CHAPTER 3

CONCEPTS OF CONTROL OF GRID CONNECTED CONVERTERS WITH EMPHASIS ON SYNCHRONOUS REFERENCE FRAME CONTROLLER

3.1 INTRODUCTION

In distributed generation various renewable energy sources may be available and the voltage-current characteristics of each of them will have a distinctive pattern. Depending on the type of generating system, different type of converter configurations and control structures are adapted for effective transfer of power from these generators to the utility. This chapter presents a technical introduction to the concept of current control of grid connected converters used in distributed generation for power transfer. This chapter starts with the generic structure of the converter systems and briefs about control a strategy in different reference frames and explains the synchronous reference frame control in detail.

3.2 OVERVIEW OF GRID CONNECTED CONVERTER STRUCTURE

In distributed generation, most of the times, the outputs of a good number of renewable energy sources are either dc or variable ac, for e.g. in solar PV the output is dc whereas in wind or micro-turbines the output is variable ac. This demands a power electronic interface between the renewable source and the grid, which can convert the available dc to the phase, form and magnitude as demanded by the grid. In addition, independent active and reactive power control, improved power quality and grid synchronization are
achieved through the power electronic interface. The control structures are to be developed for these power electronic interfaces such that the grid connection requirements imposed by the utility are met in a viable and economical way.

Figure 3.1 Grid connected PV system topologies

Different type of converters are proposed in the literature vary from the line commutated converters to multi stage converters to multi-level converters etc. Very common topologies found in most of the literature are single and two-stage converter schemes as shown in Figure.3.1 with their desired control capabilities.

Figure 3.2 Three phase Voltage source inverter connected to grid
In a two stage converter system the first stage is typically a dc-dc converter used for maximum power point tracking, and the grid side converter takes care of the synchronization, power control, taking care of power quality issues etc. In contrast all these control capabilities are obtained through the inverter control in a single stage converter scheme. A switched mode voltage source inverter as shown in Figure. 3.2 with gate controlled devices like IGBT, MOSFET etc, are commonly found and used in the literature for ac voltage generation.

3.3 GENERAL STRUCTURE OF CONTROL OF GRID CONNECTED CONVERTERS

Grid connected converters find application in a wide variety of fields such as distributed generation, Active power filters, UPF rectifiers, HVDC systems etc. These converters works as inverters when the power flow is from the dc side to ac side and vice versa when they operate as rectifiers. The control capabilities and the structure of these converters are very much generic irrespective of the mode of operation, except the direction of power flow.

Some of the control capabilities of such inverters are (a) AC voltage generation (b) Independent control of active and reactive powers (c) synchronization to grid, (d) meeting or exceeding the harmonics standards, (e) control under grid fault and distorted grid conditions and (v) islanding detection and isolation. These capabilities are achieved through feedback controllers with different controlled and controlling parameters.

The generic structure of the grid-connected converter system is shown in Figure. 3.3, wherein a dc link is shown feeding a voltage source inverter and controlled by various stages of controllers. Irrespective of the number of power stages present in the scheme the grid side converter and its
associated control will be similar to Figure 3.3. The choice of control strategy is determined by the type of control intended, the system stability and power quality.

Figure 3.3 General structure of control of grid connected converter

3.4 POWER CONTROLLERS

There will be an active power control loop normally an outer loop, to control the active power delivered. This will generate a reference quantity to the inner control loop by various strategies. Commonly used strategies are either instantaneous power balance or Maximum Power Point Tracking
(MPPT) algorithms. In Figure 3.3 the power balance control block receives the dc link voltage as input and compares with its reference quantity if instantaneous power-balance method of active power control is used. The fundamental concept behind this theory is that the capacitor voltage depends on the energy balance between the power received by the VSI and the power delivered by it. If these two are equal then the dc-link voltage will remain constant. If power received by VSI is greater than the power delivered by it, then the extra energy will be put into the capacitance which in turn will elevate its voltage. On the other hand if the power delivered by VSI is greater than the power received, then the additional power is supplied by the capacitor results in the reduction of its voltage. Thus by monitoring the dc-link voltage it is possible to deliver a required amount of active power.

For different renewable energy sources maximum power point tracking algorithms are available which will be used either through additional converter stages or through software implementation. In micro grids there will be active-reactive power references directed by a central control station, maintaining the generation demand balance within the local area. Under these conditions the power reference will be available directly for the control loop, then the actual power delivered will be calculated and compared with the reference.

Similarly by monitoring the grid voltage the reactive power can be maintained in the grid connected systems through the reactive power control block. This block receives the reference quantity according to one or more of the following requirements (i) the reactive power support to be provided by the converter, (ii) The power factor at which the current to be delivered, (iii) voltage control at the ac grid. Nevertheless, most of the time the reactive power reference is set to zero for delivering current at unity power factor.

These loops use controllers for forcing the actual quantities to follow the reference quantities. A PI controller found used in most of the
literature because neither the dc link voltage nor the power values will have the phase, frequency information rather they are mere dc values. They are just values or numbers so it is sufficient to use simple first order controllers which will not increase the order of the system so that to have a well guarded phase margin to maintain stability of the overall system.

3.5 CURRENT CONTROLLERS

The output of the power controller is received as input for the inner faster current controllers. These inner current loops should produce the necessary voltage and frequency references for the PWM block which follows them. The inverter output voltage is the vector sum of the ac grid voltage and the series drop of the filter as well as the grid impedances. Therefore the current controller algorithm should estimate the converter output voltage for a given power reference accounting the filter drop and maintains the power flow to follow the reference. There are various type of current controllers used with various reference frames adapted by various authors in the literature for grid connected converters. Some of the common reference frame controllers are

(i) Natural reference frame controllers
(ii) Stationary Reference frame controllers
(iii) Synchronous Reference frame controllers

3.5.1 Natural reference frame or abc reference frame controllers

In this type of control the quantities to be controlled are maintained in their natural reference frame itself. Figure 3.4 shows the control of VSI in abc reference frame adapted by Timbus et al. (2009). Here the controlled quantities are the phase currents $i_a, i_b$ and $i_c$ they are kept in the same form and the comparison and control happens in the same frame. So, for controlling three phase currents three controllers are required, and the neutral point of the
output transformer is to be connected with the inverter’s ground point so as to control the phase current independently. The outer loop can have simple PI controllers as both the controlling quantities are mere dc quantities.

![Control of grid connect VSI in abc reference frame](image)

**Figure 3.4 Control of grid connect VSI in abc reference frame**

The dependency of the phase currents on each other should be considered while designing the controller. The commonly used controllers for current regulation in this reference frame are hysteresis controller, dead beat and bang-bang controllers etc. Requirement of large sampling frequency so as to have large switching frequency is a major bottleneck in this scheme. Also another main limitation is that the switching frequency is not constant and so the harmonics as well. So, designing the output filter becomes a challenge or rather the filter will be bulky and expensive. Yet, its faster dynamics makes it a suitable contender for grid connected applications.

### 3.5.2 Stationary α-β frame controllers

![Control of grid connect VSI in α-β reference frame](image)

**Figure 3.5 Control of grid connect VSI in α-β reference frame**
The control of the grid connected VSI in $\alpha-\beta$ reference frame is shown in Figure 3.5. Here the number of controlled parameters are reduced from three to two, but with an additional computational overhead introduced due to the reference frame transformation of the three phase quantities into two phase quantities. The controller can no longer be the conventional PI controller as the quantities even after transformation are still time varying. So, the well known limitation of PI controller for ac quantities the steady state error will persist if used. A new class of controller called the PR controllers are advocated which, can operate directly with time varying $abc$ quantities.

PR controller, proposed by Timbus et al. (2006), R. Teodorescu et al. (2006) and Li et al. (2012), for grid connected applications tracks the ac reference quantities with zero steady state error without introducing any phase delay. However, PR controller is very sensitive to the grid frequency fluctuations, as it introduces infinite gain at grid frequency. It is shown by Zmood & Holmes (2003) that, if the frequency is outside the band the system may go to unstable conditions unless, the band is wide enough which in turn causes increased steady state error. In addition, harmonic compensations can also be introduced without affecting the fundamental component control is an added advantage for PR controllers.

### 3.5.3 Basics of Synchronous Reference frame controllers

Linear PI regulators are time tested and proven first order controllers having ample phase margin makes it best suitable for the control of dynamically interacting control systems. However, the main limitation as mentioned above is its incapability in tracking AC reference quantities because, a PI controller has infinite gain only at DC or zero frequency as shown in its bode plot in Figure 3.6. Consequently, if the references are time varying quantities, then the PI controller does not work well, as the integral action in PI regulator is very much allied to the averaging of the errors, and
the ac quantities having zero average value results failure of the integral action in the PI regulators.

If the ac quantities are suitably represented as dc quantities to the regulator then the PI regulators can be comfortably used to gain the advantages of it. One of the solutions to this technical hitch is to adapt a reference frame transformation for the conversion of the ac quantities of a constant frequency into dc quantities temporarily for taking control action. Figure 3.7 shows the representation of the alternating controlled parameters represented in different reference frames in a typical control loop as depicted by Rakesh Parekh (2005).
Thus in this control method the ac quantities are first transformed into dc quantities using synchronously rotating reference frame transformations as done by Choi & Sul (1998), Kadri (2011), Haque (2010), Waleed Al-Saedi (2013), Bin Liu (2013), Milosevic (2003), Zmood & Holmes (2003), Noroozian et al. (2010). These transformations make it possible to derive a dc control loop to track the ac quantities with zero steady state error. The information about the phase, of the grid voltage is necessary for the $abc \rightarrow dq$ transformations. Several techniques are available in the literature for obtaining the instantaneous phase information of the grid voltage, but synchronous-reference-frame (SRF) Phase Locked Loop (PLL) (SRF-PLL) are reported to be the state of the art technique and so the same is utilized in the present research work.

3.5.4 Reference Frame Transformations

(a) Two-phase Representation of Three-phase Variables in the Stationary Reference Frame

The method of representing three-phase signals by an equivalent set of two-phase signals is in use for several decades for the purpose of simplification of the calculations and is proposed by Clarke (1950) (1951). This transformation fetched its name as Clarke’s transformation due to its inventor. It transforms three-phase $abc$ signals in a two phase orthogonal system in stationary reference frame called $\alpha-\beta$ frame where both the $\alpha$ and $\beta$ axes are locked in position by the transformation. This transformation is now broadly used in the electrical machine analysis and in the control of power electronic converters due to the advantage of working with reduced number of signals than the actual. The orthogonal stationary reference frames $\alpha$ and $\beta$ are shown in Figure 3.8 and equation (3.1) presents the Clarke transformation to convert the $abc$ currents to $\alpha-\beta$ currents.
Figure 3.8 Two phase current signals from a three phase system with stationary reference frame (α-β) and synchronously rotating reference frame (d-q)

The abc to α-β transformation is shown in matrix form as,

\[
\begin{bmatrix}
I_{\alpha} \\
I_{\beta} \\
I_{\gamma}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix}
\] (3.1)

The scaling factor 2/3 is considered for amplitude invariant transformations. In a balanced three phase systems \(I_a + I_b + I_c = 0\) and \(I_\gamma = 0\) resulting in a simplified transform as,

\[
\begin{bmatrix}
I_{\alpha} \\
I_{\beta}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix}
\] (3.2)
This means that with two measured line currents the $\alpha-\beta$ current components can be calculated. Also, in many of the practical applications like grid synchronization, variable frequency drives etc. only line to line voltages are accessible rather than the phase to ground voltages, even then, the $\alpha-\beta$ components of the voltages can be calculated from the line to line voltages using equation 3.2. The simplified inverse transform for converting the quantities back to $abc$ is given as,

\[
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} = \frac{3}{2} \begin{bmatrix}
\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}}
\end{bmatrix} \begin{bmatrix}
I_a' \\
I_b' \\
I_c'
\end{bmatrix}
\]  

(3.3)

(b) Two-phase Representation of Three-phase Variables in the Synchronously rotating Reference Frame

The three phase signals represented in the stationary reference frame are time varying quantities as the frame is stationary. If the quantities need to look like time invariant, then the observer or the frame of reference should also be rotating along with the rotating space vector. Such a frame of reference is called the $dq$-Synchronous Reference Frame (SRF), proposed by Park (1929) for the analysis of synchronous machines. Considering the q-axis to be leading the d-axis by $90^0$ as shown in Figure 3.8, the transformation from $abc$ signals to $dq0$ signals is given as,

\[
\begin{bmatrix}
I_d \\
I_q \\
I_0
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\cos \theta & \cos (\theta - 2\frac{\pi}{3}) & \cos (\theta + 2\frac{\pi}{3})
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix}
\]  

(3.4)
Where, $\theta$ is the reference phase angle shown in Figure. 3.8, thus this transformation requires the reference phase angle information. As mentioned above the phase angle information is obtained using PLLs. The inverse transformation of $dq0$ to $abc$ is given as,

$$
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & -\sin \theta & 1 \\
\cos (\theta - \frac{2\pi}{3}) & -\sin (\theta - \frac{2\pi}{3}) & 1 \\
\cos (\theta + \frac{2\pi}{3}) & -\sin (\theta + \frac{2\pi}{3}) & 1
\end{bmatrix}
\begin{bmatrix}
I_d \\
I_q \\
I_0
\end{bmatrix}
$$

The zero sequence components in equation (3.4) & (3.5) can be ignored when considering three phase three wire systems using the simplified transforms as treated in the stationary reference frame.

3.5.5 Modeling of Synchronous Reference Frame Current Controllers for Grid Connected VSI

Control of grid connected VSI in synchronous reference frame (SRF) starts with the transformation of the control variables from their natural frame, i.e. time varying frame into SRF. Then, the control variables appear as dc quantities and the control action is performed with simple PI controllers with the transfer function as

$$ F(s) = K_p + \frac{K_i}{s} $$

Where, $K_p$ is the proportional gain and $K_i$ is the integral gain.

Figure 3.9 shows the circuit diagram of three phase grid connected VSI. The three pole voltages of the inverter are shown as $u_a$, $u_b$, and $u_c$, the grid voltages are shown as $e_a$, $e_b$, and $e_c$. $L_f$ in Figure 3.9 is the filter inductance, $R$ is the
resistance from the inverter till the grid, $L_g$ is the line inductance. The currents injected into the grid in each phase are shown as $i_a$, $i_b$ and $i_c$.

![Figure 3.9 Three phase grid connected VSI](image)

**Figure 3.9 Three phase grid connected VSI**

![Figure 3.10 Inverter feeding to the grid - A single phase equivalent circuit](image)

**Figure 3.10 Inverter feeding to the grid - A single phase equivalent circuit**

The single phase equivalent circuit of the three phase grid connected VSI is presented in Figure 3.10. The differential equation for the system of Figure 3.10 for the shown current/power flow direction is expressed as,

$$
\begin{bmatrix}
  u_a \\
  u_b \\
  u_c \\
\end{bmatrix} = R \begin{bmatrix}
  i_a \\
  i_b \\
  i_c \\
\end{bmatrix} + L \frac{d}{dt} \begin{bmatrix}
  i_a \\
  i_b \\
  i_c \\
\end{bmatrix} + \begin{bmatrix}
  e_a \\
  e_b \\
  e_c \\
\end{bmatrix}
$$

(3.7)

Where, L is the total inductance from the inverter to the mains, i.e. $L = L_i + L_g$. Equation (3.7) can be rewritten as
On differentiating equation (3.11) & (3.12) results

\[ L \frac{di_{abc}}{dt} + Ri_{abc} = u_{abc} - e_{abc} \]  
(3.8)

\[ L \frac{di_{abc}}{dt} + Ri_{abc} = \Delta v_{abc} \]  
(3.9)

Where, \( \Delta v_{abc} = u_{abc} - e_{abc} \). The abc to dq transformations for the line currents in

matrix form is given as,

\[
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
    \cos \omega t & \cos(\omega t - 120^\circ) & \cos(\omega t + 120^\circ) \\
    -\sin \omega t & -\sin(\omega t - 120^\circ) & -\sin(\omega t + 120^\circ)
\end{bmatrix}
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix}
\]  
(3.10)

Where \( \omega = \frac{2 \pi f}{120} \) and \( f \) is the grid frequency. Equation (3.10) can be resolved as

separate expressions of \( i_d \) and \( i_q \) as,

\[
i_d = \frac{2}{3} \begin{bmatrix}
    i_a \cos \omega t + i_b \cos(\omega t - 120^\circ) + i_c \cos(\omega t + 120^\circ)
\end{bmatrix}
\]  
(3.11)

\[
i_q = -\frac{2}{3} \begin{bmatrix}
    i_a \sin \omega t + i_b \sin(\omega t - 120^\circ) + i_c \sin(\omega t + 120^\circ)
\end{bmatrix}
\]  
(3.12)

Similarly \( \Delta v_{abc} \) transformed to dq results,

\[
\Delta V_d = \frac{2}{3} \begin{bmatrix}
    \Delta v_a \cos \omega t + \Delta v_b \cos(\omega t - 120^\circ) + \Delta v_c \cos(\omega t + 120^\circ)
\end{bmatrix}
\]  
(3.13)

\[
\Delta V_q = -\frac{2}{3} \begin{bmatrix}
    \Delta v_a \sin \omega t + \Delta v_b \sin(\omega t - 120^\circ) + \Delta v_c \sin(\omega t + 120^\circ)
\end{bmatrix}
\]  
(3.14)

On differentiating equation (3.11) & (3.12) results \( di_d/dt \) and \( di_q/dt \) as,

\[
\frac{di_d}{dt} = \frac{2}{3} \begin{bmatrix}
    \frac{di_a}{dt} \cos \omega t + \frac{di_b}{dt} \cos(\omega t - 120^\circ) + \frac{di_c}{dt} \cos(\omega t + 120^\circ)
\end{bmatrix}
\]

\[
-\frac{2}{3} \omega \begin{bmatrix}
    i_a \sin \omega t + i_b \sin(\omega t - 120^\circ) + i_c \sin(\omega t + 120^\circ)
\end{bmatrix}
\]  
(3.15)

\[
\frac{di_q}{dt} = -\frac{2}{3} \begin{bmatrix}
    \frac{di_a}{dt} \sin \omega t + \frac{di_b}{dt} \sin(\omega t - 120^\circ) + \frac{di_c}{dt} \sin(\omega t + 120^\circ)
\end{bmatrix}
\]

\[
-\frac{2}{3} \omega \begin{bmatrix}
    i_a \cos \omega t + i_b \cos(\omega t - 120^\circ) + i_c \cos(\omega t + 120^\circ)
\end{bmatrix}
\]  
(3.16)
Obtaining the values of \( di_a/dt \), \( di_b/dt \) and \( di_c/dt \) from equation (3.9) results,

\[
\begin{align*}
\frac{di_a}{dt} &= \frac{\Lambda v_a}{L} - \frac{R}{L} i_a \\
\frac{di_b}{dt} &= \frac{\Lambda v_b}{L} - \frac{R}{L} i_b \\
\frac{di_c}{dt} &= \frac{\Lambda v_c}{L} - \frac{R}{L} i_c
\end{align*}
\]

(3.17)

Substituting the values of equation (3.17) into equation (3.15) gives,

\[
\frac{di_a}{dt} = \frac{2}{3} \left[ \left( \frac{\Lambda v_a}{L} - \frac{R}{L} i_a \right) \cos \omega t + \left( \frac{\Lambda v_b}{L} - \frac{R}{L} i_b \right) \cos(\omega t - 120^\circ) + \left( \frac{\Lambda v_c}{L} - \frac{R}{L} i_c \right) \cos(\omega t + 120^\circ) \right] + \omega i_a
\]

(3.18)

On rearranging equation (3.18),

\[
\frac{di_a}{dt} = \left[ \frac{2}{3} \left( \frac{\Lambda v_a}{L} \cos \omega t + \frac{\Lambda v_b}{L} \cos(\omega t - 120^\circ) + \frac{\Lambda v_c}{L} \cos(\omega t + 120^\circ) \right) \right] - \frac{2}{3} \left( i_a \cos \omega t + i_b \cos(\omega t - 120^\circ) + i_c \cos(\omega t + 120^\circ) \right) + \omega i_a
\]

(3.19)

In equation (3.19) Term I is \( \Delta V_d \) from equation (3.13) and Term II is \( i_d \) from equation (3.11). Rewriting equation (3.19) using these values gives,

\[
\frac{di_a}{dt} = \frac{1}{L} \Delta V_d - \frac{R}{L} i_d + \omega L i_q
\]

(3.20)

\[
L \frac{d(\Delta i_d)}{dt} = \Delta V_d - R i_d + \omega L i_q
\]

(3.21)
Substituting $\Delta V_d = u_d - e_d$, results, the $d$-axis inverter output voltage to be established to deliver the $d$-axis current $i_d$ into the grid against its voltage $e_d$.

$$u_d = e_d + Ri_d + L \frac{di_d}{dt} - \omega Li_q$$  \hspace{1cm} (3.22)

Proceeding in a similar way to find the $q$-axis inverter voltage component by substituting the values of equation (3.17) into equation (3.16) gives,

$$\frac{di_q}{dt} = \frac{2}{3} \left( \Delta V_a \sin \phi t + \Delta V_b \sin (\phi t - 120^\circ) + \Delta V_c \sin (\phi t + 120^\circ) \right) \sin (\phi t + 120^\circ) - \omega i_d$$ \hspace{1cm} (3.23)

On rearranging equation (3.23),

$$\frac{di_q}{dt} = \left[ \frac{2}{3} \left( \Delta V_a \sin \phi t + \Delta V_b \sin (\phi t - 120^\circ) + \Delta V_c \sin (\phi t + 120^\circ) \right) \right] - \frac{2}{3} R \left( i_a \sin (\phi t) + i_b \sin (\phi t - 120^\circ) + i_c \sin (\phi t + 120^\circ) \right) - \omega i_d$$ \hspace{1cm} (3.24)

In equation (3.25) Term I is $\Delta V_q$ from equation (3.14) and Term II is $i_q$ from equation (3.12). Rewriting equation (3.25) using these values gives,

$$\frac{di_q}{dt} = \frac{1}{L} \Delta V_q - \frac{R}{L} i_q - \omega Li_q$$ \hspace{1cm} (3.26)
\[ L \frac{d i_q}{dt} = \Delta V_q - Ri_q - \omega L i_d \]  

(3.27)

Substituting \( \Delta V_q = u_q - e_q \), results, the \( q \)-axis inverter output voltage to be established to deliver the \( q \)-axis current \( i_q \) into the grid against its voltage \( e_q \).

\[ u_q = e_q + Ri_q + L \frac{d i_q}{dt} + \omega Li_d \]  

(3.28)

Equation (3.7) can be written in synchronously rotating reference frame from the results of equations (3.22) and (3.28) as,

\[ u_{dq} = L \frac{d i_{dq}}{dt} + jL \omega i_{dq} + e_{dq} \]  

(3.29)

By taking Laplace transform of equation (3.29), the complex transfer function \( G(s) \) is derived as,

\[ G(s) = \frac{1}{(s + j\omega)L + R} \]  

(3.30)

this current controller is presented in block diagram form in Figure 3.11, where the grid voltage is modelled as a load disturbance, which is subtracted from the control voltage signal \( u \), i.e. the inverter pole voltage for the required output current vector. The power electronic circuit which supplies the voltage \( "u" \) is a voltage source inverter produces the desired voltages with no time delay and with low harmonic distortion.

**Figure 3.11 Block diagram of the current controller**
Thus the reference required for the inverter control is established using equations (3.22) and (3.28). Based on these equations the general block diagram for current control of grid connected VSI in synchronous reference frame is obtained as shown in Figure. 3.12, where \( i_d^* \), \( i_q^* \) are \( d \) and \( q \) axes reference currents respectively. A PLL gives the necessary phase information of the grid voltage to the \( abc-dq \) transformation blocks.

![Diagram](image-url)

**Figure 3.12 General block diagram of current control of VSI in synchronous reference frame**

The voltage drop due to the line impedance is compensated using a PI controller of equation (3.6) in each control loop. The control equations for \( u_d \) and \( u_q \) are given as

\[
 u_d = e_d - \omega L_i + \left( K_p + \frac{K_i}{s} \right) (i_d^* - i_d) \tag{3.31}
\]
\[ u_q = e_q + \omega L_i_q + \left( K_p + \frac{K}{s} \right)(i_q^r - i_q) \]  

(3.32)

Also the active power \( P \) and reactive power \( Q \) in the SRF using \( dq \) quantities are given as

\[ P = \frac{3}{2} \left( u_d i_d + u_q i_q \right) \]  

(3.33)

\[ Q = \frac{3}{2} \left( u_d i_q - u_q i_d \right) \]  

(3.34)

By observing the equations (3.33) & (3.34) it is understood that the active and reactive powers depends on both \( d \) and \( q \) axis quantities. So it will not be possible to control \( P \) & \( Q \) independently, means that a decoupling is required between these equations. If \( u_q \) is made zero by some means, then the active and reactive power are controlled independently by the \( d \)-axis current and the \( q \)-axis current respectively. This provides the required decoupling between these two equations. Voltage \( u_q \) can be made zero if the \( d \)-axis is align with the voltage space-vector, making the \( q \)-component always zero. This condition is achieved, if voltage at the PLL’s connection point is taken as the reference for \( dq \) frame transformations then the space-vector is aligned with the \( d \)-axis thus, \( u_q = 0 \). Now, the active and reactive power equations are decoupled and expressed as,

\[ P = \frac{3}{2} u_d i_d \]  

(3.35)

\[ Q = \frac{3}{2} u_d i_q \]  

(3.36)

With reference to equations (3.22) & (3.28), \( u_d \) and \( u_q \) are the control voltages in \( d \) and \( q \) axes respectively, and will get updated upon a change in the reference quantities which inturn will change the active or reactive power delivered by the inverter. It can be observed that still there exists a cross coupling between the \( d \) axis and \( q \) axis voltages due to the
presence of the complex inductance drops represented by the terms $j\omega L_i$ in equation (3.29). Here, the $d$ axis control voltage $u_d$ not only depends on the $d$ axis current but also on the $q$ axis current and vice versa, i.e. two first order systems, are interacting with each other resulting a cross couplings. Because of the presence of the cross coupling terms still complete independency in the active-reactive power control is not achieved.

### 3.5.6 Cross Coupling Cancellation

The removal of cross coupling is discussed by Fernando Briz et al. (2000) and Ostlund Stefan (2008) for vector control of induction motor. The cancellation of cross coupling is done by cancelling the complex drop due to the inductance by moving the pole of the plant $G(s)$ from $-\left(\frac{R}{L} + j\omega\right)$ to $-\left(\frac{R}{L}\right)$ in synchronous reference frame and by adding a real zero by the compensator. This is achieved by selecting a control voltage $u_{dq}$ as,

$$u_{dq} = u_{dq}^* + j\omega L_i_{dq}$$  \hspace{1cm} (3.37)

By substituting $u_{dq}$ from equation (3.37) in equation (3.29) a feed forward decoupling is introduced and the control equation for the decoupled system is obtained as,

$$L \frac{di_{dq}}{dt} = u_{dq}^* - Ri_{dq} - e_{dq}$$  \hspace{1cm} (3.38)

It is evident that there is no cross coupling in equation (3.38) as there is no complex valued coefficients. Equation (3.37) is modelled as an inner feedback loop and a current regulator having its output as $u_{dq}^*$ is designed as an outer loop for the decoupled system.
The block diagram of the decoupled control system with the new control voltage as in equation (3.37) is given in Figure 3.13, where $i_{dq}$ is the reference vector expressed as

$$i_{dq} = i_d^* + j i_q^*$$

(3.39)

The transfer function of the decoupled system from $u_{dq}^*$ to $i_{dq}$ is expressed as,

$$G'(s) = \frac{1}{sL + R}$$

(3.40)

![Figure 3.13 Current control with an inner decoupling loop](image)

Now this first order complex valued system with no interacting terms can be regulated using PI controller with transfer function as $F(s) = k_p + k_i/s$.

Summarizing the feed forward decoupling process in the grid connected VSIs as follows: There exists a dependency of active and reactive powers on each other due to the non-unity power factor current delivered with the presence of filter and the source inductances. This is causing a cross
coupling term linking the d-axis and q-axis control loops in SRF control schemes as seen from equations (3.22) and (3.28) represented by the $i_{dqOL}$ terms in each equation. This makes the control action to be influenced by the structure and model of the system, i.e. whenever the current delivered by the converter changes or the inductance seen by the converter changes the performance is affected. In order to make the control insusceptible to these changes a feed forward decoupling term using the grid impedance value is introduced in the control loops. These feed forward decoupling terms remove the cross coupling between the active and reactive power loops resulting, a complete independency in the active and reactive power controls.

### 3.5.7 Tuning of the PI controllers for the grid connected VSI

The transfer function of PI controller mentioned in equation (3.6) is repeated here for the sake of reference as,

$$F(s) = K_p + \frac{K_i}{s}$$

The constants $K_p$ and $K_i$ decides the transfer function and the location of the poles and zeros of the PI compensator. Commonly, $K_p$ and $K_i$ are selected by trial-and-error in most of the literature. But in the current research work a method called “loop shaping” is followed for tuning the PI-controller proposed by Ostlund Stefan (2008), Harnefors Lennart & Hans-Peter Nee (2002). It starts by assigning a reasonable rise time for the closed loop system. For the present work, a rise time of 1ms is considered, which is very much possible using Transistor/IGBT inverters.

With $G'(s)$ being a complex order one system, the resulting closed loop transfer function is also intended to be obtained as order one, i.e.
\[ G_c(s) = \frac{\alpha}{s + \alpha} \]  

\text{(3.40)}

Where \( \alpha \) is the closed-loop system bandwidth. For a first order system the standard relationship between the rise time \( t_r \) and bandwidth is,

\[ \alpha t_r = \ln 9 \]  

\text{(3.41)}

So, the specification for the rise time can be correlated with the specification for bandwidth of the closed loop system. The closed loop transfer function is obtained using \( F(s) \)-the compensator transfer function from equation (3.6) and the plant transfer function of the grid connected VSI from equation (3.40). But the closed loop transfer function for a negative feedback system is expressed as,

\[ G_c(s) = \frac{F(s)G'(s)}{1 + F(s)G'(s)} \]  

\text{(3.42)}

So, if \( F(s)G'(s) \) is selected as,

\[ F(s)G'(s) = \frac{\alpha}{s} \]  

\text{(3.43)}

Then,

\[ G_c(s) = \frac{F(s)G'(s)}{1 + F(s)G'(s)} = \frac{\alpha/s}{1 + \alpha/s} = \frac{\alpha}{s + \alpha} \]  

\text{(3.44)}

By observing equation (3.44), it is found that it is equal to equation (3.40). That means the desired closed loop response is achieved. The simplification of equation (3.43), results,

\[ F(s) = \frac{\alpha}{s} (G'(s))^{-1} = \frac{\alpha}{s} (sL + R) = \alpha L + \frac{\alpha R}{s} \]  

\text{(3.45)}
Equation (3.45) appears to be similar to equation of the PI controller equation (3.1), so by comparing equation (3.1) and equation (3.45) the $K_p$ and $K_i$ values are obtained as,

$$
K_p = \alpha L \\
K_i = \alpha R
$$

(3.46)

Using this method the controller parameters are expressed as the required closed loop bandwidth and the parameters present in the plant transfer function, i.e. L and R. This method of tuning of PI controller avoids the trial and error steps and gives better stability for the entire bandwidth especially for systems with PWM switching converters.

### 3.5.8 Synchronous Reference Frame Phase Locked Loop (SRF-PLL)

An important part of grid connected converters is the synchronization module. The voltage, phase and frequency of the converter should track the grid quantities continuously to maintain the asynchronous link. Failing to maintain such a link may lead firstly to large circulating currents which may damage the converter and its associated equipments, secondly the direction of power flow i.e. it cannot be maintain always from the dc side to ac side. This issue is not very critical when the power is fed into the large electrical grids, where the frequency is relatively stiff due to large capacity generators. It is a known fact that, in AC power systems, the frequency stability is a function of the inertia of the generators and loads connected to it. Moreover, it also depends on the magnitude of load change and/or generator prime mover power output changes.

When it comes to small AC micro-grids the inertia and system frequency stability becomes a questionable issue. Because small micro-grids will not have large inertia generators, and the power output from renewable
sources are highly intermittent and fluctuating, thus demanding an accurate synchronization technique. The synchronization algorithm is expected to gives the phase of the grid voltage vector which can be used to synchronize the grid currents and voltages.

When the control algorithm gives out the d-axis and q-axis reference voltages for the inverter, then the Pulse Width Modulator should generate the gating signals such that the reference voltages are seen at the output of the inverter. Many types of PWM techniques are available in the literature as mentioned in chapter 2, but in the current research work Space-vector PWM (SVPWM) is followed which is explained in Appendix 1. For the SVPWM the reference needs to be in the form of a space-vector, specified with a magnitude and a phase. The magnitude information comes from the control algorithm, but the phase information should be generated from the grid voltage. A PLL is used to obtain the phase information for the reference frame transformation blocks as well as for the SVPWM block.

Even though quite a lot of techniques are available for grid synchronization of VSIs, the state of the art suggests the use of the synchronous-reference-frame phase locked loop (SRF-PLL) to obtain the instantaneous phase information of the grid voltage. It is basically a simple closed-loop control scheme formed with a phase detector, a PI regulator acting as a filter, and a unit vector generator. It has inbuilt feature for rejection of grid harmonics and any other disturbances if at all present in the grid voltage.

The block diagram of the SRF-PLL is presented in Figure 3.14. The phase detection unit of SRF PLL is merely a reference frame transformation unit which transforms the three phase voltages into dq voltages in SRF. The angle of the space vector resulting from the transformation is being synchronized with the grid voltage phase angle. A PI controller is used
to force the $q$-axis voltage zero under steady state resulting the output unit sine wave or the grid phase angle $\theta$ in phase with the grid voltage. Unit $\sin$ or unit $\cos$ waves are generated from the PLL for the obtained values of $\theta$ 'using a sine or cosine look-up tables stored in the memory as unit vectors. Depending on the type of PWM used either unit sine wave or the instantaneous phase “$\theta$” of the grid voltage from PLL can be used as reference.

![Figure 3.14 Synchronous reference frame PLL](image)

The concept of SRF PLL is explained through mathematical relationships as follows, the Rotating reference frame transformation from stationary $\alpha\beta$ frame is given by

\[
v_q + jv_d = (v_\alpha + v_\beta) e^{-j\theta}
\]

\[
v_q = V_m \sin (\theta - \theta')
\]

\[
v_d = V_m \cos (\theta - \theta')
\]

Where,

\[
v_\alpha = V_m \sin (\theta)
\]

\[
v_\beta = V_m \cos (\theta)
\]
With $\theta = \omega t$, For $\theta = \theta'$, $v_q = 0$; and for small $(\theta - \theta')$ it can be assumed that

$$v_q \approx V_m (\dot{\theta} - \dot{\theta'})$$

(3.49)

The PI controller forces the $v_q$ component to zero thus tracks the instantaneous phase angle of the grid.

### 3.5.9 Implementation of SRF current controller for grid connected VSI in MATLAB/Simulink

The basic grid connected system of Figure 3.12 is implemented in MATLAB/Simulink for design and decoupling verification. This helps to understand the system operation under various conditions without direct hardware implementation. Various aspects of the system like dynamic response, steady state response, frequency tracking, harmonic content, active power delivered and reactive power consumption are studied through simulation.

It consists of a 3 leg IGBT VSI connected to grid through an L filter. It is used to interface a 1kVA inverter to the grid with the current control is being achieved using a PI controller. SVPWM is used to generate the gate pulses for the inverter, with code written in Embedded MATLAB function presented in Appendix 2. The inverter is synchronized with the grid using SRF PLL. The design of the power circuit is as follows

**(a) Selection of switching frequency**

Switching frequency is selected as 4 kHz, as described by Ned Mohan et al. (2008) that in most applications the switching frequency is selected either less than 6 kHz or greater than 20 kHz to be above the audible range. A relatively low value of switching frequency is selected for the current research work so as to reduce the switching losses as well as the
sampling frequency of the ADC of the microcontroller while hardware implementing.

**(b) Output filter design**

Harmonics filter is designed such that it attenuates the ripples at switching frequency \( f_s \). The value of \( L \) is chosen such that the ripples at \( f_s \) are attenuated by 80 times to that of the fundamental frequency components at the output of the inverter. i.e.

\[
2\pi f_s L = 80 \times (2\pi f_s L)
\]

(3.50)

So, the drop in the series filter inductor at the rated output condition due to fundamental component of current is 80 times less compared to the drop due to the switching frequency current component. And this fundamental drop at rated output condition is only 2% of the rated output phase voltages, means that increase in the kVA rating of the inverter is only 2%. An \( L \) value of 11mH is designed which fulfills all the requirements mentioned above.

**(c) DC link voltage selection**

The rated output line to line RMS voltage is 400V. The power capacity of inverter designed is 1 kVA.

Output voltage of SVPWM inverter =

\[
v_{\text{L-L}\text{(rms)}} = 1.15 \times 0.612 \times m_a V_{dc}
\]

(3.51)

Considering the least possible \( m_a \) as 0.8

\[
400 = 1.15 \times 0.612 \times 0.8 \times V_{dc}
\]

\[
\therefore V_{dc} = 710 \text{ V}
\]

So DC link voltage is fixed as 710V.
(d) PI controller tuning

From equation (3.41) with a reasonable and achievable rise time of 1 ms, the bandwidth is found to be 2197 rad/s. From equation (3.46) the values of $K_p$ and $K_i$ are found to be 24 and 505 respectively, the internal resistance of the inductor is found to be 0.23Ω. Figure 3.15 shows the root locus plot of the loop transfer function $F(s)G'(s)$ with the tuned values of $K_p$ and $K_i$. It is found from the root locus plot that the chosen values results a stable loop.

![Root Locus Plot](image)

**Figure 3.15 The root locus ploted with the designed $K_p$ & $K_i$ values**

**Table 3.1 System specifications**

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>1 kVA</td>
</tr>
<tr>
<td>Output Line Voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Output Current</td>
<td>1.44 A</td>
</tr>
<tr>
<td>DC Link Voltage</td>
<td>710 V</td>
</tr>
<tr>
<td>Converter</td>
<td>3 leg IGBT inverter</td>
</tr>
<tr>
<td>Output Filter</td>
<td>L filter = 11mH</td>
</tr>
</tbody>
</table>
3.5.10 Simulation Details of the current controlled VSI in SRF

Figure 3.16 shows the whole closed loop circuit with the specifications as mentioned in Table 3.1. It consists of three leg IGBT/diode inverter block, the abc-dq transformation blocks, L filter, three phase voltage source representing the grid, PLL block, PI controller and the SVPWM block. Each sub system is expanded in following Figures from 3.17 to Figure. 3.21.

Figure 3.16 The closed loop system of contol of grid connected VSI in SRF

Figure 3.17 Control block
The SRF PLL is modeled in MATLAB as shown in Figure 3.18. The block takes phase voltage of the grid as input. Mask parameters are values of $K_p$, $K_i$, initial values of frequency and nominal value of grid phase voltage. The block outputs are instantaneous frequency, grid phase angle $\theta$, $\sin \theta$ and $\cos \theta$. Second order filter is used to remove ripples in frequency estimate. $K_p$ and $K_i$ values used are 180 and 3200 respectively.

**abc to $\alpha\beta$ transformation block and Cartesian to Polar transformation block**

**Figure 3.19 The transformations block**

(a) Clarke's transformation

(b) Cartesian to polar co-ordinate transformation
SVPWM block

SVPWM block shown in Figure 3.20 takes the instantaneous values of magnitude and angle based on which it produces the gate pulses for the inverter. The block estimates the sector and also the duty ratio for each input and the control signal for arm is generated which is compared with a centre aligned triangle pulse. The operation is performed only in every 0.25 ms so that the same can be used as sampling interval while hardware implementing. Embedded MATLAB code for the same is provided in the Appendix 2.

Figure 3.20 SVPWM calculation block

Figure 3.21 Three leg IGBT inverter
3.5.11 Simulation results

3.5.11.1 Steady state grid current

Figure 3.22 Steady state waveform of current injected into the grid and Voltage at PCC

Figure 3.23 Steady state current with zoomed scale

Figure 3.22 and Figure 3.23 shows the current delivered to the grid and voltage at PCC for a power reference of reference of 275 W till 0.6s and subjected to a step change to 1450W during 0.6 to 1.2 s. The rise time for the response to the step change in the $P_{\text{ref}}$ is less than .0025 seconds which shows the ability of controller to track step changes.
**Harmonic Analysis of the current injected**

Figure 3.24 show the FFT analysis of the grid current as a frequency spectrum. THD is well below 5%. All the components are having a magnitude less than 3% which satisfies all grid codes. The Lowest order harmonic appears at 4 kHz the switching frequency and the subsequent harmonics at its multiples.

![FFT analysis of grid current](image)

**Figure 3.24 FFT analysis of grid current**

Figure 3.25 shows the active and reactive power delivered for step changes in their references along with the current delivered. Since power is fed at unity power factor into the grid, the reactive power component is nearly zero for $Q_{ref} = 0$. During t=0.6 s to 1.2 s the $P_{ref}$ is given a step change from 275 W to 1450 W and it is observed from Figure 3.25 that the value of power injected increases instantaneously. But there is no significant change in reactive power for a change in active power. This shows that active and reactive component of power could be independently controlled in the case of SRF-PI current control when delivering power to the grid.
3.5.11.2 Study with step change in grid frequency

The developed grid connected system is studied by introducing a step change in the frequency. Figure 3.26 shows the variation in grid current for a step change of grid frequency from 50 Hz to 52 Hz introduced during 0.4s to 0.6s. The scale is so presented that the find the variation before and after 0.4s. The current instantaneously follows the change in frequency without losing stability. The magnitude of injected current remains the same inspite of frequency changes. This shows that the controller is immune to frequency changes. Such a step change in frequency is not expected in practical situations but this result has been included to demonstrate the fastness of tracking. In practical case frequency variation is restricted to a small band of ± 1Hz.
The developed grid connected system is tested for variation in the grid voltage as this is also a common scenario especially in micro-grids. Figure 3.27 shows the variation in grid current for a variation of line to line voltage of grid from 220 V to 240 V. It is seen that there is no variation in grid current for variations in grid voltage. Correspondingly the inverter voltage increases from 127 V (phase) to 139 V in order to inject same current to a higher grid voltage.
3.6 DISCUSSIONS

The results are summarized as:

1. Both two stage and single stage converters are commonly used converters for grid connected PV systems, with the commonality that the grid side converter is a three phase VSI connected to grid through output filters.
2. L filters are extensively preferred as they are simple first order with large phase margins, to accommodate sensor introduced phase shifts.
3. The control structure has an active and a reactive power control loops as outer loops to regulate the amount of power delivered by the VSI.
4. There are inner current loops which works with the references from the outer power loops and delivers the required voltage reference for the PWM block.
5. The reference for the outer loops can be active and reactive power values obtained from MPPT or from a central control station.
6. The most preferred choice of regulators is PI regulators implemented in SRF.
7. The control voltage equations of the VSI for controlling the active-reactive powers are found interacting i.e. they are cross-coupled.
8. Using the grid impedance value the cross coupling is decoupled, by a feed forward loop.
9. The performance of the controller for grid connected VSI with the designed components are tested using simulation studies for a specific power reference.
10. The testing is extended for step change in power references and under non-ideal grid conditions.
11. From the steady state results it is observed that the SRF-PI controller show a superior axis decoupling performance in terms of reference tracking capability, working with abnormal grid conditions and transient response during step change etc.

3.7 CONCLUSION

The grid connected inverter with L filter is simulated using MATLAB and it is found that the simulation results are matching with the design values. It can be concluded that PI controllers are best suited even for grids in which the values of grid voltage and grid frequency are changing during the operation. From the introduction of the step change in the power references the tracking accuracy of the SRF-PI controllers is evident. A decoupling term using the grid impedance value is introduced in the control loops to remove the cross coupling between the active and reactive power loops. Therefore, the active and reactive power reference changes are not inducing transient changes in each other because the system is now completely decoupled. Also the proposed system does not pollute the grid as THD of grid current is well within the limits.