CHAPTER 4
CURRENT CONTROLLERS IN
TRANSFORMERLESS PV INVERTER TOPOLOGIES

4.1 INTRODUCTION

This chapter provides review and analysis of current controllers for PV inverters. Mostly when voltage source inverters are used, grid current need to be controlled for active and reactive power exchange. The general block diagram for a current controller in PV system is shown in Figure 4.1.

Figure 4.1 General Block Diagram of Current controller for PV grid connected inverter system

According to Teodorescu et al (2011), PWM current control techniques can be classified as

- ON-OFF controllers
  - Hysteresis Controllers
  - Predictive Controllers
- With Pulse width modulators
- Linear controllers
  - PI Controllers
  - Dead-Beat Controllers
  - Resonant Controllers
- Non-Linear controllers
- Passivity controllers
- Fuzzy controllers

This chapter compares classical Proportional Integral (PI) controllers and Proportional Resonant (PR) controllers. PR controllers are further classified as ideal and non-ideal controllers. PI, PR, both ideal and non-ideal controllers are compared (Teodercu et al 2004, Xiaoqiang et al 2008, Gazoli et al 2012). The work is done in MATLAB/SIMULINK.

Xiaoqiang et al (2008) has proposed a virtual capacitor concept to limit DC injection in bipolar PWM. The author has used ideal PR controller along with the modeled capacitance.

Since, unipolar PWM has higher efficiency and better power quality, it has been chosen for evaluation of DC injection elimination in this chapter. The ideal PR controller gives undamped oscillation that render the system unstable. The gain in ideal PR is infinite which saturates the output. Bandwidth is too narrow which makes the system highly sensitive.

This chapter also proposes a non-ideal PR controller which is more stable and less sensitive. The gain is finite and does not saturate the output. This non-ideal PR controller is used in conjunction with modeled capacitance in a unipolar PWM inverter considering the advantages of the same. Equal
value filter inductors are used which eliminate the differential mode component inherent in the common mode voltage.

4.2 COMPARISON OF CONTROLLERS

4.2.1 Proportional Integral Controllers

Block diagram of PI controllers are shown in Figure 4.2.

![PI Controller Block Diagram](image)

**Figure 4.2 PI Controller Block Diagram**

PI controller has the ability to compensate current distortion due to dead-time. PI controller guarantees accurate steady state error tracking only for DC signals. It gives a finite error while tracking sinusoidal references as shown in Figure 4.3.

![PI controller Responses for a) step reference b) sinusoidal reference](image)

**Figure 4.3 PI controller Responses for a) step reference b) sinusoidal reference**
This is attributed to the poor performance of the integral action when the reference is sinusoidal. The amplitude of steady state error depends on closed loop system gain and phase at the selected reference signal frequency.

PI Controller transfer function $G_{PI}(s)$ is given as

$$G_{PI}(s) = K_p + \frac{K_i}{s}$$ \hspace{1cm} (4.1)

To overcome the drawback of sinusoidal reference tracking by PI controller, it is implemented in a dq frame rotating at angular speed $\omega$, ($\omega = 2\pi f$, where $f$ is the grid frequency). The PI controller transfer function after dq frame transformation is given as

$$G_{PI_{-dq}}(s) = \begin{bmatrix} K_p + \frac{K_i}{s} & 0 \\ 0 & K_p + \frac{K_i}{s} \end{bmatrix}$$ \hspace{1cm} (4.2)

In order to compensate for harmonics produced by inverse sequence of grid voltage under unbalanced condition, reference frames in positive as well as negative sequence have to be considered. Rotating frames cannot be used with single phase systems. Therefore additional delay block has to be used to create the necessary quadrature component to convert it into two phase systems.

### 4.2.2 Proportional Resonant Controllers

The complexities of adapting PI controller to track sinusoidal signal by frame transformations can be avoided using resonant controllers. Resonant controllers are developed based on internal model principle which states that to ensure perfect tracking and rejection of disturbances, the model of
disturbance needs to be included within the controller. The resonant controller is implemented using a generalized integrator. The integrator is a double integrator that gives infinite gain at a particular frequency, called resonance frequency (Teodorscu et al 2006). The proportional with resonant controller is shown in Figure 4.4. As can be seen in the block diagram, voltage feed forward is not necessary as in PI controller.

\[ G_{PR}(s) = G_{PI}(s - j\omega) + G_{PI}(s + j\omega) \] 

(4.3)

\[ = \left( K_p + \frac{K_i}{s - j\omega} \right) + \left( K_p + \frac{K_i}{s + j\omega} \right) \]

\[ G_{PR}(s) = 2K_p + \frac{2K_i s}{s^2 + \omega^2} \] 

(4.4)

This gives the transfer function of an ideal PR controller with infinite gain at \( \omega \). The dynamics of the system such as bandwidth, phase and gain margins are determined by \( K_p \) value. \( K_i \) can be adjusted to maintain the gain of the controller.

**Figure 4.4 Proportional Resonant Controller Block Diagram**
Thus a PR controller in stationary frame is equivalent to two PI controllers added, one rotating in synchronous frame and the other rotating in counter synchronous frame with angular velocities $\omega$, each (Buso&Mattavelli 2006).

### 4.2.3 Non-Ideal Proportional Resonant Controllers

The block diagram and implementation of non-ideal PR controller is same as that of ideal controller. For non-ideal PR, the integral part is modified considering a cut off frequency $\omega_c$, such that $\omega_c << \omega$.

\[
\frac{K_i}{1 + \frac{s}{\omega_c}} \tag{4.5}
\]

\[
G_{pl}(s-j\omega) \rightarrow K_p + \frac{K_i}{1 + \frac{s-j\omega}{\omega_c}} \tag{4.6}
\]

\[
G_{pl}(s+j\omega) \rightarrow K_p + \frac{K_i}{1 + \frac{s+j\omega}{\omega_c}} \tag{4.7}
\]

\[
G_{PR\_non\_ideal} = G_{pl}(s-j\omega) + G_{pl}(s+j\omega) \tag{4.8}
\]

\[
G_{PR\_non\_ideal}(s) = K_p + \frac{K_i}{1 + \frac{s-j\omega}{\omega_c}} + \frac{K_i}{1 + \frac{s+j\omega}{\omega_c}} \tag{4.9}
\]

\[
G_{PR\_non\_ideal}(s) = 2K_p + \frac{2K_i(\omega_c s + \omega_c^2)}{s^2 + 2\omega_c s + (\omega_c^2 + \omega^2)} \tag{4.10}
\]
\[ G_{PR\text{-non-ideal}} = 2K_p + \frac{2K_s \omega_c s}{s^2 + 2\omega_c s + \omega_c^2} \]  \hspace{1cm} (4.11)

By using non-ideal PR controller, gain can be made finite and therefore prevents the system from saturation. \( \omega_c \) can be varied to adjust the band width. This fine adjustments in band width can be used to reduce sensitivity of the controller towards very small frequency fluctuations.

4.3 DC INJECTION ELIMINATION USING NON IDEAL PR CONTROLLER IN UNIPOLAR PWM INVERTER

As suggested earlier, the necessity of efficient topologies for photovoltaic (PV) inverters is a concern presently. With the advent of transformerless inverters, the size, volume and cost of PV inverters can be decreased. Efficiency can be increased nearly by 2% by avoiding the galvanic connection. With no galvanic isolation comes the problem of DC injection which poses serious problems like core saturation of distribution transformers and cable corrosion and has to be limited as per IEEE standards (Gertmar et al 2012). A series capacitor in the output of the inverter can limit DC as per analysis done in chapter 3 and proposed by Xiaoqiang et al (2008). This section presents a modified Proportional - Resonant (PR) controller which has better stability and sensitivity than proposed by Xiaoqing et al (2008). The controller is used in conjunction with model capacitor in the output of the inverter avoiding real capacitor overcoming drawbacks of voltage drops and reverse polarity effects. Moreover the proposed control strategy is applied in a unipolar switched H Bridge inverter. A comparison of the DC injection with and without the controller is presented for unipolar pulse width modulated (PWM) inverters.

The series capacitance is modeled along with the PR controller thereby avoiding use of expensive AC capacitors and additional circuitry for
reverse polarity effects. Ideal PR controller used in earlier system produces undamped output and gives saturation problems of the inverter.

This section proposes a non-ideal PR controller to be used in conjunction with model capacitor to achieve better stability and sensitivity and avoid saturation problems. Also equal value filter inductors are used in the inverter output to limit the differential mode component inherent in the common mode model.

![Figure 4.5 Main Circuit Diagram](image)

Unipolar switching is used with the H-bridge shown in Figure 4.5 and the modes of operation has already been explained in chapter 3.

### 4.3.1 Design of Controller

The component used to block DC is the capacitor. In case of half bridge inverters, one of the DC link capacitor is always in the conducting path and blocks DC.

An AC capacitor can block dc injection but amount to large amount of series voltage drop based on the output currents of highly rated inverter. In order to prevent reverse polarity effects on the polarised capacitor, complex DC voltage control methods have to be used. Electrolytic capacitors produce small amounts of AC voltage ripple (Blewitt et al 2010, Berba et al 2012).
Since these capacitors are polarised, they may not be able to withstand reverse voltages. Non-polarised capacitors available are of low capacitances that may cause voltage drops.

A simple linear model, as shown in Figure 4.6, of an H Bridge inverter can be obtained by considering that the DC link voltage is constant, a large DC link capacitance can make the voltage constant, and also the switching frequency should be considerably large.

![Linear model of the inverter](image)

Figure 4.6 Linear model of the inverter

![Bode plot](image)

Figure 4.7 (a) Bode plot of $I_o/I_{ref}$ with and without capacitor
Figure 4.7  (Continued) (b) Bode plot (c) Step response of ideal and non-ideal PR controller d) Step Response of \( \frac{I_o}{I_{\text{ref}}} \) for different values of capacitors
The PR controller is based on the internal model principle. According to this principle, the models of the reference and disturbance are included in the feedback loop. This ensures a very good tracking of the reference in the stationary frame and rejection of disturbances. Stationary proportional integral (PI) controller often produces steady state error in tracking a sinusoidal reference. Synchronous PI reduces steady state errors but its implementation is complex. PR controller offers an additional integrator and is much simpler to implement. The controller avoids the use of a real time capacitor and uses a model of capacitor in its feedback loop. Gain of the controller is given by

\[ G_{PR_{\text{non-ideal}}}(s) = K_p + \frac{K_i \omega Cs}{s^2 + 2\omega s + \omega^2} \]  

(4.12)

\[ \frac{I_0}{I_{ref}} = \frac{KCsG_{PR_{\text{non-ideal}}}}{LCs^2 + RCs + KCsG_{PR_{\text{non-ideal}}}(s) + 1} \]  

(4.13)

where \( G_{PR_{\text{non-ideal}}}(s) \) denotes the non–ideal PR controller transfer function, \( K_p \) is a constant of proportionality and \( K_i \) is a constant of integration, \( K \) is the overall controller gain, \( L=L_R+L_Y \), \( \omega \) is the resonant frequency and \( \omega_c \) is the cut off frequency such that \( \omega_c << \omega \).

Figure 4.7(a) shows the effect of capacitor in system response. It can be seen that by adding capacitance the magnitude plot gives a zero response to zero frequency. The proposed controller is a non ideal PR controller other than that used previously. The ideal PR controller is undamped and has lesser sensitivity due to the very narrow bandwidth. Due to the infinite gain, the inverter output is almost saturated in an ideal PR which can be seen in Figure 4.7 (b),4.27 (c). With the non ideal PR controller, the overall system is under-damped and has better sensitivity because of the adjustable bandwidth which takes care of small variations in frequency. By introducing \( \omega_c \), into the controller design, the bandwidth becomes adjustable.
and as can be observed in Figure 4.7 (b), (c) is more sensitive to frequency variations.

Figure 4.7 (d) shows that as the capacitance increases the dynamic response becomes slow. It can be seen that too small a value of capacitance causes fundamental voltage drop. So a choice has to be made between achievement of a good dynamic response and limited fundamental frequency voltage drop. The controller gives a finite gain and prevents inverter from saturation. Thus this type of controller brings about zero steady state error and better rejection of selected noise as compared to PI controller. This controller has been designed for 50Hz frequency.

4.3.2 Implementation

To validate and analyse the quality of output for unipolar PWM with and without the controller, simulations were performed in MATLAB/Simulink.
Figures 4.8 (a) & 4.8(b) shows the simulation circuits. A DC offset is provided in the sinusoidal reference current, which is effectively eliminated by properly tuning the P+R controller. The PWM delay in the output current is taken care of by time delay introduced in the feedback loop which ensures a sinusoidal error signal given as input to the controller. The overall gain is so fixed as to take care of the stability of the system.

4.3.3 Results

4.3.3.1 Unipolar without Controller

It can be observed through fast Fourier transform (FFT) analysis that DC component present is above the IEEE limits as can be seen in Figure 4.9 (a) & 4.9(b). The utility voltage used is 311Vrms and DC link voltage of 450V. The filter inductors used are 0.1H each and resistor value is 2Ω.

![Output Current](image)

(a)

Figure 4.9 Unipolar Output without controller (a) Output current
Figure 4.9 (continued) Unipolar Output without controller (b) FFT Analysis of Output current

4.3.3.2 Unipolar with controller

It can be observed that DC component is limited to zero as shown in Figure 4.10 (a)&4.10(b). The DC block capacitor is selected as 20mF. The controller gains are $K$ is 400, $K_p$ is 1 and $K_i$ is 10. $\omega_c$ is chosen as 10rad/sec to make the controller sensitive to frequency variations.
Figure 4.10 (continued) Unipolar Output with controller b) FFT Analysis of Output current

4.4 SUMMARY

DC component is an important problem with transformerless inverters which can be avoided by choosing appropriate control strategy, PWM techniques and topology of inverter. This chapter shows that the modified proportional resonant controller along with non real capacitor and equal value inductors can be used to reduce DC Injection. The modified non ideal PR controller has better sensitivity and gives a finite gain compared to the ideal PR controller. A unipolar PWM, in spite of having a varying common mode voltage, gives a good response to the DC blocking capacitor and non-ideal PR controller.

By comparing PI, ideal PR and non-ideal PR, it has been understood that PI has drawbacks in tracking sinusoidal reference. PR
controllers avoid frame transformations as required by PI in tracking sinusoidal reference. Ideal PR, has infinite gain and is highly sensitive and is unstable but non-ideal PR has finite gain and adjustable bandwidth which makes the system less sensitive. Stability of the system is much enhanced by non-ideal PR.