interfacing inverter with the proposed approach can be utilized to: Reactive power compensation; current harmonics compensation at PCC; and current unbalance and neutral current compensation in case of 3-phase 3-wire system. Moreover, with adequate control of grid-interfacing inverter, all the four objectives can be accomplished either individually or simultaneously. The modeling and simulation of grid interfacing inverter controlled with instantaneous reactive power theory (IRP) also known as p-q theory with PI controller has been developed using MATLAB/Simulink. The current unbalance, current harmonics and reactive power compensation, due to unbalanced and
non linear load connected at PCC, are compensated effectively such that grid side currents are always maintained as balanced and sinusoidal. Inverter is not connected to grid and load common point (PCC) by using PI controller the THD of the grid current before at 0.2 sec, is 2.94%. Inverter is connected at PCC after 0.2 sec the grid currents THD is reduced to 2.58%. The inverter generates compensation current depend on load demand. The harmonic content (<5%) level IEEE standard.

REFERENCES