Abstract—Grid connected PWM-VSIs are being increasingly used for applications such as Distributed Generation (DG), power quality, UPS etc. Appropriate control strategies for grid synchronisation and line current regulation are required to establish such a grid interconnection and power transfer. Control of three phase VSIs is widely reported in literature. Conventionally, d-q control in Synchronous Reference Frame (SRF) is employed for both PLL and line current control where PI-controllers are used to track the DC references. Single phase systems do not have defined direct (d) and quadrature (q) axis components that are required for SRF transformation. Thus, references are AC in nature and hence usage of PI controllers cannot yield zero steady state errors.

Resonant controllers have the ability to track AC references accurately. In this work, a resonant controller based single phase PLL and current control technique are being employed for tracking grid frequency and the AC current reference respectively. A single phase full bridge converter is being operated as a STATCOM for performance evaluation of the control scheme.

I. INTRODUCTION

Now a days, grid connected pulse width modulation based voltage source inverters (PWM-VSIs) are becoming exceedingly popular for applications such as DG, power quality, UPS etc. Filters are invariably required to bring down the current and voltage distortions caused by harmonics injected by the VSI into the grid. Many a times, a transformer is also employed after the filter stage to adjust the output voltage level to that of the grid.

It is a well known fact that power transfer can take place between two active sources only if their frequencies are matched. In the present case, the two active sources are the grid and the power converter respectively. To establish power transfer between them, grid frequency must be accurately known. Typically, a Phase Locked Loop (PLL) is employed for the purpose of tracking grid frequency. Also, for the overall control, current regulated PWM methods are preferred to voltage controlled PWM methods due to high dynamic performance requirements [4]. Thus a current controller is required to regulate the converter line current.

The control of three phase VSI is widely reported in literature [5]. Typically, d-q control/vector control technique is employed where the AC quantities are transformed to DC through Synchronous Reference Frame (SRF) transformation. Consequently, all references become DC in nature and conventional PI controllers would suffice to yield zero steady state errors. The design of PI controllers and PLL implementation (for grid synchronisation) are quite straightforward and well discussed in literature [1].

However, for single phase systems, SRF transformation is not feasible as direct and quadrature axes are not defined. All references in this case are AC in nature [9]. As a result, usage of PI controllers cannot yield zero steady state errors [6]. Its performance may be acceptable if the system bandwidth is very high. But many a times, bandwidth is limited especially at higher power levels. Again, single phase PLL implementation is not as straightforward as the three phase case. In this work, to address these problems, a resonant integrator is being employed for both single phase PLL implementation and line current regulation. The control scheme is implemented on a 3kVA, 240V single phase full bridge converter which is being operated as a STATCOM. Grid interfacing is done through an integrated higher order filter-transformer. The controller design for the system is explained in section-II.
II. RESONANT INTEGRATOR

A resonant integrator is a generalised AC second order integrator with a tuned resonant frequency $\omega_0$ [3], [8]. The construct of a resonant integrator is shown in Fig.2 and its transfer function is given by Eq.(1). The gain of the resonant controller is infinite at the tuned resonant frequency.

$$H(s) = \frac{p(s)}{e(s)} = \frac{k_i s}{s^2 + \omega_0^2} \quad (1)$$

When $\omega_0$ is set to zero, it reduces to a simple integrator or an integral controller. An Integral controller offers infinite gain only at DC. This essentially means for DC references, the loop gain of a system with a PI controller becomes infinity and thus steady state error is forced to zero. For a reference of any other frequency, loop gain is finite and hence steady state error is also finite.

On the contrary, a proportional-resonant (PR) controller makes the system loop gain infinite at the tuned resonant frequency $\omega_0$ and thereby eliminating any steady state error at that frequency. This can be shown by using internal model principle [6]. For a grid connected application, $\omega_0$ could be appropriately set corresponding to grid frequency (50Hz) such that line current tracks the AC reference.

III. SINGLE PHASE PLL

A PLL structure is a feedback control system that automatically adjusts the phase of a locally generated signal to match the phase of an input signal. A general single phase dq-PLL structure shown in Fig.4. This scheme is based on a three phase dq-PLL except for the orthogonal vector generation scheme. Details of orthogonal vector generation is explained in section-III(A). In case of a three phase PLL, a set of three grid voltages are available as input, and the required stationary frame orthogonal vectors ($V_\alpha$ and $V_\beta$) are generated by conventional three phase to two phase transformation. Once the orthogonal vectors are found, SRF transformation can be applied to obtain the corresponding d-q components of the grid voltage space. SRF transformation is given by,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos (\phi) & \sin (\phi) \\ -\sin (\phi) & \cos (\phi) \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (2)$$

which finally yields the required governing equation,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \frac{3}{2} V_g \cos (\omega t - \phi) \\ \frac{3}{2} V_g \sin (\omega t - \phi) \end{bmatrix} \quad (3)$$

Now, by suitably setting the references, the grid voltage spacer could aligned along either d or q axis. For instance, to align the grid spacer along q-axis, it is required to set $V_d$ to zero. Information about the grid voltage peak is not required. Once this alignment is done, q-axis would correspond to real power axis and d-axis would stand for reactive power. Method of symmetrical optimum may be used to calculate the PLL’s PI controller gains [1].

In case of a single phase PLL, the two orthogonal vectors must be generated from the single available grid voltage. Various single phase PLL schemes such as transport delay method [2], pure integrator method, all-pass function method, inverse Park transformation method [2] etc. are available. Each differs from the other in the way of generation of these orthogonal vectors. In this work, the required orthogonal vectors are generated with the help of a resonant integrator [3].
A. Orthogonal vector generation

Fig.6 represents a scheme for generating two orthogonal sine waves.

![Resonant integrator based orthogonal vector generation scheme for single phase PLL](image)

It uses two integrators connected back to back. $V_g$ represents the grid voltage. Here, $\omega_0$ is set corresponding to 50Hz. The structure offers infinite gain to error (which is at 50Hz at the start) and ensures that it quickly converges to zero. Thus, $V_{ph}$ is always made to follow the 50Hz component of $V_g$. This is exemplified by Fig.7 and Eq.(4). It can be seen that the structure inherently has filtering property for input frequencies other than 50Hz.

$$V_{ph}(s) = \frac{\omega_0 s}{s^2 + \omega_0 s + \omega_0^2} \quad (4)$$

Fig.8 shows the frequency response of the quadrature component $V_{qd}$.

$$V_{qd}'(s) = \frac{\omega_0^2}{s^2 + \omega_0 s + \omega_0^2} \quad (5)$$

It can be clearly seen that the DC gain of Eq.(5) is unity. This means, if the grid voltage $V_g$ happens to have a DC offset, it would directly get reflected in $V_{qd}'$. But this is not the case with $V_{ph}$, $V_d$ and $V_q$ are no longer DC quantities due do the DC offset present in $V_{qd}'$ and this introduces ripples in the PI controller output of the PLL. These DC offsets may be introduced in the sensor stage and/or in the analog to digital conversion process in the digital controller.

IV. SINGLE PHASE CLOSED LOOP CONTROL

A single phase full bridge power converter is being operated as a STATCOM. The power circuit of the system is shown in Fig.1. The overall control structure to operate the power converter as a single phase STATCOM is shown in Fig.10. For closed loop control, an outer voltage loop for DC bus voltage maintenance and an inner current loop for converter line current regulation are required. A PI controller would suffice for outer voltage loop. For the current loop, a PR controller is being employed. The inner current loop is designed to be...
faster than the outer voltage loop. The control loop bandwidths used in the design are,

\[ f_{BW(outer)} \leq \frac{f_{BW(inner)}}{10} \]  

(6)

\[ f_{BW(inner)} \leq \frac{f_{SW}}{10} \]  

(7)

A. DC bus voltage determination

Before closing the control loop, it is essential to know the desired boost level of DC bus voltage so as to set reference for the outer voltage control loop. This value for the STATCOM, depends on the maximum amount of leading reactive current that needs to be drawn from the grid for a given value of filter inductance.

\[ V_{i(peak)} = V_{dcbus} = V_{g(peak)} + \omega LI_{g(peak)} \]  

(8)

Assume \( V_{dcbus} = 400V \)  

(10)

B. Control strategy

In a conventional three phase case where d-q control is employed, \( I_q \) and \( I_d \) represent real current and reactive current reference respectively (in synchronous reference frame), provided the grid spacer is aligned along q-axis [5]. For brevity, same notation is being followed here. However, in this case they represent the actual peak values of real and reactive current references respectively in stationary reference frame. In the three phase case, SRF transformation enables decoupling of active and reactive currents and hence makes independent control active and reactive power possible. In the present case, such an isolation is achieved with the help of PLL which produces sinusoidal unit vectors in phase and quadrature with the grid voltage.

Since the active power requirement in the system is directly reflected as fall in the DC bus voltage, the output of the outer voltage loop is taken as the peak of active current reference denoted as \( I^*_q \) as shown in Fig.10. The corresponding active AC current reference is obtained by merely multiplying the in-phase unit vector with \( I^*_q \). On similar lines, the reactive current reference is obtained by merely multiplying the quadrature unit vector with \( I^*_d \) [10]. Desired \( I^*_q \) may be set externally in the controller. But this is not the case with \( I^*_d \), as it is set by the voltage controller. Feed-forward essentially helps in improving the dynamic performance of the system and completes the decoupling of active and reactive currents. In the present case, the inductive drop feed-forward terms for the current loop can be obtained from the phasor diagram shown in Fig.11. \( V_{gFF} \) represents the grid voltage feed-forward term.

C. Current controller design

PR controller gains can be obtained from the gains selected for the equivalent PI controller (DC compensation network)
for the system. Then, it is transformed into an equivalent AC compensation network [9]. The so obtained regulator gains for the PR controller are,

\[ k_p|_{PR} = k_p|_{PI} \]  
\[ k_i|_{PR} = 2k_i|_{PI} \]

The design procedure here is similar to that of the three phase case [5]. The relevant plant transfer function is given by,

\[ G(s) = \frac{i_i(s)}{V_i(s)} = \frac{1}{R_f + sL_f} \]

The desired PI controller constants are,

\[ k'_p = \frac{L_f}{T_{bw}}, k'_i = k_p\omega_{bw} \]

Therefore, the corresponding constants for PR-controller are,

\[ k_p = \frac{L_f}{T_{bw}}, k_i = 2k_p\omega_{bw} \]

D. Voltage controller design

For DC bus voltage controller design, the gain of inner current loop can be assumed to be unity (from Eq.(6) and Eq.(7)). To begin with, the same design methodology as that of a three phase case is adopted.

\[ k = \frac{I_{dc}}{I_{ac}} = \frac{V_i - i_r(rms)}{\sqrt{2}V_{dc}} \]  
\[ k_k_v = \frac{1}{sT_v} \]  
\[ k_v = \frac{\sqrt{2}CV_{dc}}{V_i - i_r(rms)T_v} \]

The voltage controller gains were slightly varied from design values to achieve satisfactory system response. The design values are listed in Table.I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{rated}$</td>
<td>3kVA</td>
</tr>
<tr>
<td>$V_{rated}$</td>
<td>240V</td>
</tr>
<tr>
<td>$I_{rated}$</td>
<td>12.5A</td>
</tr>
<tr>
<td>$f_{dc-bus}$</td>
<td>400V</td>
</tr>
<tr>
<td>$f_{bw}$</td>
<td>10kHz</td>
</tr>
<tr>
<td>$f_{bw(inner)}$</td>
<td>600Hz</td>
</tr>
<tr>
<td>$k_p$</td>
<td>4.68</td>
</tr>
<tr>
<td>$k_i$</td>
<td>35286</td>
</tr>
<tr>
<td>$f_{bw(outer)}$</td>
<td>8Hz</td>
</tr>
<tr>
<td>$k_v$</td>
<td>2.5</td>
</tr>
<tr>
<td>$T_v$</td>
<td>120ms</td>
</tr>
</tbody>
</table>

V. EXPERIMENTAL RESULTS

A 3kVA IGBT based single phase full bridge power converter was operated as a STATCOM. Sine-triangle comparison PWM technique was employed for switching the IGBTs of the power converter. FPGA based digital platform with ALTERA CYCLONE EP1C12Q240C8 chip was employed for control implementation. Experimental results pertaining to PLL responses are shown in Fig.(14-15) and those pertaining to current controller performance are shown in Fig.(16-17). Fig.14 shows the response of the PLL at start-up. The PLL is able to track the grid voltage within half a cycle. Fig.15 shows that the PLL continues to track the grid voltage even with 40% sag. Fig.16 shows the current feedback and reference signals in the digital controller and the measured output current and voltage at 2.5 kVA leading p.f steady state operation. Fig.17 shows the measured output current and grid voltage for a reactive leading reference current change from 10% to 90% in the digital controller. Fig.18 gives a close up view of the output current transient for a leading reactive reference current change from 10% to 90%. It can be noticed that the inverter current starts tracking the reference within a quarter cycle.

VI. CONCLUSION

A single phase full bridge grid interactive power converter has been designed and tested. A resonant integrator based PLL
and AC current controller has been designed for fast transient response of less than a quarter cycle. Experimental results pertaining to STATCOM mode of operation with reactive power reference have been furnished. This type of a power converter control finds application in DG, power quality, UPS etc.

REFERENCES


