Grid Connected Photovoltaic Systems: Challenges and Control Solutions - A Potential Review

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***Abstract*—The thirst for energy has brought out the existence of grid connected solar photovoltaic systems to meet out the reduction in the energy bill, which act as a cost saving methodology with simultaneous gain of incentives from the government for transporting the power to the national grid. Hence the operational objectives and the control strategies employed for its efficient operation are to be well studied. This paper thus discusses in detail about its topology, grid standards, real time challenges and objectives incorporating even the ancillary control schemes. A review is made on the control techniques which are made available for the DC (PV side) and AC side (grid side). A comparative analysis is made on each of the techniques based on the response parameters concluding the suggestion of most appropriate strategy for tolerable operation of grid connected photovoltaic systems.**

***Index Terms*—grid connected photovoltaic system, MPPT control, current control, phase synchronization and direct power control**

I. Introduction

The installation of Solar systems in India had risen from 35.15MW in 2011 to 941.25MW in 2012 and India aims at achieving 20GW solar power installations by 2020 and also to achieve grid parity by 2020 [1]. India is likely to install additional capacity of 1300MW to 1400MW of solar powered plants in 2013-2014. Thus it is clearly inferred from the figures above that the usage of solar energy is on rise. Solar photovoltaic systems are broadly classified into stand alone PV systems and grid connected PV systems. Solar PV serves as a sole source of energy satisfying the load demand in stand-alone systems where as in grid connected PV systems, the main AC grid also supports the occurring load demand. The total installed capacity of grid interactive renewable power (inclusion of all sources), which was 19,971.03MW as in 2011 had gone up to 24,914.24MW in 2012 indicating a growth of 24.75%. The installed grid connected solar power is 1035MW and the cumulative capacity of off-grid solar PV is 85MW as in October 2012 [2]. Hence the installation of grid connected photovoltaic systems goes on rise in comparison to stand alone systems.

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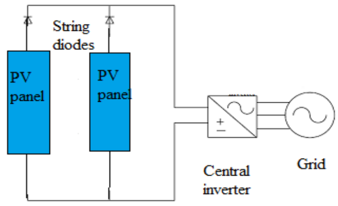
The rise is also due to the Government's support and attractive incentives to the installation of PV systems. A great deal of research has been done on the grid connected PV system. Thus, it becomes essential to know the control techniques employed in grid connected solar PV systems. As solar PV systems integrate both the direct current mode and the alternating current mode, the control of both the DC side or the PV side and the grid side or the inverter side comes into picture. Out of the above two controls the AC side control poses more complexity and is harder to implement. This article will be helpful for budding researchers with the projection of technical challenges and solution for grid connected PV systems.

II. Structure of Grid Connected PV System

The topologies of grid connected PV system occur in three forms as shown in Fig. 1(a), Fig. 1(b) and Fig. 1(c). They are the Central Inverter topology, String topology and Module topology [3], [4].



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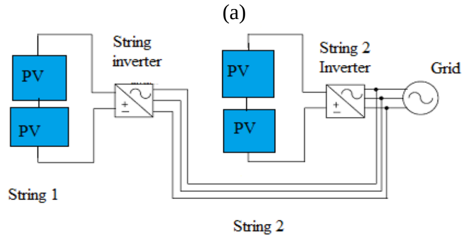

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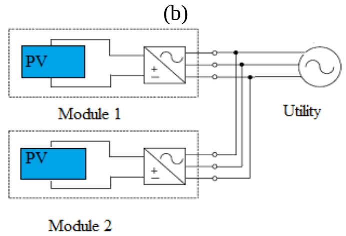

(c)

Figure 1. Existing topology of grid connected photovoltaic systems: a) central topology b) string topology c) module topology

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TABLE I. COMPARISON OF PV SYSTEM TOPOLOGY

Type of PV System topology	Centralized Topology	String Topology	Modular Topology
Type of connection	PV panels are interfaced to single, centralized inverter	PV panels connected in strings comprise an inverter	Each PV module has an inverter integrated to it
Advantages	Low specific inverter cost, Robust & easy maintenance with increased system efficiency. The efficiency of the system is 97.5% [6]	Each string can be oriented in directions of maximum power.	The introduction of converter separately reduces the inverter functionality. Each panel can be optimally tracked
Disadvantages	High mismatch loss, inverter sensitivity to the voltage on DC side	Inverter sensitivity increases.	High cost per peak KW power. Lower efficiency and difficulty in maintenance.
Usage	Typically in residential application	Typically used in large power plant application	Not mostly used. But typical for power applications up to 200W.

In central inverter topology the integrated arrangement of the PV module is connected to a centralized inverter to the grid where as in string topology, each PV string is connected to an inverter which finally supplies the grid. Instead of strings of PV, each PV module is connected to an inverter in module topology [5]. A comparison of the same is shown in Table I.

The selection of the above topology is made with the priority of power handling capability. For lower power photovoltaic system module topology is recommended. A choice of centralized and the string is made with large scale power systems. For more optimal power maxima and large power capacity string topology is preferred than centralized where as a trade off occurs in concern with the cost. Hence there occur many factors such as cost, maximum power control, efficiency, power handling capacity, feasibility issues etc., which are discussed in the literatures listed below [6], [7].

There are structures with transformer based and transformer less grid connected PV systems [6]. Transformer less topologies are classified as topologies with single stage boost and double stage boost.

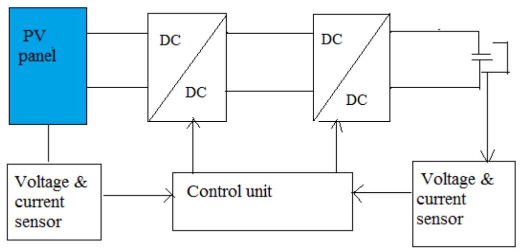
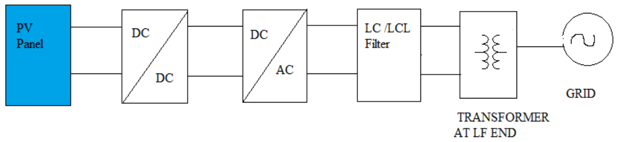
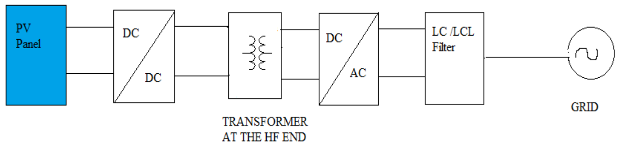


Figure 2. Double stage boost transformer less topology

The above double boost system as seen in Fig. 2 has numerous advantages like wide MPP range, less DC capacitance value and less number of sensors. A disadvantage lies with the input ripple current value. If a compromise is made on the efficiency, size, cost and ripple current, photovoltaic panel with single stage boost is preferred. If isolation is required, transformer embedded topology is acquired where it occurs either at the low frequency side (grid side) or at the high frequency side (DC side) as in Fig. 3(a) and Fig. 3(b). Isolation provides adequate protection to the system by offering fixed system grounds [6]. Both the transformer based technologies are currently prevailing and the efficiency is around 93 to 95% [6]. Losses occur more in the transformer at the HF side. Other solutions for isolation include full-bridge isolated converter, Single-Inductor push-pull Converter (SIC) and Double-Inductor Converter (DIC).



(a)



(b)

Figure 3. Transformer at the low frequency and high frequency ends respectively

The benefits of the topology shown in Fig. 3 includes low ripple current value, absence of electrolytic capacitance and efficient [6] in comparison with the double boost and isolated models. The only disadvantage lies in the control mechanism where the gate pulses to the converter switches are derived. The duty cycle control or reference voltage control is handled by the DC-DC converter where as the inverter is responsible for the current control mechanism.

III. ISSUES AND CHALLENGES OF PV SYSTEM TOPOLOGY

Due to the random and intermittent nature of the renewable sources, integration of it into the grid causes technical challenges to be targeted and solved. The technical challenges cover the reduction in power quality, power fluctuation causing unreliability, storage, protection issues, optimal positioning of Distributed Generator (DG) and anti islanding [8], [9].

A. *Problems Concerned with Power Quality*

As the renewable DG's are integrated through a power electronic converter to the grid they usually inject harmonics into the system. Harmonics are caused by the switching mechanism of the power electronic switches in the inverter which produce poor quality of power to be supplied to the customers. Hence soft switching control schemes of the inverter were introduced to overcome the harmonics. Active or passive filters can also be employed for the same.

Change in the frequency and the operating voltage can also occur due to the varying nature of the DG which affects the power flow [8]. The disconnection and reconnection of renewable energy source to the grid depending on the load demand causes voltage flicker. Appropriate tap settings for the transformer connecting the feeder to the grid should be made, which is more useful when two or more feeders are supplied by the same transformer, but the DG is concentrated on only one of the above feeder [10]. In addition, digital voltage control algorithms evolve [9] to solve the problem. Unbalanced voltage profile arises due to the interconnection of single phase source with the three phase load or vice-versa. Unbalanced voltage will further lead to unbalanced current which deduces the quality of the system [11], [12].

B. Storage

Due to the incorporation of renewable or PV source in the grid power path flow, the standard of the grid comes down. The grid may act as a source or sink of power in accordance to the power generated from the distributed generator (PV). If the PV power generation is surplus or in case of a weak grid, battery can be made as a choice of storing the excess power [8]. But introducing a battery to the grid connected PV systems invites issues of sizing and battery current and voltage control.

C. Protection Issues

Traditional power systems are protected by over-current/overvoltage relays and circuit breakers. But as energy conversion systems (solar) are introduced the protection of the network becomes more complex. The issues of alteration in the short circuit level, lack of sustained fault current and reverse power flow persists.

D. Short Circuit Level Change

The short circuit level is an important design parameter in the design of protective devices such as circuit breakers and relays. This is usually characterized by the equivalent system impedance [8] at the fault point and indicates the amount of fault current for the relay to act upon the fault. The equivalent impedance does not vary with the grid powered network systems, but varies with the DG network systems as the input changes to it changes instantaneously. Since the SCC varies the forecast of the fault current magnitude changes which cannot be withstood by the designed circuit breaker rating right through the operation.

E. Reverse Power Flow

Conventional power systems possess unidirectional power flow. But as a renewable energy source is integrated to the conventional power system the power flow reversal takes place which alters the operation of protection circuits [8].

F. Lack of Sustained Fault Current

For the protection of the system from the fault current switch gear and circuit breakers are installed, which differentiates the fault current from the normal current. This differentiation is made with the significant increase in the fault current than the normal current. If the magnitude of the fault current varies from the DG then there is a tough task for the circuit breaker to identify the fault current amidst the normal current. Solar systems mainly employ power electronic switches which do not supply sustained fault currents [8].

G. Islanding

Islanding is a unique problem of the grid connected PV system. Islanding occurs on grid failure. Auto reclosure valve at the point of common coupling of the renewable generator to the grid is kept open offering the separation of the utility network with the grid. Else the voltage builds up on power generation without the energy absorption by the grid causing huge voltage unbalance resulting in system deterioration. Thus the anti islanding control technique came into picture [8], [11] for addressing the above problem. The standard anti islanding control techniques include over-voltage relay, under-voltage relay, over-frequency and under frequency relays. In addition to the standard schemes active and passive schemes are introduced for reducing the probability of islanding. Voltage harmonic monitoring, phase jump detection and slide mode frequency shift, branch out from passive schemes whereas Impedance measurement and active frequency drift come under the active scheme.

IV. Grid Interconnection Standards

As the issues with the grid standards go on high, the design of the grid connected PV is subjected to follow grid standards which vary with the location of the grid over the globe. Some of the most important standards are the International Electro technical commission standards and Institute of Electrical Engineering standards. More specifically, IEEE standard 1547-2003 is employed for interconnecting distributed sources with power systems [13] and IEC61727 [14] second edition 2004-2012 for PV system interaction with the utility. Voltage, DC injection, flicker, frequency distribution or harmonics and power factor limits for tolerable operation of 10 to 30KW grid connected PV system as shown in the Table II below.

TABLE II. Grid Standards

Performance Parameters	IEC61727	IEEE1547
Nominal Power	10kW	30KW
Maximum current THD	5.0%	5.0%
Harmonic current	(3-9) 4.0% (11-15) 2.0% (17-21) 1.5% (23-33) 0.6%	(2-10) 4.0% (11-16) 2.0% (17-22) 1.5% (23-34) 0.6%, (>35) 0.3%.
Power factor at 50% of rated power	0.90	-
DC current injection	Less than 1.0% of rated output current	Less than 0.5% of rated output current
Voltage range	85%-110 %	88%-110%
Frequency range for normal operation	50±1Hz	59.3Hz to 60.5Hz

V. Control Objectives of Grid Connected PV System

The control objectives of grid connected system are partitioned mainly into DC side control and AC side control represented in Fig. 4. The common functions of GPV include DC voltage control [15] adapting input voltage variations, grid synchronization for unity power factor control and grid current control for system stability [15].

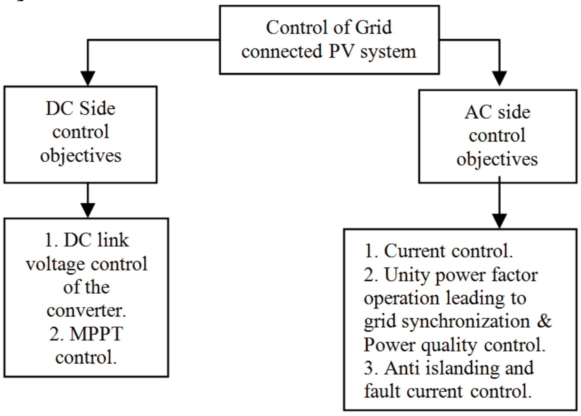


Figure 4. Existing control objectives of grid connected PV system

The specific application of grid connected PV system includes the maximum power point tracking control, Anti islanding as per IEEE1574 standards, unity power factor operation, fault current control harmonic control and voltage fluctuation control thereby maintaining the power quality standards. Other ancillary applications include sun tracking, plant monitoring and active or reactive power control.

A. Specific DC Side Function

1) MPPT control

The power output of the PV is maximum only at a particular point corresponding to the maximum voltage level as shown in the Fig. 5 below. This point varies with the input irradiation and temperature, which has to be tracked for maximum energy extraction throughout the plant operation. MPPT occurs in three different modes of control, namely the reference voltage, reference current and the duty cycle control for ensuring instantaneous peak power thereby maintaining constant voltage output.

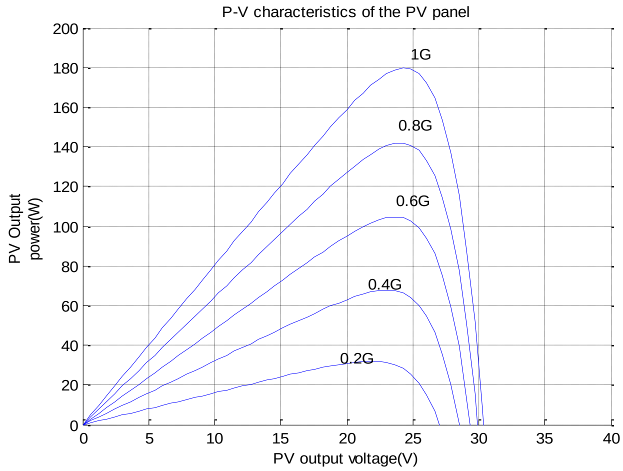


Figure 5. Simulated P-V curve of PV panel

Relatively many MPPT algorithms have come into existence as discussed in the literatures [16]-[22]. A comparison of the widely used MPPT algorithms is made below in the Table III.

TABLE III. Comparison of MPPT Algorithms

MPPPT Methods	Methodology	Convergence Speed	Complexity	Efficiency
Perturb and observe	Checks the difference in power between present and the future instant of points on P-V curve	Medium	Low	99.3% of the actual maximum power [19], [20]
Incremental conductance	Monitors the slope of the P-V curve and detects the maximum power region	Fast in comparison with P&O	Medium	99.2% of the actual P(max) [19], [20]
Fractional open circuit	Employs the relation $V_{mpp}=K\times V_{(oc)}$ to find MPP.	Less	Low	93.1% of the actual P(max) [19], [20]
Fractional short circuit	Employs the relation $I_{mpp}=K\times I_{sc}$ to find MPP.	Less	Low	Nearer to the above efficiency
Fuzzy logic control	Usage of membership function and rule base engine for tracking MPP	Fast	High	99% of actual maximum power [22]
Neural network MPPT	Neurons with a set of training rules to detect MPP	Fast	High	92% of the actual Maximum power [22]

B. Anti-Islanding Control Techniques

1) Passive control method

This method measures the voltage at the generator end as the power flow between the DG and the grid causes imbalance leading to a fluctuation in the voltage level. A voltage relay detects the variation in voltage and leads to the separation of the DG from the grid. For fast response a voltage surge relay is more preferable. Frequency relays also detect the under and over frequency condition by which islanding is carried out [8].

2) Active control method

Active control methods are pre forecasting methods by which the system is tested before hand by subjecting it to disturbances. The system responses are studied for the injected disturbances. Reactive error export, Fault level monitoring, system impedance monitoring and frequency drift are a few active control methods [8].

3) Telecommunication based methods

A computerized communication channel is established between the protective structures and the sensors to the DG. When an island occurs the circuit breaker is instructed through a SCADA system [8] for it to act on the problem. Rate of change of frequency is another method where the rate of change of frequency is continuously monitored and if it reaches beyond a preset value the DG is isolated from the grid.

VI. Grid Control Techniques

The grid control techniques form the essential and the complex function for the standardized operation of the grid connected PV system as described in Fig. 6. These techniques focus on the methodologies for the generation of PWM pulses to the converter or inverter switches which offers sinusoidal grid current injection to the system. This section encloses in detail about the control techniques reviewed in the literatures [23]-[29] with a comparison of it making a brief conclusion.

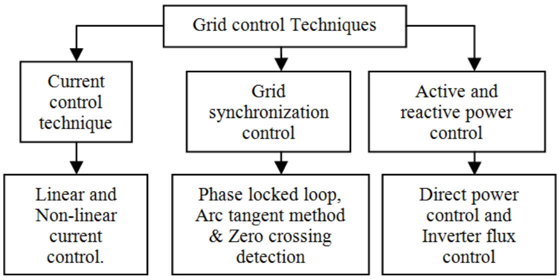


Figure 6. Classification of grid control techniques

A. *Current Control Techniques in Grid Connected PV System*

The current control is responsible for the stability of the grid current. The design of the controller for comparison of grid reference current with the actual brings the evolution of linear and non-linear current control technique. They are further subdivided into strategies such as PI current control, PR resonant current control, dq frame current control, dq frame current control with feed forward harmonic compensation [30]-[41]. The non –linear techniques include the Hysteresis current control, predictive current control or dead beat control, sliding mode control [42]-[48]. Direct power control forms the ancillary control part [49]-[51].

1) *PI current control*

A typical PI current control is shown in Fig. 7. The P controller's steady state error is eliminated by adding an integral component to the transfer function [24]. The reference current is obtained from the grid voltage on employing a gain. The measured output inverter current is compared with the above reference and the error is controlled by a PI current controller. The integral part of the PI compensator minimizes errors at low frequency, while proportional gain is related to the amount of ripple or reduces the transient response. The PWM signal is finally obtained from the processed control signal in the PWM generator block in comparison with constant frequency triangular signals of fixed switching frequency [30]-[32]. As the output grid voltage should be in phase with the output current, the reference current was obtained from the grid voltage leading to unity power factor operation. The maximum slope of error signals should never exceed the triangular slope of the carrier signals. Additional problems may arise from multiple crossing of triangular boundaries. The advantage of the PI control includes the reduction in the steady state error and less effect of DC-side ripple on the inverter load side waveforms.

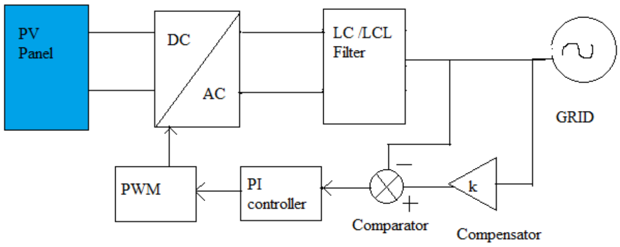


Figure 7. PI current control flow diagram

2) *DQ frame current control*

Most of the PI controller's applications are in dq control, since they have an acceptable performance while regulating the DC variable [24]. Here as shown in Fig. 8 the current vector components are defined in rotating synchronous coordinates d and q. These are employed in industrial applications where small phase or amplitude errors will cause a change in the operation of the system. The controlled output current has to be in phase with the grid voltage and hence the transformation (abc to dq) uses the phase angle generated from the grid voltage. The actual DC output voltage is compared with the reference DC voltage obtained from the MPPT. The error is controlled by a PI regulator to obtain the reference direct axis current. The reference direct axis current is compared with the actual transformed DC component current to obtain direct axis voltage reference (V_d). The quadrature axis reference current is made zero and is compared corresponding to q-axis current to obtain a quadrature axis voltage reference V_q reference [15], [33]. The obtained d and q voltage vectors are finally transformed to synchronous frame for the generation of PWM pulses to the inverter. PLL is used for phase synchronization or the unity power factor operation. The dq0 transform reduces three-phase AC quantities into two DC quantities which facilitates easier filtering and control. Active and reactive power can also be controlled independently by controlling the dq components.

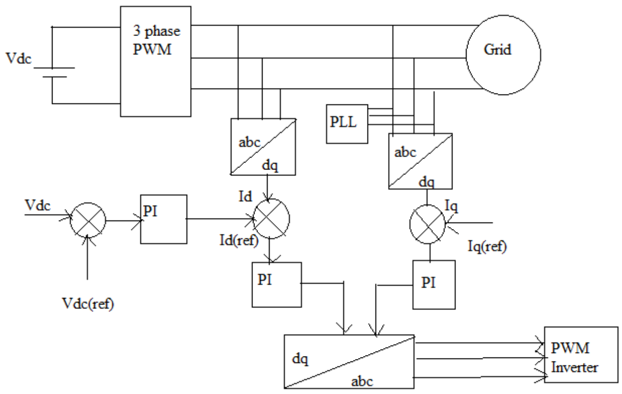


Figure 8. DQ frame control with harmonic compensation

The above stationary components are re-transformed to synchronous rotating frame for the generation of PWM signals.

3) *PR resonant control*

The dq frame current control and control with harmonic compensation requires quite a lot of calculations like coordinate transformations, addition of harmonic compensator which sub includes cross couplings of d and q axis for improved dynamic response. But in PR resonant control the transformations are reduced and cross coupling is removed, which makes the implementation of the control technique simpler. Moreover PR controller achieves very high gain in a narrow frequency band centered around the resonant frequency [35]-[39].

The transfer function of the PR resonant control is given by:

$$G(s) = k_p + k_i * s/(s\wedge 2 + \omega \wedge 2) \quad (1)$$

where K_p and K_i are the proportional and the integral control gains. ω corresponds to the resonant frequency.

The width of the frequency band about the resonance point depends on the integral time constant of K_i.

Harmonic compensation as in the dq current control can also be achieved by PR control. A typical Harmonic Compensator (HC) can be introduced for compensation of selective harmonics like the third, fifth, and seventh harmonics and its corresponding transfer function is shown below.

$$Gh(s) = \sum_{h=3,5,7} K_{ih} * (s/(s\wedge 2 + (\omega h)\wedge 2)) \quad (2)$$

where ω is the natural resonance frequency, h is the harmonic number and K_{ih} is the integral gain of the related harmonic. A comparison of current control schemes are tabulated in Table IV and Table V.

TABLE IV. COMPARISON OF CONTROL STRATEGIES WITH UNIQUE FEATURES

Control Techniques	High gain	Steady state error Elimination	Dynamic response	Harmonic Compensation
PI control	At lower frequencies	Good	Fast	Poor
PR control	Around resonant frequencies	Very good	Rapid	Poor
DQ control with harmonic compensation	High gain at integral multiples of fundamental frequency	Very good	Slow	Good

TABLE V. COMPARISON OF LINEAR CURRENT CONTROL TECHNIQUES

Linear current control techniques	Current THD	Advantages	Disadvantages
PI Current control	8% of the peak rms current value [31]	1. Devoid of transformations which increases complexity 2. Less effect of DC side ripple on the inverter	1. Multiple triangular signal crossing occurs on the generation of PWM. 2. Difficulty in removing the steady-state error in a stationary reference frame. 3. Less robust.
Dq frame current control	3.5% [41]	1. Accurate control on grid imbalances can be achieved. 2. Elimination of steady state error	1. System complexity increases as synchronous transformations are involved.
PR current control	1.46% [37]	1. More robust and high gain. 2. Capability of eliminating steady-state error when regulating sinusoidal signals	1. Complex but not as complex DQ control
DQ frame control with harmonic compensation	Not accurately available. But Lesser than above methods as harmonic compensator is involved.	1. Harmonic compensation is done by adding the respective harmonic order to the PI controller 2. Enhances system stability	1. Complexity arises by adding harmonic compensator.

4) Discussion and conclusion of linear control techniques

PI current control is typically a simple control offering the objective of phase synchronization among grid voltage and grid current with less concentration over the THD limits. Steady state error elimination is also poor in comparison with the other linear methods. Thus, if a cost effective or complexity selection line occurs PI current control is more preferable. If the dynamic response of the controller is not the most important aspect to be considered then PR controllers are employed. Dynamic response varies with the solar input conditions. Though PR Resonant control offers more robust operation than the PI control, DQ control with harmonic compensation can always be recommended as the system remains stable even to disturbances in spite of the complexity in transformation.

B. Non-Linear Current Control Techniques

1) Hysteresis current controller

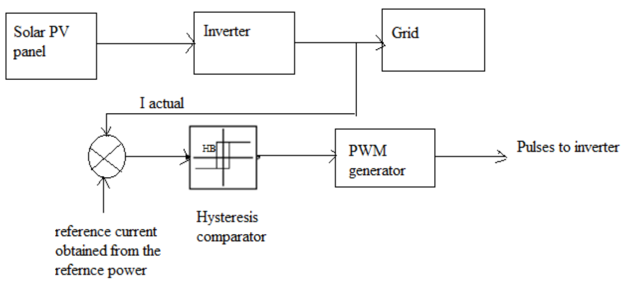


Figure 9. Hysteresis current controller applied to grid connected PV systems

The hysteresis control limits the control range to the hysteresis band which is set by the error in the reference current and the measured output current [42], [43] as seen in Fig. 9. The lowest error is set by the lower limit of the hysteresis band and the highest error is set by the upper limit of the hysteresis band. As the current increases and crosses the upper hysteresis limit, the lower device is turned on. As the current falls and crosses the lower band the upper device is turned on. The advantages of hysteresis control are its simplicity, robustness, lack of tracking errors, independence of load parameter changes, and extremely good dynamics limited only by switching speed and load time constant [42]. Though, it has some disadvantages which are the variation in converter switching frequency with the output inverter voltage and rough operation due to the inherent randomness caused by the limit cycle or the hysteresis band, protection of the converter becomes difficult.

2) Constant switching frequency operation of hysteresis current controller

The tolerance band or the hysteresis band amplitude can be varied according to the AC-side voltage or by means of a PLL control. The other way of maintaining the switching frequency is to decouple the error signals by subtracting an interference signal derived from the mean inverter voltage [29] as shown in the Fig. 10 below.

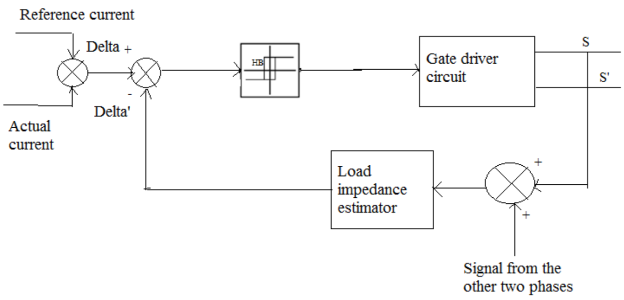


Figure 10. Decoupled, constant average switching frequency hysteresis controller [29]

3) Current regulated delta controller

The current regulated delta controller is same as the hysteresis controller with a latching device [25] attached to it represented in Fig. 11. The advantage of this control is to control the switching frequency to our desirable frequency by enabling the latch with a clock signal. The reference three phase grid currents are compared with the actual currents resulting in an error signal which is further given as input to the comparator. The comparator acts as a hysteresis band limiter limiting the current between the upper and the lower band limits. The pulses thus generated are given to the latching circuit as binary values. The value 1 indicates the latch is enabled for PWM generation. The clock signal is also responsible for the inverter to track the reference current with the actual currents effectively.

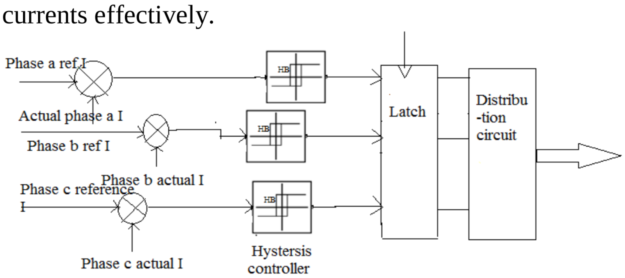


Figure 11. Current delta regulated control methodology

The harmonic compensation is held effectively without inclusion of a separate harmonic compensator.

4) Modified ramp type controller

The ramp controller described in Fig. 12 involves the comparison of the triangular signals of fixed amplitude and frequency with the error signals derived from the current controller. The triangular signals act as a carrier wave with error signals modulating it. Constant switching frequency is achieved as triangular signals with fixed frequency are employed. The disadvantage of this control is that the output current has amplitude and phase errors. In order to overcome the disadvantage phase shifters are included where the triangular wave of constant amplitude are phase shifted by 120 °[25]. The schematic is shown below.

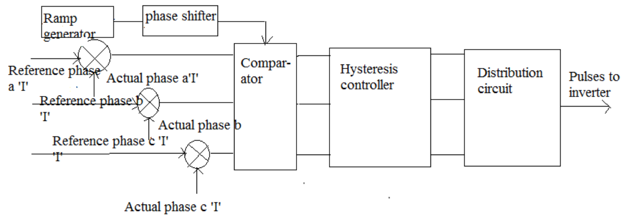


Figure 12. Modified ramp type controller methodology

5) Deadbeat/Predictive control

Dead beat predictive time control employs a discrete-time model which is able to predict the current in the future (time *k*+1) based on actual or present measurements (at time *k*) and the converter voltage to be applied. These predicted values will be used as inputs for a cost function block and the voltage vector producing the lowest value of the cost function is selected to be applied during the next sampling instant [44]-[46]. This kind of controller though well known for their inclusion of nonlinearities of the system, high precision of current control and fastest transient response causes computational complexity leading to large control loop time period and sensitivity changes to plant uncertainties. When the choice of the voltage vector is made in order to nullify the error at the end of each cycle, the predictive regulation is rightly called “dead beat control”. The dead beat control topology is adopted as shown in Fig. 13.

The future value of load current is given by:

$$I(k+1) = (T(s)/L)*(V(k)-e(k)) + I(k)(1-R*T(s)/L) \quad (3)$$

where $V(k)$ and $I(k)$ is the measured grid current the future value of reference current is determined by using Lagrange quadratic extrapolation.

$$I*(k+1) = 3I(k) - 3I*(k-1) + I*(k-2) \quad (4)$$

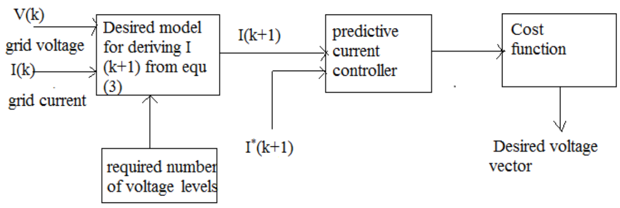


Figure 13. Deadbeat/Predictive current control algorithm

6) Sliding mode control

Sliding mode control shown in Fig. 14 is a non-linear control or a system motion control which is robust in the presence of parameter uncertainties and disturbances. It is more suitable for time varying systems. It has the ability to regulate the system to follow the trajectories defined by the sliding surface which is mostly similar to the hysteresis band in the hysteresis current control. The equilibrium state is constructed so that the system is restricted to a desired manifold and has a desired behavior. The three steps which involve the design of the sliding mode controller is the selection of the sliding surface, obtaining the equivalent control and finally selecting the nonlinear control input to ensure Lyapunov stability criterion [47]. The motion of the system as it slides along these trajectories is called a sliding mode and the geometrical locus consisting of the boundaries or trajectories is called the sliding surface. The design of the sliding surface depends on the photovoltaic array voltage and the inductor current and has the role of controlling the solar array power and the inductor current [48]. The reference inductor current is expressed as a function of solar array power for simultaneous control of the above stated variables.

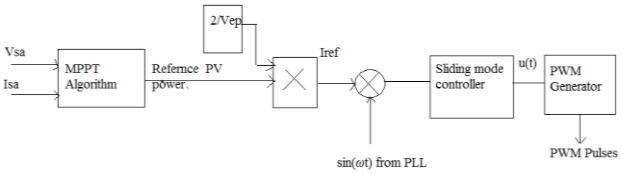


Figure 14. Sliding mode controller for grid connected PV system

$$I_{ref} = 2\,\mathrm{P}_{ref}\sin(\omega t)/V_{EP} \tag{5}$$

Slide Controller output u(t) is given by:

$$u(t) = (R_{L}i_{L} + e_{s}(t) + 2\,\mathrm{P}_{ref}\cos\omega t L_{n}\omega / V_{EP} - \eta L_{n}\,\mathrm{sgn}(\sigma))/V_{sa} \tag{6}$$

P_{ref} represents the reference power to be tracked, i_L represents the inductor current, V_{EP} represents the peak grid voltage and V_{sa} represents the photovoltaic array voltage. The control input is finally compared with reference carrier ramp voltage for the generation of switching pulses to the inverter. A comparison of described non-linear control techniques is shown in Table VI.

TABLE VI. COMPARISON OF NON-LINEAR CURRENT CONTROL

Non-linear current control	THD	Advantages	Disadvantages
Hysteresis current control	4.41% [25]	Robust control and extremely fast dynamic response	Switching loss, increase making the protection of the control circuit difficult.
Dead beat current control	1.92% [45]	High precision of current control and includes non-linearity.	Computational complexity increases as the voltage vector input increases.
Sliding mode control	7.48%	More suitable for non-linear time varying system.	Good knowledge of sliding surface selection and stability criterion is necessary.
Current regulated delta controller	4.74% [25]	Constant switching frequency operation is achieved with ease than adaptive hysteresis	-
Modified ramp type controller	2.68% [25]	Absence of phase error	Transmission delay occurs
Direct power control	Not discussed	Extremely fast dynamic response	Stability depends on the load parameters

7) Direct power control

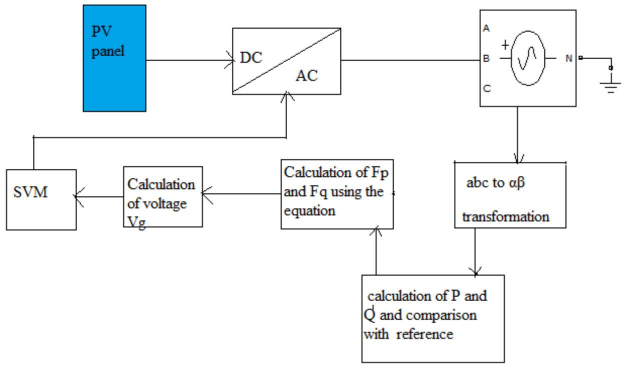


Figure 15. Direct power control using sliding surface for grid connected PV systems [49]

In Fig. 15 as seen above, the grid voltages are transformed to the stationary reference coordinates, namely α and β. The active and reactive power is derived from $V_{g\alpha}$, $V_{g\beta}$ and $I_{g\alpha}$, $I_{g\beta}$ by employing the (7) and (8).

$$P(actual) = -1.5(V_{g\alpha}I_{g\alpha} + V_{g\beta}I_{g\beta}) \tag{7}$$

$$Q(actual) = -1.5(V_{g\beta}I_{g\alpha} - V_{g\alpha}I_{g\beta}) \tag{8}$$

The state variable for the sliding surface defined by F and is calculated with respect to the active and reactive powers P and Q. Thus, finally the control law is defined with the value of F_p and F_q as follows [49].

$$V_g = (1/D)\{(F_p + K_{p1}\,\mathrm{sgn}(S_p) + (F_q + K_{q1}\,\mathrm{sgn}(S_q))\} \tag{9}$$

Finally PWM are generated by using the control input to the space vector modulation unit for the operation of the inverter.

The conventional direct power control [49], [50] involves the synchronously transformed co-ordinates d and q and current control loops for deriving the active and reactive power, whereas in the improved direct power control the calculation of sliding surface and its state variable itself leads to direct regulation of powers. Hence improved transient performance is achieved.

8) Discussion and conclusion of non-linear control techniques

Hysteresis controllers as discussed above are more reliable and robust, but problems occur with the switching loss resulting in increased THD of 4.41% as cited in the literature reviewed. Application of sliding mode controller over the inverter side is scarce as the diversity of switching frequency renders large amount of disturbance shooting up the THD. Moreover the real time implementation of sliding mode controller is complex in comparison to the above non-linear techniques. Current regulated delta controller and modified ramp type controller incorporate a hysteresis controller in its methodology and can be chosen if more clean operation of grid connected PV system is required with less THD than hysteresis. Direct power control is preferred for indirect power control by direct instantaneous current control. The dead beat control offers clean and stable grid current injection to the grid, maintaining the THD of around 1.92%. But the computational complexity increases. Thus the most adaptable method on real time is hysteresis controller, which has acceptable THD limiting to 5% as per IEEE1547 grid standards. If a more accurate THD is the trade off criteria then, a current regulated delta controller and the modified ramp type controller can be considered.

VII. Phase Synchronization Techniques

A. Phase Locked Loop

Phase locked loop is employed for unity power factor control in grid connected photovoltaic systems. The phase angle corresponding to the synchronous frequency and utility voltage is derived which is responsible for phase synchronization of grid voltage and grid current [52]-[56]. A comparison of the same is shown in Table VII.

TABLE VII. Comparison of PLL Techniques

PLL Technique	Methodology for deriving ϴ	Advantages	Disadvantage
Synchronous Reference Frame PLL	Integrating the controlled quadrature voltage output	Clearly acceptable results under undistorted & balanced supply voltages	The output of the PLL becomes distorted under unbalanced supply voltage condition
Double synchronous frame PLL	A stationary frame(αβ) transformation is employed with integrating the controlled stationary voltages to obtain ϴ	Eliminate the distortions in the output completely under unbalanced conditions	-
Synchronous frame PLL with positive filter	Same as Double synchronous frame PLL with a filter added	More compatible for rapidly changing supply conditions	Components increase as the filter is added.
Synchronous reference frame PLL with sinusoidal signal integrators	Sinusoidal signal integrators replaces the positive sequence filter	Accurate phase angle computation	Integrators are responsible for the interruption of noise into the system.
Double Second Order Generalized Integrator	Posses two stage sinusoidal signal generators collectively called as double second order generalized integrator	Accurate computation of positive sequence amplitude is achieved	-

B. Zero Cross Detection

The easiest and simplest way of knowing the phase of a sinusoidal wave is to detect the zero crossing of the wave. A digital filter detects the first sign change of the sampled values to mark the instant of zero crossing. Probably in addition a hysteresis band filter can also be used for eliminating the false zero crossing. The final objective is to obtain the fundamental component corresponding to the line frequency. Though the method has some advantages, phase tracking is not viable with the detecting points leading to slow dynamic performance [55]. Significant line voltage distortion caused by device switching can easily corrupt the output of a zero-crossing detector. Hence accurate tracking of grid voltage cannot be achieved by ZCD when applied to systems that are grid connected.

C. Arc Tangent Function

This is an added technique for detecting the phase angle and frequency of the grid voltage. An orthogonal voltage system is required in order to implement this technique. This method is mostly applied to adjustable speed drives which require transformation of the feedback signals to a reference frame suitable for control purposes [55]. However, this method has the drawback that requires additional filtering in order to obtain an accurate detection of the phase angle and frequency in the case of a distorted grid voltage. Therefore, this technique is not more suitable for grid-connected photovoltaic systems which are always unreliable.

VIII. Conclusion

The basic control objectives and challenges of the grid connected solar photovoltaic systems are well defined. Most of literature limit to the control strategies employed in the inverter. They don't collectively concentrate on the application of control techniques to the grid as above. The conventional control strategies and the advancement made in it are also cited. Advantages, disadvantages, and the application of the control techniques are also specified. The total harmonic distortion limits of each control strategy are observed and a strategic conclusion is made on the performance comparison.

References

[1] *Energy Statistics*, 20th issue, Central Statistics Office, Ministry of Statistics and Programme Implementation, India, 2013, pp. 18-59.

[2] IEC 2013 Long Term Energy Security, February 2013, pp. 9-21.

[3] M. Johns, H. P. Le, and M. Seeman, "Grid-Connected solar electronics, contemporary energy issues," University of California at Berkeley, pp. 1-12, 2009.

[4] S. Nema, R. K. Nema, and G. Agnihotri, "Inverter topologies and converter structure in photovoltaic applications: A review," *Journal of Renewable and Sustainable Energy*, vol. 3, no. 1, pp. 227-243, 2011.

[5] H. B. Massawe, "Grid connected photovoltaic systems with smart grid functionality," Ph.D. dissertation, Department of Electrical Engineering, NTU, Singapore, 2013.

[6] R. Teodorescu, "PV inverters structures, and control, tutorial on power electronics for PV power systems integration," in *Proc. IEEE International Symposium on Industrial Electronics*, Italy, 2010, pp. 3-47.

[7] M. Carlos and B. Domingo, "Analysis and control of single phase single stage grid connected photovoltaic inverter," in *Proc. ACES Meeting*, 2008.

[8] A. Rajapakse, D. Muthumuni, and N. Perera, "Grid integration of renewable energy systems," in *Renewable Energy*, InTech, 2009, pp. 109-131.

[9] A. S. Anees, "Grid Integration of renewable energy sources: Challenges, issues and possible solutions," in *Proc. IEEE International Conference on Power Electronics*, Delhi, 2012, pp. 1-6.

[10] A. Uchida, S. Watanabe, and S. Iwamto, "A voltage control strategy for distributed networks with dispersed generations," in *Proc. IEEE-PES General Meeting*, Florida, 2007, pp. 1-6.

[11] C. Larsen, P. E. Brooks, and J. D. T. Starrs, *A Guide to PV Interconnection Issues*, 3rd ed., North Calorina: Interstate Renewable Energy Council, 2000, pp. 1-35.

[12] S. Marko and I. Darula, "Large scale integration of renewable electricity production into the grids," *Journal of Electrical Engineering*, vol. 58, pp. 58-60, 2007.

[13] IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, IEEE Standard 1547, 2003.

[14] Characteristics of the Utility Interface for Photovoltaic (PV) Systems, IEC 61727 CDV (Committee Draft for Vote), 2002.

[15] L. Hassaine, E. Olias, J. Quintero, and V. Salas, "Overview of power inverter topologies and control structures for grid connected photovoltaic systems," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 796-807, 2014.

[16] T. Esram and L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Transactions on Energy Conversion*, vol. 22, pp. 439-446, 2007.

[17] A. Safari and S. Mekhile, "Simulation & hardware implementation of incremental conductance MPPT with direct control method using Cuk converter," *IEEE Transactions on Industrial Electronics*, vol. 58, pp. 1154-1161, 2011.

[18] V. Salas, E. Olias, A. Barrado, and A Lazaro, "Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems," *Solar Energy Material for Solar Cells*, vol. 90, pp. 1555-1578, 2006.

[19] S. Jain and V. Agarwal, "Comparison of the performance of maximum power point tracking schemes applied to single-stage grid-connected photovoltaic systems," *IET Electric Power Application*, vol. 1, pp. 753-762, 2007.

[20] D. P. Hohm and M. E. Ropp, "Comparative study of maximum power point tracking algorithm," *Progress in Photovoltaic Research & Application*, vol. 11, pp. 47-62, 2002.

[21] Y. H. Chang and W. F. Hsu, "A maximum power point tracking of PV system by adaptive fuzzy," in *Proc. International Conference on Engineers and Computer Scientist*, Hongkong, 2011, pp. 16-18.

[22] C. B. Salah and M. Ouali, "Comparison of fuzzy logic and neural network in maximum power point tracker for PV systems," *Electric Power Systems Research*, vol. 81, pp. 43-50, 2011.

[23] R. A. Mastromauro, M. Liserre, and A. Dell'Aquila, "Control issues in single stage photovoltaic systems: MPPT, current & voltage control," *IEEE Transactions on Industrial Electronics*, vol. 8, pp. 241-253, 2012.

[24] H. Mojgan, A. Zaharin, A. Toudeshki, and M. Soheilirad, "An overview on current control techniques for grid connected renewable energy systems," in *Proc. International Conference on Computer Science and Information Technology*, 2012, vol. 56, pp. 119-126.

[25] N. M. Kumar, B. V. Reddy, B. R. Narendra, and B. C. Babu, "Analysis of different current control techniques for grid connected inverter system," *International Journal of Emerging Trends in Engineering and Application*, vol. 5, pp. 678-699, 2012.

[26] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Transactions on Industrial Electronics*, vol. 53, pp. 1398-1409, 2006.

[27] A. Timbus, M. Liserre, R. Teodorescu, P. Rodriguez, and F. Blaabjerg, "Evaluation of current controllers for distributed power generation systems," *IEEE Transactions on Power Electronics*, vol. 24, pp. 654-664, 2009.

[28] L. Malesani and P. Tomasin, "PWM current control techniques of voltage source converters - A survey," in *Proc. International Conference on Industrial Electronics Control and Instrumentation*, Maui, 1993, pp. 670-675.

[29] M. P. Kazmierkowski and L. Malesani, "Current control techniques for three phase voltage source PWM converters: A survey," *IEEE Transactions on Industrial Electronics*, vol. 45, pp. 691-702, 2008.

[30] J. Selvaraj, N. A. Rahim, and C. Krismadinata, "Digital PI current control for grid connected PV inverter," in *Proc. IEEE International Conference on Industrial Electronics and Applications*, Singapore, 2008, pp. 742-746.

[31] A. I. Maswood and M. A. Rahman, "Performance parameters of a pulse-width modulation voltage source inverter with proportional-integral controller under non-ideal conditions," *Electric Power Systems Research*, vol. 38 pp. 19-24, 1996.

[32] D. N. Zmood and D. G. Holmes, "Stationary frame current regulation of PWM inverters with zero steady state error," in *Proc. 30th Annual PESE Meeting*, 2003, pp. 814-822.

[33] A. Nachiappan, K. Sundararajan, and V. Malarselvam, "Current controlled voltage source inverter using hysteresis controller and PI controller," in *Proc. International Conference on Power, Signals, Control and Computation*, Kerala, 2012, pp. 1-6.

[34] G. M. Azevedo, M. C. Cavalcanti, F. A. S. Neves, L. R. Limongi, and K. C. Oliveira, "Grid connected photovoltaic topologies with current harmonic compensation," in *Proc. International Symposium on Industrial Electronics*, Italy, 2010, pp. 2394-2399.

[35] A. F. Cupertino, J. T. Resende, H. A. Pereira, and S. I. Seleme, "A grid-connected photovoltaic system with a maximum power point tracker using passivity-based control applied in a boost converter," in *Proc. IEEE International Conference on Industrial Application*, 2012, pp. 1-8.

[36] S. E. Evju, "Fundamentals of grid connected photo-voltaic power electronic converter design," Master of Science dissertation, Department of Electric Power Engineering, NTNU, Singapore, June 2007.

[37] R. Teodorescu and F. Blaabjerg, "Proportional-Resonant controllers. A new breed of controllers suitable for grid-connected voltage-source converters," in *Proc. 9th International Conference on Optimization of Electrical and Electronic Equipments*, Optim, 2004, pp. 9-14.

[38] E. Twining and D. G. Holmes, "Grid current regulation of a three-phase voltage source inverter with an LCL input filter," *IEEE Transaction on Power Electronics*, vol. 18, pp. 888-895, 2003.

[39] D. Zammit, S. C. Staines, and M. Apap, "Comparison between PI and PR current controllers in grid connected PV inverters," *International Journal of Electrical, Electronic Science and Engineering*, vol. 8, pp. 54-58, 2014.

[40] H. G. Jeong, G. S. Kim, and K. B. Lee, "Second-Order harmonic reduction technique for photovoltaic power conditioning systems using a proportional-resonant controller," *Energies*, vol. 6, pp. 79-96, 2013.

[41] Z. A. Ghani, M. A. Hannan, and A. Mohamed, "Simulation model linked PV inverter implementation utilizing dSPACE DS1104 controller," *Energy and Buildings*, vol. 57, pp. 65-73, 2013.

[42] N. A. Rahim, J. Selvaraj, and C. Krismadinata, "Hysteresis current control and sensorless MPPT for grid-connected photovoltaic systems," in *Proc. IEEE International Symposium on Industrial Electronics*, 2007, pp. 572-577.

[43] S. R. Bowes and S. Grewai, "Three-Level hysteresis band modulation strategy for single-phase PWM inverters," in *Proc. IEEE Electric Power Application*, 1999, pp. 695-706.

[44] M. Pastor and J. Dudrik, "Predictive current control of grid-tied cascade H-bridge inverter," *Automatika Journal for Control Measurement Electronics Computing & Communications*, vol. 54, pp. 308-315, 2013.

[45] T. F. Wu, K. H. Sun, C. L. Kuo, and C. H. Chang, "Predictive current controlled 5-kw single-phase bidirectional inverter with wide inductance variation for dc microgrid applications," *IEEE Transactions on Power Electronics*, vol. 25, pp. 3076-3084, 2010.

[46] M. A. Rezaei, S. Farhangi, and G. Farivar, "An improved predictive current control method for grid-connected inverters" in *Proc. First IEEE Power Electronic and Drive Systems*, 2010, pp. 445-449.

[47] I. S. Kim, "Robust maximum power point tracker using sliding mode controller for the three-phase grid-connected photovoltaic system," *Solar Energy*, vol. 81, pp. 405-414. 2007.

[48] I. S. Kim, "Sliding mode controller for the single-phase grid-connected photovoltaic system," *Applied Energy*, vol. 83, pp. 1101-1115, 2006.

[49] J. Hu, L. Shang, Y. He, and Z. Q. Zhu, "Direct active and reactive power regulation of grid-connected DC/AC converters using sliding mode control approach," *IEEE Transactions on Power Electronics*, vol. 26, pp. 210-222, 2011.

[50] L. Xu, D. Zhi, and L. Yao, "Direct power control of grid connected voltage source converters," in *Proc. IEEE Power Engineering Society General Meeting*, 2007, pp. 1-6.

[51] J. Alonso-Martinez, J. Eloy-Garcia, and S. Arnaltes, "Direct power control of grid-connected PV systems with three level NPC inverter," *Solar Energy*, vol. 84, pp. 1175-1186, 2010.

[52] L. Limongi, R. Bojoi, C. Pica, F. Profumo, and A. Tenconi, "Analysis and comparison of phase locked loop techniques for grid utility applications," in *Proc. Power Conversion Conference*, Nagoya, 2007, pp. 674-681.

[53] F. Mur, V. Cardenas, J. Vaquero, and S. Martinez, "Phase synchronization and measurement digital systems of AC mains for power converters," in *Proc. IEEE International Power Electronic Congress*, 1998, pp. 188-194.
[54] A. Timbus, R. Teodorescu, F. Blaabjerg, and M. Liserre, "Synchronization methods for three phase distributed power generation systems. An overview and evaluation," in *Proc. IEEE 36th Power Electronic Specialist Conference*, 2005, pp. 2474-2481.
[55] F. Lov, M. Ciobotaru, D. Sera, R. Teodorescu, and F. Blaabjerg, "Power electronics and control of renewable energy systems," in *Proc. International Conference on Power Electronics and Drives*, 2007, pp. 6-27.
[56] N. Mohan, *Power Electronics: Converters, Circuit and Applications*, 5th ed., John Wiley & Sons, 2007.

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