Phase shift control and controller area network assisted proportional resonant control for grid integration of single phase voltage source inverters

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Abstract

Grid integration of inverters using renewable sources of energy is essential for providing a secure and clean source of power supply. Many techniques developed so far control the grid current to realize the regulation of power flow to the power grid. However, implementation of communication assisted synchronization methods for single-phase full-bridge inverters is not found to be discussed in the literature. The focus of this research is to conceptualize, simulate, and implement two control techniques, namely Phase Shift Control (PSC) and Controller Area Network Assisted Proportional Resonant Control (CANAPRC) for single-phase inverters. In the PSC method, the inverter injects the desired real power into the grid by controlling the phase angle between converter and grid voltages. A low complexity synchronization procedure was adopted using single-phase PLL to generate a reference voltage signal using the PSC method. In contrast, the CANAPRC method outputs a current reference created by the resonant controller using a communication network. The inverter can pump the required real and reactive power to the grid with reduced harmonics, enhanced power-sharing and transient stability using the two strategies. Simulations in MATLAB R2016a analyze the two models out effectively. Prototype models validate the proposed control strategies.

1 | INTRODUCTION

Advanced technologies have been developed over the years in making cost-effective and grid friendly converters. The power electronic technology that interfaces the DC/AC source available from distributed generation (DG) with the existing AC source open from the utility is called Voltage Source Converters. Power flow in either direction, minimum variations at the grid side current, and regulation of power are the significant advantages of using voltage source converters. Different topologies for Voltage Source Converters (VSCs) have been analyzed and compared on the grounds of the mode of operation and performance for the grid integration [1], [2].

For the grid interconnection, the most common renewable energy source used in grid-connected inverters is the photovoltaic source. The conventional PV topologies are classified into the ones accompanied by DC/DC converter and other devoid of DC/DC converter. Authors analyzed various single-phase converter structures for on-grid Photo Voltaic plants summarising the inverter types and their historical development in [3]. Also, the Photo-Voltaic inverters are classified on the grounds of the power handling stages. Reliability and maturity of various techniques in renewable energy systems is also a widely considered topic [4].

The different methods of grid interconnection for the single-phase inverters are current hysteresis control (CHC), Voltage-Oriented Control (VOC), and Proportional Resonant based control (PR) [5]. It is a common practice to apply the current control methodologies to distributed generation systems when it comes to controlling strategies. For such systems, the current pumped into the grid follows a sinusoidal reference. In hysteresis current control, output current follows a reference waveform. The inverter’s switches ramp current flow through the filter up and down such that it follows the reference. The
VOC method uses an outer loop for controlling the voltage at the dc link and inner loop for regulating the flow of current in the grid. The benefit of using the Proportional Resonance based control is that a sinusoidal reference current can be tracked without any error at the steady-state in magnitude and phase.

Recent literature throws light on various techniques for regulating power for on-grid single-phase inverters. To list a few, Cha et al. presented and experimented with the current control based on the Proportional Resonant current control strategy and proved the effectiveness of these over the conventional PI control [6], but in Cha’s work, the absence of a communication network leads to reduced power sharing and voltage regulation. Park et al. designed a methodology such that inverter can operate in lead, lag, and the combination injecting real and reactive power components. However, the authors have given due emphasis only on the derivation of the transfer function for the current loop and have not generalized the results [7]. Ching-Ming et al. developed a power tracking technique for a quicker tracking response in photo-voltaic units [8]. The results were not experimentally validated. Azary et al. discusses a transformerless topology of single-phase single-stage flying inductor type capable of suppressing leakage current by the grounding of PV array [9]. The relevant aspects of synchronization could have been precisely discussed, though. Chen et al. proposed a one-dimensional optimization algorithm that determines the tracking performance of the controller [10]. This algorithm helped to adapt Proportional Resonant controllers over different working stages with a minimal error while tracking grid current. Davoodnejhad et al. proposed a technique that exploits the average inverter voltage to tune the band using hysteresis control [11]. The key features of this method were fixed frequency, voltage polarity estimation and grid voltage calibration. Design for current injection using a PI voltage regulator and PR current controller is presented in [12], but the authors did not prove it experimentally.

Orthogonal voltage generation based methods like Park and Hilbert transformation suffer from drawbacks of high complexity and poor response [13]. Though PLL supporting artificial intelligence controller was developed, it is found to be more complex for PV inverters [14]. An IRP-RC theory to improve power quality in DG integrated systems is formulated in [15]. Zhou et al. studied the repetitive controller adapting frequency variations in the grid [16]. Singh et al. reviewed single-phase AC–DC power quality conditioners in [17, 18]. A review of various current control strategies for grid connection of PV systems has been presented extensively by authors in [19]. For household Photovoltaic power generation, a single-phase cascaded H-Bridge multilevel PV inverter was designed using a novel power adaptive control with an extended operating range by Zhao et al. in [20].

Shadmand et al. presented a decoupling power control technique for grid-connected inverters using model predictive control [21]. To add on, Ozturk et al. proposed a new technology called the direct digital synthesis for stand-alone and grid-connected operation for photo-voltaic grid tie micro inverters [22]. An optimal controller that uses a linear quadratic regulator was modelled to minimise harmonic distortion for a five level U-cell inverter [23]. The method provides flexibility and can be easily designed on a simple and affordable digital signal processor. A second-order generalized integrator based PLL recently investigated by Ikken et al. used a strategy to test its ability to create orthogonal tension system in single-phase inverters [24].

From the literature, different methodologies such as repetitive controller, instantaneous reactive power theory, model predictive controller, direct digital synthesis have been studied and effectively practiced for grid-tied inverters. However, communication-assisted grid synchronization techniques are not found to be implemented effectively for single-phase systems of H-bridge converters. Here, the research work finds a new current control called CANAPRC for a single-phase inverter, and this has been simulated and developed in hardware. Besides the CANAPRC, simulation and experimental validation of the simple control called phase angle control has also been presented.

To summarise, in this research work,

1) A low complexity synchronization procedure was adopted using a single-phase PLL to create a voltage reference using the Phase Shift Control (PSC).
2) The author’s design ensures a sufficient increase in active power injection in PSC by controlling the phase angle between the inverter and the grid. The design is economical considering low filter component, small DC link voltage and low rating of the switches.
3) Experimental set up using dSPACE controller validate the proposed method to show that the power-sharing ratio of the inverter and the grid improves to around 31.59% with an increase in phase angle from 5° to 60°.
4) As the next strategy, a novel communication aided synchronization for single phase inverter using CANAPRC is developed.
5) The control scheme’s capability to supply the requisite power to the utility mains for different loads with enhanced power sharing, transient stability, and reduced distortions at the utility side is the breakthrough in work.
6) Simulation and experimental models were also built for sufficient validation of the CANAPRC control strategy.

The paper contains six sections. Section 1 gives an introduction to single-phase voltage source converters and their interconnection to the power grid. Section 2 deals with the basic concepts of synchronization. The third and fourth sections explain the Phase Angle Control and Proportional Resonant current control, respectively. Section 5 gives the model description. The simulation and hardware results obtained by the two novel strategies are presented in Section 6.

2 | CONCEPT OF SYNCHRONIZATION

The synchronisation of inverters to the grid is the process of matching its voltage magnitude, frequency and phase with that of the grid. This section briefly describes the process of
synchronization. The primary step of grid synchronization is to estimate the grid voltage and identify its amplitude, and this is carried out by the grid synchronizer. The grid voltage estimator measures the voltage of the grid at its input. At the same time, its output consists of a signal aligned parallel to the input, $v_{g\parallel}$ (parallel component) and another signal that is 90 deg leading the grid voltage signal, $v_{g\perp}$ (orthogonal). Control of reactive power is possible only if the orthogonal component is present [25]. Figure 1 illustrates the block schematic of the grid

The state space model for the grid synchronizer is displayed in Figure 2. Here, $v_{g}$ represents the grid voltage signal with a frequency $\omega$. The signal output is $x_1$ and tracks the grid voltage, $v_{g}$. The input to the estimator is $v_{g} - x_1$ and output is $x_1$, which acts as the parallel component of $v_{g}$. Let the state matrix be $\hat{A}$. The oscillating frequency, $\omega_0$ is provided by the state matrix. An infinite gain is achieved by the estimator at the oscillating frequency, that is, $\omega_0$. The state space equations are obtained as in Equations (1) and (2).

The factor, $k_{sync}$ in Equation (1) is used to damp the system and expands the bandwidth while reducing the gain at $\omega_0$. As a consequence, $x_1$ follows the grid voltage signal $v_{g}$ and rejects other components of frequency appearing from it. Then, the signal $y_1$ is represented as $v_{g\parallel}$ aligned parallel to the grid voltage and the output $y_2$ is represented as $v_{g\perp}$ that lies perpendicular to grid voltage. The next part of synchronisation is the identification of grid voltage for calculating the magnitude of the grid voltage. The equation for amplitude identification is

$$\hat{V}_g = \sqrt{V_{g\parallel}^2 + V_{g\perp}^2}. \quad (3)$$

Equivalently, we may also write

$$\hat{V}_g = \sqrt{x_1^2 + x_2^2}. \quad (4)$$

There are other methods to identify the magnitude of the grid’s voltage for synchronisation. Detecting the peak point for
the grid voltage or estimating each of the output of the estimator is the option. These options come devoid of the square root operand. The method of detection of the peak is found more accurate compared to the grid voltage estimation method.

3.1 PHASE SHIFT CONTROL

PSC is a simple control method for regulating real power flow in inverters by changing the phase angle between the inverter and the grid. Consider the operation of a switch-mode converter, depicted in Figure 3, for utility interface for further understanding of the PSC. Let \( v_s \) be the supply voltage, \( V_f \) be the drop in voltage through the interconnecting inductor \( V_i \) and \( V_{\text{conv}} \) be the voltage across the converter. Applying Kirchoff’s laws,

\[
V_f = V_{\text{conv}} + V_i. \tag{5}
\]

Assuming \( V_f \) as a sinusoidal quantity, let the fundamental frequency components of \( V_{\text{conv}} \) be represented as vectors \( V_{\text{conv}1} \) and that of the source current be \( I_{11} \), respectively. Then,

\[
V_{11} = j\omega I_{11} I_{11}. \tag{6}
\]

Consider \( \Delta \) OBC in Figure 4, showing the phasor diagram of the switch-mode converter. The following equations can be derived from the above diagram.

\[
\frac{V_{11}}{\sin \delta} = \frac{V_{\text{conv}1}}{\sin(90 - \delta)} = \frac{V_{\text{conv}1}}{\cos \delta}. \tag{7}
\]

\[
V_{11} \cos \delta = V_{\text{conv}1} \sin \delta. \tag{8}
\]

Real power supplied from AC source to converter is obtained as below,
From the above equation, it is clear that active power varies by changing the angle $\delta$. In the inverter mode of operation, the inverter voltage leads the grid voltage by phase angle, $\delta$. For every increase in phase angle $\delta$, there is an increase in the real power injected to the grid. In the PSC method, a single-phase SRF PLL senses the grid voltage phase angle. In this work, the PLL and the associated PSC algorithm has been implemented on dSPACE digital controller. The dSPACE controller operates faster than a microprocessor and is compatible with all versions of MATLAB. The modelled PLL does not require any frame transformation calculations, as the controller does not work on stationary $\alpha\beta$ frame when compared to other classical single-phase PLL algorithms. This synchronous reference frame PLL is capable of providing reliable phase angle information while lowering the grid voltage distortions. Phase detection and the consequent shift in phase angle as per the reference active power input could be easily carried out from the dSPACE control desk with least complexity.

A function is simulated to shift the phase of the inverter’s voltage, with respect to the voltage of the grid. It is necessary to identify a function that defines the reference voltage for the Pulse Width modulated single-phase inverter to implement PSC. Let variable “$x$” represent the phase angle, “$m_a$” modulation index, and “shift” represent the phase shift. After that, consider function “$a$” to represent the reference voltage that depends on phase angle, “$x$”, modulation index, “$m_a$”, and the phase shift, “shift”. The Matlab file builds the program below the execution of the synchronization model. The use of function $a$ has been demonstrated in Figure 9 in Section 5. The equation for the reference voltage that defines the function “$a$” can be written as below

$$V_{ref} = m_a \times \sin(x + \text{shift})_k.$$

Reactive power injection is not possibly controlled in this method. The DC link voltage is monitored and the error in the reference and actual value is fed to PI controller whose implementation in the dq transformation is relatively complex compared to PR controller in the stationary frame.

4 \ PROPORTIONAL RESONANT CURRENT CONTROL

The common practice is to employ the current controller for the grid interconnection of single-phase inverters to gain control
over current flow to the grid. As with the case of three-phase VSI’s, it is not feasible to vary the direct (P) and quadrature (Q) components of power of the VSI’s by the variation of d-axis and q-axis current components. Therefore, a current reference has to be created for the controller to regulate the active and reactive power flow in the circuit [26]. Usually, in sine PWM, we transform 3-phase phasors into DC signals by Park’s transformation. This is achieved by using a simple PI regulator.

In high switching frequency applications, quantities which are non-DC can be controlled using a low-complex PI compensator due to high switching frequencies, but high-frequency switching is not a right choice considering the switching loss associated with the switches. Therefore, for an inverter that is switching at the low switching frequency, for example, 10 kHz, a PI controller is found incapable enough to keep a track on the reference signal. It is, therefore, necessary to adopt a higher-order compensator in this case.

The circuit for output filter of the single-phase inverter is shown in Figure 5. Here, \( v_t(t) \) represents the converter’s terminal voltage and is composed of a fundamental and higher frequency terms of harmonics. \( v_g(t) \) denotes the grid voltage signal. The solution of the grid current in the \( s \)-domain obtained from the superposition theory gives the transfer function, \( H_f(s) \) as described below:

\[
\frac{I_g(s)}{V_t(s)|V_g=0} = \frac{-sC_jR_d + 1}{s^2L_iC_f + sC_fR_d\left(L_i + L_g\right) + s\left(L_i + L_g\right)},
\]

(11)

\[
\frac{I_g(s)}{V_g(s)|V_t=0} = \frac{s^2L_iC_f + sC_jR_d + 1}{s^4L_iC_f + s^2C_fR_d\left(L_i + L_g\right) + s\left(L_i + L_g\right)},
\]

(12)

From the above equations, the grid current \( I_g(t) \) varies with \( V_t(t) \) and \( V_g(t) \). Before the design of the loop compensator, it is possible to model the inverter by combining the above equation, which yields the following equation.

\[
I_g(t) = G_f(t) \left( \frac{s^2L_iC_f + sC_jR_d + 1}{sC_jR_d + 1} V_g - V_t \right),
\]

(13)

where,

\[
G_f(t) = \frac{sC_jR_d + 1}{s^4L_iC_f + s^2C_fR_d\left(L_i + L_g\right) + s\left(L_i + L_g\right)}.
\]

(14)
Equation (10) is used as the transfer function, $H_f(s)$ of the filter. With a switching frequency of 10 kHz, the lowest possible harmonics, “$h$” is $(2m-1)$, where $m$ is the frequency modulation ratio. According to IEEE standard, $H_f(j\omega_g) < 0.3\% \times \sqrt{2 I_{grid}}$. This equation forms the guideline for choosing the values of $L_i$, $L_g$, $C_f$ and $R_d$ in the output filter of the proposed model, the design values of which are discussed in Section 6.

The schematic representation of the current controller is given in Figure 6. For a given system, a PR controller, $G(s)$, is later placed to the control plant. The controller tracks the real value of the grid current so that it matches the reference current. The resonant controller, with $K_p$ being proportional gain and $K_i$ being integral gain outputs a reference voltage.
An ideal PR compensator has the following transfer function,

\[ G_{pr}(s) = K_p + \frac{2 \times K_i}{s^2 + \omega^2}. \] (15)

The above equation has been obtained on transformation from the synchronous frame of reference (using Proportional Integral controller) to the stationary frame of reference. The controller has gain approaching infinity at the resonant frequency \( \omega_o \), and hence there is no steady-state error, a shift in phase as well as gain at other frequencies. The proportional gain, \( K_p \), can be tuned in a similar manner to that of a PI regulator and governs the characteristics of the controller, such as phase margin, gain margin, and bandwidth.

The transfer function of an approximate PR compensator is presented below

\[ G_{pr}(s) = K_p + \frac{2 \times K_i \omega_{cut-off} s}{s^2 + 2 \omega_{cut-off} s + \omega^2}. \] (16)

CANAPRC is developed as the modification to conventional PR control in single-phase inverters by the authors. The control scheme was implemented with the aid of CAN channels from KVASER hardware driver support, where the network carried the necessary data to drive the designed controller. The use of a communication network to monitor the system phase voltage and phase angle template make the synchronization process reliable when compared to the communication less schemes. Enhanced power-sharing, reduced harmonics and better transient stability are other significant advantages.

5 | MODEL DESCRIPTION

The grid current, \( I \), load voltage, \( V \), the voltage at the DC link, \( V_{DC} \), and reference voltage at the DC link, \( V_{DC}^* \), are the essential measurements for grid synchronization for a single-phase voltage source converter. The block diagram shown in Figure 7 summarizes the procedure for grid interconnection. A single-phase PLL plays the most vital role in determining the phase
FIGURE 23  Bode plot obtained using CAN assisted proportional resonant control

FIGURE 24  Photograph of interconnection of the single phase inverter to the grid using CAN-assisted proportional resonant control

angle of the grid voltage, $V$. The next step is in creating a reference from the required or target real and reactive power values. The above steps are sufficient for applying PSC.

A commonly used grid-connected system comprises a power source, a pulse width modulated inverter, and a low pass filter tied to the grid with an additional local load at the point of common connection (PCC). The circuit for the same has been shown in Figure 8. A constant DC source, $V_{dc}$, was utilized using a battery. $S_a, S_b, S_c, S_d$ represent the switches of the converter. $L_1, C_1, L_2$ form the filter, and $R$ represents the damping resistor. AC grid with internal resistance, $R_s$, and reactance, $L_s$ needs to be tied to the inverter with minimum distortions at the grid side. The static switch governs the switching instance.

The next control strategy that was tested employs a communication based current control called the Controller Area Network Assisted PR control. CAN is an advanced serial communication channel used for broadcasting information. It is known for its error detection features and fault-tolerant capabilities. CAN facilitate the smooth transition of the micro-source in the DG from voltage control mode to current control mode. It supports data transfer at a rate of 1Mb/s and is highly immune to electrical interference. During the synchronization process, the phase angle is measured and transmitted using the CAN transceiver unit, and the reference current is fed to the current controller. Here, the proportional resonant controller is used. The output signal from the current controller drives the PWM unit, and the signal is sent to the static switch to tie the inverter to the grid.

The phase angle control, as described in section III, is applied such that the inverter voltage is made to lead the grid voltage. For every increase in phase angle, a considerable increase in inverter’s active power was found. Controller Area Network Assisted Proportional Resonant Control is also tested for the same model. Both the control strategies have been validated using simulation tests and prototype models.

6  |  RESULTS AND DISCUSSIONS

6.1  |  Phase shift control

Simulation: Simulation was conducted using the model described in section II to achieve the following objectives. (1) Active grid synchronization of the single-phase VSI with the grid. (2) Reduction in distortions from the source (grid) current. (3) Control of active power injection to the grid 4) Transient stability analysis

A Simulink model of the single-phase inverter was built in MATLAB R2016a. An H-Bridge inverter composed of IGBT switches has been modelled as the micro-source. The PSC method was used to generate the reference voltage for the inverter. The system parameters used for simulating the single-phase inverter in Phase Angle Control is shown in Table 1.
The phase template of the grid was measured by using a single-phase PLL. The equality of the voltages at the output of the inverter and the power grid is checked before synchronization. This has been illustrated in Figure 9. The phase angle is increased in steps to study the load sharing. A comparison of the grid voltage phase angle measured using the SRF PLL, and the conventional PLL has been shown in Figure 10. There are slight delays and distortions in the grid voltage phase angle using conventional PLL, while the SRF PLL showed accurate measurements. Figure 11 displays the inverter voltage and inverter current for a phase angle of 5 degrees. Figure 12 displays the inverter voltage and inverter current for a phase angle of 40°.

Figure 13 displays the grid current and inverter current for the sample phase angle of 40°. FFT Analysis of grid current using the PSC method proves that the total harmonic distortion is 0.74%, and this has been verified using Figure 14. Results show that the power-sharing of the inverter varies with an increase in the phase angle. For example, when the phase shift was 5°, the power drawn from the source was 1627 W, inverter supplied power of 22.75 W, and the inverter power increased to 400 W. The power-sharing of the inverter versus the grid changed from 1.39% to 31.59% for a phase angle span of 55°. The simulation results showing the variation of phase angle and the inverter current injection is shown in Table 2. Thus, the results validate the proposed objectives.

Hardware: A hardware prototype model has also been designed and built using dSPACE controller DS1104. The setup comprises of an H bridge inverter of 500 VA capacity. A DC link voltage of 24 V was used. (2 series-connected 12 V batteries). An LCL filter, comprising inductors of 0.7 mH and capacitor of 10 μF, interfaces the inverter to the grid. A step-up transformer of 17 V/230 V has been utilized to step up the inverter’s voltage to the same level of the grid voltage. The inductors and transformer were designed and made locally. A lamp of 400 W rating forms the connected load.

Figure 15 shows the photograph of the prototype model developed for Phase Angle Control. Figure 16 shows the grid voltage and grid current waveform at upf operation after synchronisation. Figure 17 illustrates the inverter voltage and inverter’s injected current waveform for different phase angles, such as 5°, 10°, 20° and 30°. This waveform justifies that increase in phase angle has a command over the rise in the real power injection into the grid.

### Table 1: System parameters

| Item description | Values |
|------------------|--------|
| Source voltage   | 230 V, 50 Hz |
| DC Link voltage  | 24 V   |
| Filter           | $L_1 = 2$ mH, $C = 10\mu F$, $L_2 = 0.34$ mH |
| Transformer      | 21/230 V, 500 VA |
| Load             | 2 kW   |

### Table 2: Simulation results

| Sl: no | Phase angle | Inverter power | Source power | Load power | Inverter current |
|--------|-------------|----------------|--------------|------------|------------------|
| 1      | 5           | 22.75          | 1627         | 1645       | 7.91∠80.67       |
| 2      | 10          | 64.34          | 1587         | 1645       | 9.53∠64.98       |
| 3      | 20          | 147.8          | 1506         | 1645       | 14.05∠47.54      |
| 4      | 40          | 292.1          | 1368         | 1645       | 24.67∠40.07      |
| 5      | 60          | 400            | 1266         | 1645       | 35.21∠43.03      |

### Table 3: System parameters

| Item description | Values |
|------------------|--------|
| Source voltage   | 230 V, 50 Hz |
| DC link voltage  | 145 V   |
| Filter           | $L_1 = 2$ mH, $C = 10\mu F$, $L_2 = 2$ mH |
| Transformer      | 150/230 V, 500 VA |
| Load             | 2 kW   |

### 6.2 Controller area network assisted proportional resonant control

Simulations were also performed using a CAN-based PR controller. The CAN interface device is supported using a hardware driver. The driver for Simulink is from KVASER. The
**TABLE 4** Comparison of control strategies

| Name of control strategy                      | Source current THD | Power sharing   | Transient Stability | Computational Burden | Implementation |
|-----------------------------------------------|--------------------|-----------------|---------------------|----------------------|----------------|
| Phase angle control                           | 0.74%              | Very high       | 25 ms               | 10 ms                | DSP/FPGA       |
| CAN-assisted proportional resonant control    | 2.4%               | Very high       | 15 ms               | 20 ms                | DSP/FPGA       |
| Conventional control strategies               | ≤5%                | Poor            | Weak                | High                 | DSP/FPGA       |

**FIGURE 26** Inverter tied to the grid injecting a current of 1.68 A at a voltage of 130 V for a connected load of 600 W

The simulation of the CAN channel requires the configuration of two virtual channels. It is necessary to load three simulation blocks for configuration, packing and transmission of the data/signal to the Simulink window from the Vehicle Network toolbox. The CAN Pack unit passes the data from the PLL to the Transmit Unit. The speed of the CAN bus selected is 500000 bits/s. Later, the CAN message is received by the CAN Receive unit. This message is finally retrieved using the CAN Unpack Unit.

The system parameters used for simulating the single-phase inverter in CAN Assisted PR Control is shown in Table 2.

The CAN output signal, which carries the phase angle information required for the synchronisation process has been obtained and is furnished in Figure 18. Grid current signal and injected current of inverter obtained using CAN-assist Proportional Resonant Control is furnished in Figure 19. Figure 20 illustrates the power sharing obtained using CAN-assisted Proportional Resonant Control. Figure 21 shows the FFT analysis report obtained using the same control. The bode plot was obtained, and it shows that the system achieves maximum gain and phase at the resonant frequency of 1125 Hz. Moreover the controller has been checked for its robustness during transient conditions. A fault was simulated from 0.3 s to 0.34 s and the grid current became stable after about 15 ms. This is shown in Figure 22. The root locus was also plotted to prove the stability of the system. Figures 23(a) and 23(b) illustrate the bode plot and the root locus plot of the PR controller, respectively.

The hardware set up of this control was also tested using dSPACE. The advantage of using this strategy lay in simultaneously achieving control over the power shared by inverter and curtailment in the harmonic distortion (THD). An LCL filter with inductor values of 2 mH and a capacitor value of 10 μF was used. Figure 24 shows the photograph of the hardware set up implemented on the dSPACE controller. A 230 V, 50 Hz inverter with a DC link voltage of 145 V, is used for interconnection to the grid. This has been illustrated in Figure 25.

The inverter is tied to the grid, injecting a current of 1.68 A at a voltage of 130 V for a connected load of 600 W. This is shown in Figure 26. The inverter is tied to the grid, sharing a current of 1 A at a voltage of 130 V for a connected load of 400 W. Figure 27 illustrates this case. Table 2 shows the comparison of results obtained using both the control techniques against the conventional methods of synchronization on the grounds of total harmonic distortion, power-sharing, transient stability, computational burden and implementation.

The above results prove that the two control strategies effectively synchronize the single-phase VSI to the grid with minimum distortions in the grid current. PSC successfully achieved control of active power using low complexity. A communication-assisted PR controller was also built effectively, first of its kind for a single-phase inverter to obtain adequate power-sharing which has been well proven through grid current, inverter current and load current waveforms.
CONCLUSION

Simulation, analysis and prototype modelling of two new, reliable, current control techniques, namely PSC and CANAPRC methods, were carried out in this research work. The phase angle between the inverter and grid voltages is altered in steps to control the real power injection to the utility in the PSC method. While, the CANAPRC is essentially a communication assisted current control scheme. The use of the communication platform assures the least errors in phase data transmission during synchronization. The advantage of the technique is that the inverter can supply the required real as well as reactive power to the AC mains with a much-reduced distortion and excellent transient stability. An improved power-sharing by the inverter was also obtained after synchronization using the control techniques. A comparison of the developed control schemes against conventional schemes has been presented. Experimental models were also developed for sufficient validation of the control techniques using dSPACE for a single-phase inverter.

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