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ADVANCES AND CONTROL TECHNIQUES IN GRID CONNECTED PHOTOVOLTAIC SYSTEM

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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.

I. INTRODUCTION

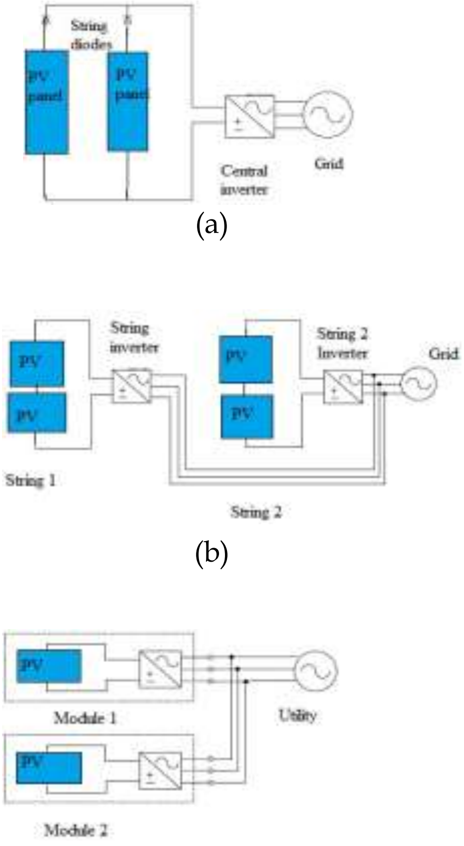
The installation of Solar systems in India had risen from 35.15MW in 2011 to 941.25MW in 2012 and India aims at achieving 20GW solar power installations by 2020 and also to achieve grid parity by 2020. India is likely to install additional capacity of 1300MW to 1400MW of solar powered plants in 2013-2014. 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. Hence the installation of grid connected photovoltaic systems goes on rise in comparison to stand alone systems.

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 directcurrent 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.



(a)

(b)

(c)

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

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.

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.

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

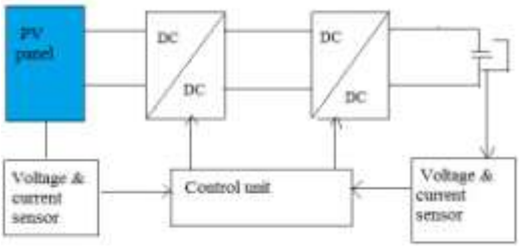
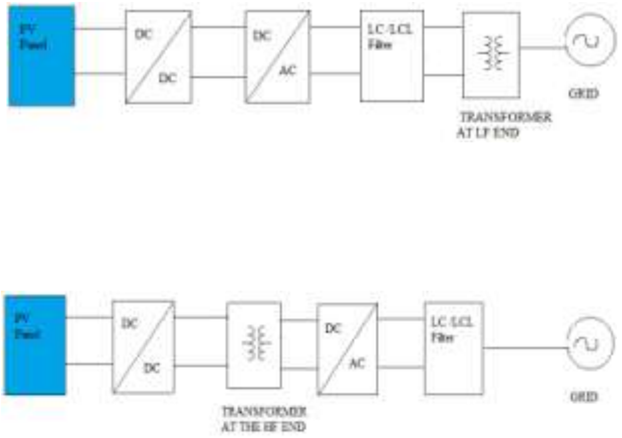


Figure 2. Double stage boost transformer less topology

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. Both the transformer based technologies are currently prevailing and the efficiency is around 93 to 95%. 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,min 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. 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.

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. Unbalanced voltage will further lead to unbalanced current which deduces the quality of the system.

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, 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 at the fault point and indicates the amount of fault current for the relay to act upon the fault. 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.

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. 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.

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.

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. 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 I below.

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 adapting input voltage variations, grid synchronization for unity power factor control and grid current control for system stability.

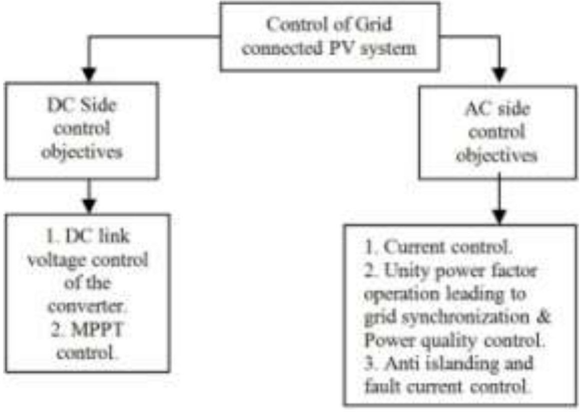


Figure 4. Existing control objectives of grid connected PV system

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. 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.

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

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.

3) Telecommunication based methods

A computerized communication channel is established between the protective structures and the sensors to the DG. Rate of change of frequency is another method

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. 5. 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 with a comparison of it making a brief conclusion.

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.

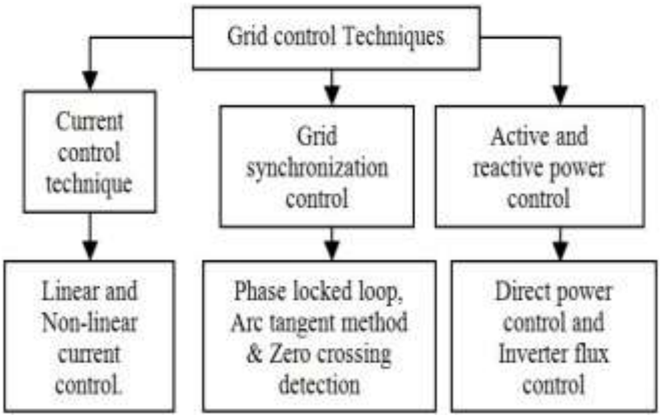


Figure 5. Classification of grid control techniques

1) PI current control

A typical PI current control is shown in Fig. 6. The P controller's steady state error is eliminated by adding an integral component to the transfer function.

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.

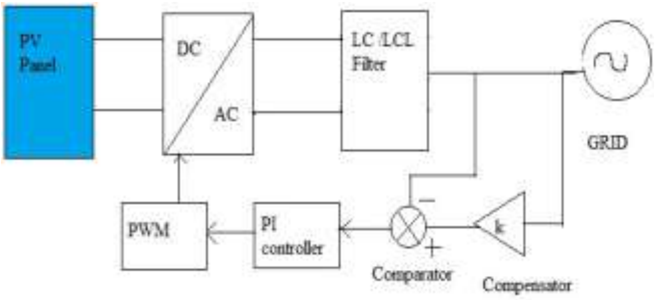


Figure 6. PI current control flow diagram

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. Here as shown in Fig. 7 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 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.

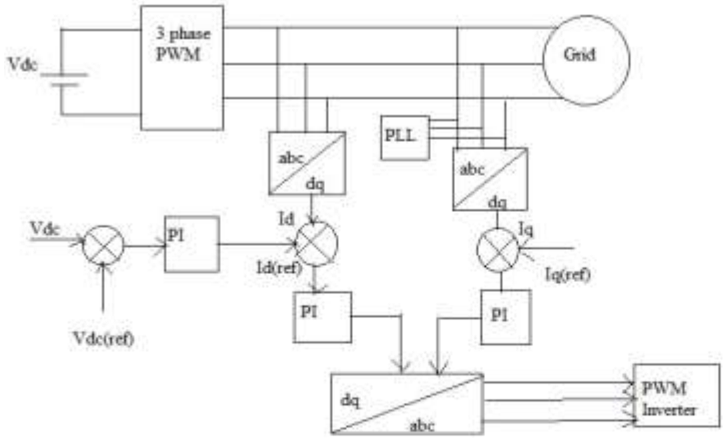


Figure 7. DQ frame control with harmonic compensation

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.

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

$$G(s)=kp\quad ki * s/(s^2\quad ^2)$$

Where k_p and k_i are the propotional and integral control gains.

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. 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*

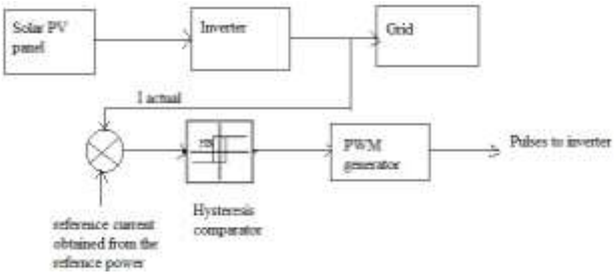


Figure 8. Hysteresis current controller applied to grid connected PV systems

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 as seen in Fig. 8. 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. 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 as shown in the Fig. 9 below

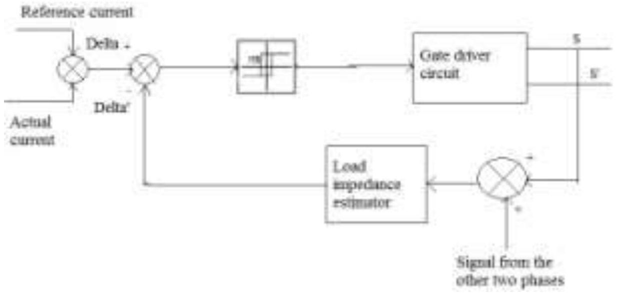


Figure 9. Decoupled, constant average switching frequency hysteresis controller

3) Current regulated delta controller

The current regulated delta controller is same as the hysteresis controller with a latching device is attached to it represented in Fig. 10 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

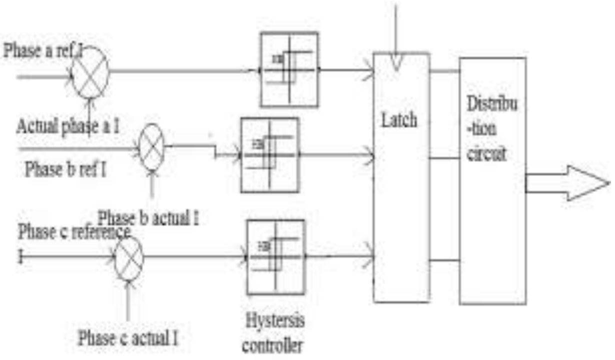


Figure 10. Current delta regulated control methodology

4) Modified ramp type controller

The ramp controller described in Fig. 11 involves the comparison of the triangular signals of fixed amplitude

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.

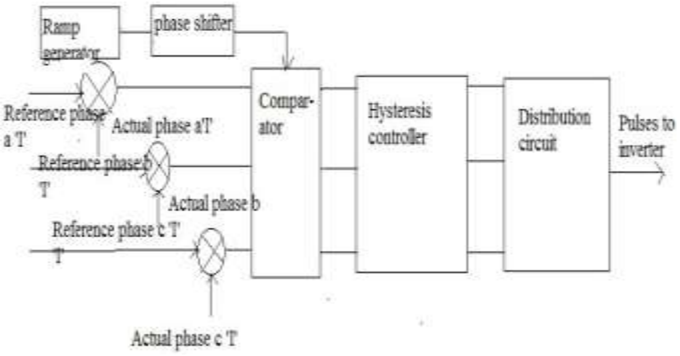


Figure 11. Modified ramp type controller methodology

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. 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. 12.

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

Where v(k) and i(k) are measured value pf grid current and future reference current.

$$I*(k\ 1)\ \ 3I(k)\ \ 3I*(k\ 1)\ \ I*(k\ \ 2)$$

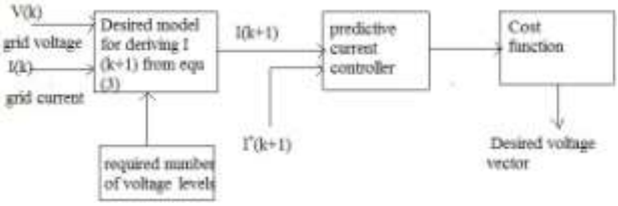


Figure 12. Deadbeat/Predictive current control algorithm

6) Sliding mode control

Sliding mode control shown in Fig. 13 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. 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.

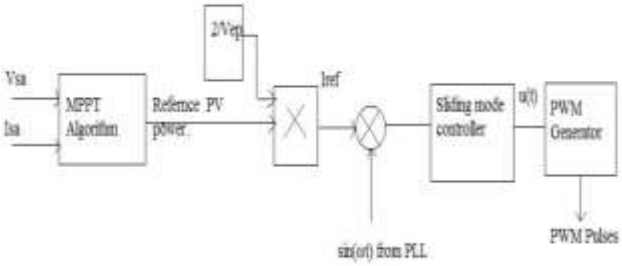


Figure 13. Sliding mode controller for grid connected PV system

7) Direct power control

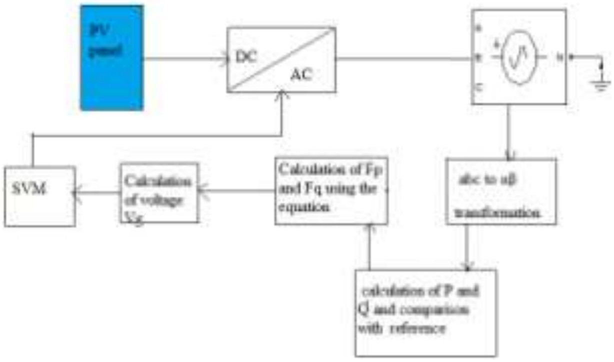


Figure 15. Direct power control using sliding surface for grid connected PV systems

$P(actual)\ \ 1.5(Vg\,Ig\ \ Vg\ Ig\ )$ (4)

$Q(actual)\ \ 1.5(Vg\ Ig\ \ Vg\,Ig\ )$ (3)

The conventional direct power control involves the synchronously transformed co-ordinates d and q and current control loops for deriving the active and reactive power.

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%.

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.

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. 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. 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 stastics and proagrame implementation, india,2013, pp.18-59

[2] 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.

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

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

[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] 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.

[10] [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.