Recent Advances and Control Techniques in Grid Connected Pv System – A Review

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Abstract- In recent years, grid connected photovoltaic system has emerged with its simplicity, reliability and endurability. The ranges of grid tie inverters (GTI) are classified as small scale as several tens of kilowatts and large scale as hundreds of megawatts. Accordingly, the standard of interconnecting to the grid is made higher extent in improving its power system reliability, efficiency and cost. Moreover, the working of grid connected inverter primarily depends on robustness in control strategy, even working in abnormal grid conditions such as deviation of voltage and frequency. This review focuses on updating grid standard codes and regulations, in addition overview of recent control strategies and direct power control. The structure of the phase locked loop (PLL) with grid synchronization techniques for single phase and three phase is discussed in brief. Investigations are performed for a fault ride through capabilities with detailed analysis of islanding detection methods with its types. The PV- STATCOM control functionality for the enhancement is discussed in detail.

Keywords: PV inverter, grid codes, islanding, power quality, grid synchronization, current control

1. Introduction

Solar photovoltaic (PV) energy conversion system has shown increase at a moderate annual rate of 60% in the last five years [1]. This is possible because of alternate clean energy sources, reduction of cost, efficiency increase of PV modules and subsidy scheme of political regulations [2]. PV installation is classified according to their functional and operating requirements named standalone and grid connected. With standalone system, remote area is supplied by DC or AC power with converters and energy storage devices [3]. On the other hand, in grid connected, generated power supply to the utility services without any energy storage equipments that have made added advantage of 99% benefit than stand alone system.

In grid connected inverter, the power generated by PV plant is directly given to the transmission line and it is distributed. Henceforth, the use of batteries and other energy storage devices is not required that makes the arrangement less space, reduced investment cost and maintenance than stand alone system [4-6]. The evolution of solid state inverter technology and its control strategy have established PV systems into the grid as shown in Fig. 1. Due to variation of input supply at the inverter side, the PV inverter topology and its control design is made robust with the promising contol structure. The dc-link voltage is fixed to supply constant voltage to the inverter.

In the present decades, transmission system operators (TSO) have come up with standard grid codes in improving the quality of power supply injected into the grid based on small, medium and large scale industries according to the generated power rating. National electricity regulatory authority has made it mandatory to use transformer in the system for the galvanic isolation purpose. However, usage of transformers makes the system bulky size and increase the cost of the system. The aforementioned problem makes the researchers to concentrate on transformerless PV system [7,8]. The growth of power electronics technology has made transformerless PV inverter well suited in kilowatt (kW) range by placing standards such as DIN VDE 01261-1. However, elimination of transformer creates leakage current [9, 10], and complication in the grid side controller. This paper gives the overview of recent advances in controllers in grid connected PV system. Section 2 illustrates standard codes and regulation of PV inverter followed by performance requirements in section 3. Control structure of PV inverter defined in detail with active power and direct power control method in section 4. Recent advances in single phase and three phase synchronization method is analysed in section 5.

Brief analysis in islanding method and its type is discussed in section 6.Finally, advances in PV inverter is reviewed.

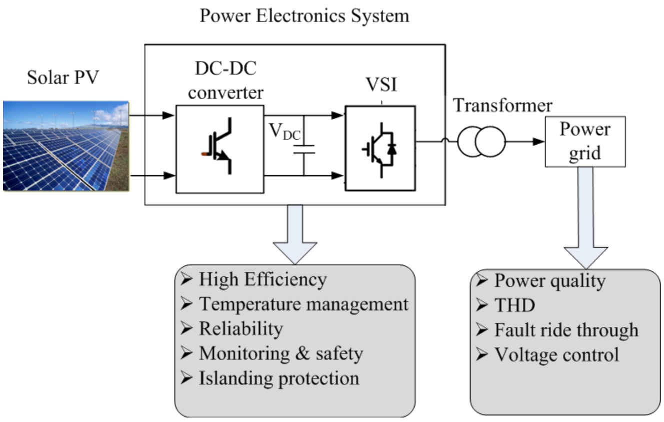


Fig. 1. Generic structure of grid connected PV system

2. Standard codes and regulation of grid PV inverters

Since grid connected PV applications are becoming more significant, a series of standard requirements and codes are regularly maintained by international and national committee to assure security and smooth transmission of electric power into the grid. The most relevant international bodies developing standard grid demand are IEEE (Institute of Electrical and Electronic Engineers) in the US, IEC (International electro technical commission) in switzerland and DKE (german commission for electrical, electronic and information technologies of DIN and VDE) in the germany leading in the PV market.

Several international standard regulations, that focus on recent developments are IEEE 1547 for interconnection of distributed generation (DG) [11, 12], IEC 61727 for characteristics of the utility interface [13], VDE 0126-1-1for Safety enhancement [14], IEC 61000 for electromagnetic compatibility [15], EN 50160 considering the public distribution voltage quality. The summary of international standard codes is defined in Table 1.

3. Performance Requirements of PV Inverters

3.1. Efficiency

The increase in use of PV inverter in domestic and industrial made to decrease the losses and concentrate on efficiency. Many industries have come up with transformerless inverter with efficient topology and control strategy removes zero crossing detection [16] with the aim of reducing the size and cost. Meanwhile number of switches is reduced with new topologies [17]. Recent studies proved that efficiency has higher values when silicon carbide (SiC), and gallium nitride (GaN) power semiconductor devices used in PV inverters [18].

3.2. Power density

The development of new PV converter topology by the manufacturer motivates to come up with very high power density. This can be achieved by employing higher switching frequencies and omission of DC/DC converter mainly for domestic and commercial applications [19].

3.3. Power Quality

Due to many power electronics, non linear, reactive loads and intermittent nature of DG makes poor power quality at PCC [20-24]. However, power quality is major consideration for stable and economical operation of grid connected inverter (GCI). However, effectual response should be taken to eradicate poor power quality. There are two response strategies to be considered. The effective strategy is active or passive power quality conditioners as dynamic voltage regulator (DVR), shunt active power filter (SAPF), unified power flow conditioner (UPQC), and power factor correction (PFC) are discussed in literature [25-28]. Former, the effective ride through approach [29,30] to mange poor power quality.

The above mentioned advanced control strategies equipped with new topologies of inverter to enhance the power quality placed at the point of common coupling (PCC) is commonly known as multi-functional grid connected inverter (MFGCI) modified from conventional grid connected inverter is discussed in detail in literature [31].

3.4. Installation cost

In recent days, reduced cost of PV modules has impacted the balance of system (BoS) cost and reduced the levelized cost of energy (LCOE). Transformerless inverter topologies with reduced number of switches have reduced the inverter cost. Installation charges vary from region to another as land, labour and other local factors [32, 33].

4. Control Structure of PV Inverter

The fundamental types of control can be classified into two types: voltage control and current control. Voltage amplitude and frequency of inverter gets synchronized with each other, when it is connected to the grid. The classical current control is classified as active power and reactive power control method. The grid frequency is tracked by a phase locked loop (PLL). The inverter assembly circuit with control strategy is shown in Fig. 2. The voltage and current of the grid is taken as reference and it is transformed to mathematical equation with current control structure and given as duty cycle to the inverter.

4.1. Active power control

The power control method defined in [34] acts as an instantaneous power and it eliminates dq components and double frequency harmonics. This makes the system more stable and tracking speed accuracy. The controller equations defines, grid voltage as $V_g(t)$ and grid current as $i_g(t)$. With the help of grid current control, active power as in equation (4) and reactive power as in equation (5) injected into the grid.

Table 1. Summary of international standard for PV applications

	Codes and standards	**Outlook and content of the standard**
Grid connected	IEC 61727,IEC 60364-7-712	Installations of buildings.
	IEC 62093, IEC 62116, IEC 61683	Utility interface and measuring efficiency.
	UL 1741,IEC 62446	Interconnected PV inverters-system documentation, commissioning tests. And use in independent power systems.
Off grid	IEC 61194,IEC 61702, IEC 62509	Battery charge controllers.
	IEC/PAS 62111, IEEE Standard 1526,	Stand-alone systems.
	IEC 62124	Rating of direct-coupled pumping systems
		Specifications for rural decentralized electrification.
Rural systems	IEC/TS 62257	Medium-scale renewable energy and hybrid systems. Safeguard from electrical hazards. Choice to select generator sets and batteries. Micro power systems and microgrids.
Monitoring	IEC 60870,IEC 61724,IEC 61850-7	Measurement, data exchange, and analysis Transmission grids and systems for power service automation Distributed energy resources and logical nodes
Electromagnetic Compatibility (EMC) / Electromagnetic Interference Emissions	EN61000	European union EMC directive for residential, private sectors, light industrial, and commercial facilities.
	FCC Part 15	U.S. EMC directive for residential, commercial, light industrial, and industrial facilities
Leakage current	VDE 0126-1-1	$I > 300$ mA at 0.3s $\Delta i > 30$mA at 0.3s $\Delta i > 60$mA at 0.15s $\Delta i > 150$mA at 0.04s
Anti-islanding	IEEE 1547/UL 1741 IEC 62116	Detects the islanding and energizes within 2 Sec.
	VDE 0126-1-1	Impedance measurement
Low voltage ride through (LVRT)	IEC 61727	$V < 50\%$ at 0.1sec $50\% \leq V < 85\%$ at 2.0 sec

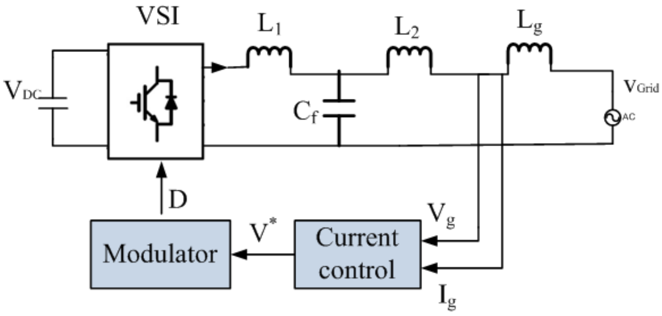


Fig. 2. Block diagram of conventional three phase distributed inverter

$$V_g(t) = V_0 \cos(\omega t) \quad (1)$$

$$I_g(t) = I_0 \cos(\omega t - \varphi) \quad (2)$$

Instantaneous power is defined as,

$$P(t) = V_g(t) * i_g(t)$$

$$= P\,[1 + \cos(2\omega t)] + Q\,[\sin(2\omega t)] \quad (3)$$

Where, $P = \frac{1}{2} V_0 I_0 \cos\varphi$ (4)

$$Q = \frac{1}{2} V_0 I_0 \sin\varphi \quad (5)$$

4.1.1 Linear and nonlinear current control

Current controllers are used to keep the steady state operation of a grid connected PV system as they can monitor the current to follow the reference current. In three phase system, active and reactive power is suitably controlled by using the approach of dq rotating synchronous frame (dq-SRF) [35]. The dq components are defined as i_d and i_q proportional to active and reactive power. In single phase system, the current dq component can also be generated by using αβ – dq transformation as shown in Fig. 3. However, β component is availed by using 90^0 phase shift of fundamental frequency. The different methods of performing 90^0 phase shift are time delay, all pass filter, hilbert transform, second order generalized integrator and enhanced phase locked loop (EPLL) [36, 37]. There are different control techniques as shown in Fig. 4. Such as proportional integral (PI) controllers with complex computational requirements and existence of steady state error as drawbacks [38]. Later, modified PI controller [40] have come up with an addition of grid voltage feed forward path and multiple-state feedback and increase of proportional gain as given in equation (6) and (7). Inclusion of these parameters have made difficult in implementing it in digital signal processor (DSP).In the next decades, most widely used proportional resonant (PR) controller eliminates steady state error with an infinite gain at selected resonant frequency [41-43]. Hysteresis controllers [44], repetitive controllers [45, 46], sliding-mode controllers [47], and so on. The deadbeat controller is from the hierarchy of predictive controllers [48], the controller is developed on the basis of the model of the filter and grid, which predicts the dynamics of the system. In transient condition due to grid fault, dead beat control as given in Fig. 5. shows superior performances in limiting the peak current [49 - 51]. Analytical model of single phase circuit is defined as in equation (8) and controlled by deadbeat control as in equation (9). Advantages and inconvenience of different current control methods is defined in Table 2.

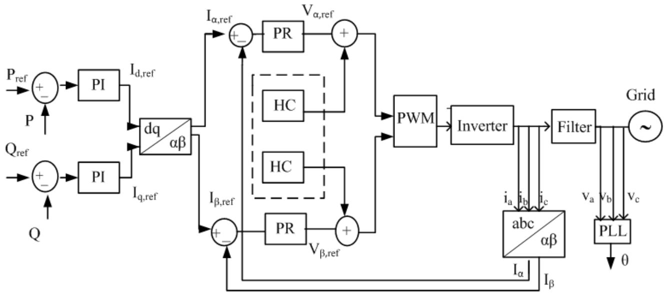


Fig. 3. Structure of harmonic compensation control strategy

PI controller transfer function is described as,

$$G_{PI} = K_P + \frac{K_i}{S} \quad (6)$$

PR controller transfer function is described as,

$$G_{PR} = K_P + K_i \frac{S}{S^2 + \omega^2} \quad (7)$$

By the mathematical model of single phase circuit,

$$L\frac{di(t)}{dt} + Ri(t) = V_i(t) - V_g(t) \quad (8)$$

Transfer function of deadbeat controller is defined as,

$$G_{DB}(Z) = \frac{1}{b} + \frac{1 - aZ^{-1}}{Z - Z^{-1}} \quad (9)$$

Where the constants a and b are defined as,

$$a = e^{-(R_t / L_t)T_s}$$

$$b = \frac{1}{R_t}(e^{-(R_t / L_t)T_s} - 1)$$

Table 2. Comparison of different control strategies

Control strategies	Associated type		Advantage	Inconvenient
	system	controller		
Dq- control [35]	Linear	PI [39]	Filtering and controlling can be easily achieved	Very poor compensation of lower order harmonics. The steady state error is not eliminated
αβ- control [36]	Linear	PR [40,41]	Very high gain at resonance frequency is achieved. The steady state error is eliminated. Complexity is less than dq High dynamic	Power factor control is not fully achieved
	Linear	Repetitive control [45]	Steady state error elimination is achieved Harmonic compensation is good	Tracking response is too slow
abc control [38]	Linear	PI		The transfer function is complex
	Linear	PR	The transfer function is simple	More complexity than hysteresis and dead beat
	Linear	Hysteresis [44]	High dynamic Fast response	Varying switching frequency High complexity of control for current regulation
	Non-linear	Dead-Beat	Tracking response is fast.Harmonic compensation is very good	Implementation in high frequency microcontroller

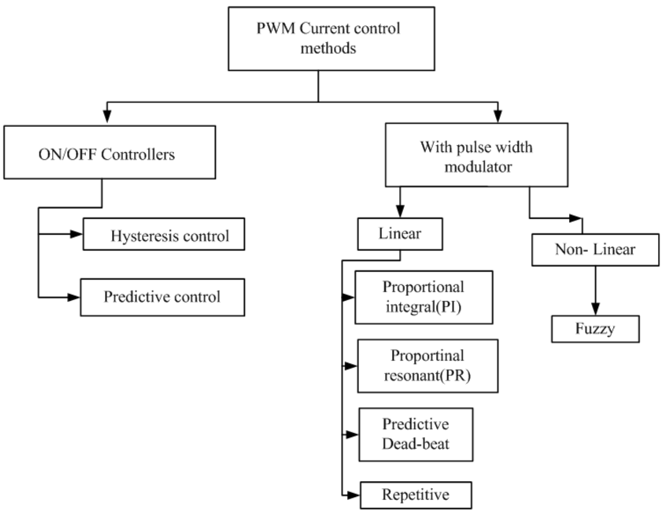


Fig. 4. Classification of current control methods

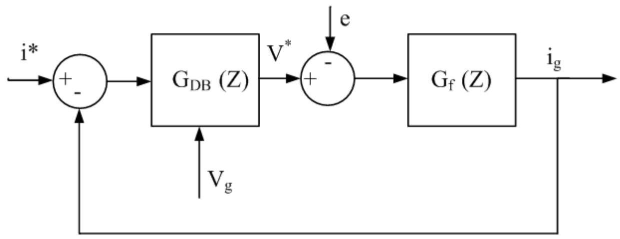


Fig. 5 Structure of deadbeat control

4.2. Direct Power control method

Khajehoddin et al., have come up with direct power control, rather controlling active and reactive power separately [52, 53]. In Fig. 6 a). i_d and i_q are dc variables known as active and reactive powers. The references for the current component is given as shown in Fig. 6 b). Further, developing a linear time invariant model for the stability purpose [54]. Grid current has a wide range of variation and variable frequency, compared to voltage. The 90^0 phase shift itself creates a barrier to increase the speed of the system response. In a three phase system, the β signal is taken through abc/αβ transformation on the current signals. Accordingly, i_d and i_q perfectly match with the dc variables. The direct power control structure as shown in Fig. 7 cancels the current harmonics by the harmonic controller block in the form of resonant controller. Later, Yongheng et al., have come up with a hybrid power control method to achieve improved thermal performance and effective utilization purpose [55- 57].

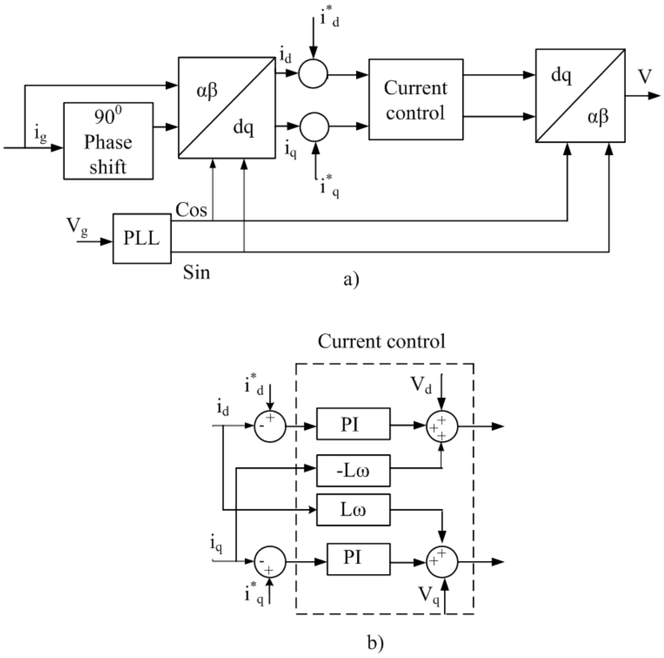


Fig. 6. a) Control structure of single phase active and reactive power, b) Current control block

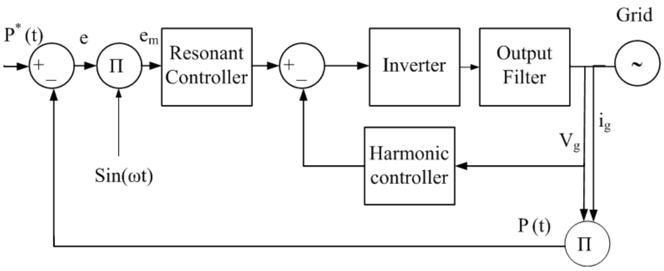


Fig. 7 Direct power control structure

5. Grid Synchronization Method

5.1. Structure of PLL

A power converter is commonly sensitive to the voltage disturbances. Since, its control system might lose controllability on the power signals under distorted conditions. In three phase system, active and reactive powers can be controlled using dq synchronous rotating frame. According to [58-60], importance of synchronization is defined as the power converter interacts with the grid at the point of common coupling. In order to reduce the undesirable effects and attenuate the voltage disturbances, synchronization should be properly designed with accurate phase locked loop (PLL) to create current waveform reference in good quality. The general technique is synchronous rotating frame PLL (SRF PLL) [61, 62].

5.1.1 Single-phase grid synchronization technique

The main aspect of interconnecting renewable energy to the grid by power converter are the magnitude and phase angle of fundamental frequency component should synchronize with the grid voltage. In the occurance of fault, the dq-PLL operates well and it tracks the phase angle. Accordingly, in

Table 3. Time response analysis of synchronization technique.

Synchronization technique	Detection time at transient response	Observance
DSOGI [63]	>40ms	longer response time
EPLL [65]	>40ms	longer response time
DDSRF [66]	40ms	fast transient response
VSPF [68]	25ms	well suited for variable frequency with disturbances
ANF	20ms	Fast dynamic response
MCCF [67]	20ms	quick and perfect segregation of positive and negative sequences and harmonic component of imbalance grid voltage.

an unbalanced fault, the dq-PLL fails to record the phase angle.Because it does not match with the positive sequence voltage due to oscillation. Though, identifying harmonic component is made similar in single phase grid synchronization method is segregated into frequency domain and time domain.

In single phase system, generation of signal in quadrature is not necessary in the input side. In orthogonal, signal generation methods are classified as PLL structure and inverse park transformation methods.

Many research works depicts various algorithm for detecting grid voltage and phase angle such as zero crossing detection, arctan function, phase locked loop under ideal grid voltage conditions. Time delay, all pass filter, hilbert transform and second order generalized integrator (SOGI) fall under aforementioned category.

Under normal grid condition without any voltage harmonic distortion, SRF PLL with high bandwidth can give an accurate and fast detection of the phase and amplitude of the grid voltage. If the utility voltage is distorted with harmonics, the SRF PLL can still work if its bandwidth reduced to cancel out the harmonics with slow process. Despite reduction of PLL bandwidth does not yield a solution for unbalanced grid voltage [63].

5.1.2 Grid synchronization techniques for three-phase systems

A grid connected power converter is sensitive to voltage disturbances. Since, it loses controllability on the power signals under distortion condition. Moreover, a power converter interacts with the grid at the point of common coupling to attenuate voltage disturbances to reduce the undesirable effects. In such cases, voltage vector disturbances are detected by the synchronization system and to react to both ride through and provide support to the grid. In three phase system, synchronous reference frame PLL (SRF-PLL) represented as dq-PLL and stationary reference frame PLL as αβ-PLL are normally used for synchronization purpose [64]. Indeed, they have difficulties in tracking phase angle during distorted conditions in the grid. To overcome this complexity, many researchers have come forward by various synchronization techniques as follows.

Ghartemani and Iravani proposed enhanced phase locked loop (EPLL) [66] to cancel the specific frequency component with the support of adaptive notch filter (ANF) for a non linear three phase system. However, in second order generalized integrator phase locked loop (SOGI-PLL) [65] response time differs due to same variable. A dual second order generalized integrator (DSOGI) proposed in [66] has good dynamics under unbalanced grid voltage conditions. A decoupled double synchronous reference frame PLL (DDSRF PLL) [67] shows fast transient response for unbalanced voltage condition with major disadvantage of complex structure. The discussed synchronization technique is shown in Fig. 8.

Later, Xiaoqiang Guo et al., [68] proposed multiple-complex coefficient filter (MCCF) based PLL as in Fig. 9. With a fast and exact extraction of positive and negative sequence of harmonic components in distorted grid voltage condition with frequency adaptive capability. In 2012, for large distorted condition, Carugati et al., [69] discovered a new algorithm called variable sampling period filter phase-locked loop (VSPF-PLL) that enhances the method to implement in DSP and microcontrollers. The time response analysis of different synchronization technique is defined in Table 3.

6. Islanding Detection

Detection of the utility grid condition is a essential feature of the DPGS units at every level. Typically, detection of a possible island condition is a significant in PV system and it is defined as anti-islanding requirement that disconnect the electric grid and PV inverters starts supplying to local loads. According to latest grid codes [70, 71], the requirement of a low voltage ride through (LVRT) [72, 73] capability and high voltage ride through (HVRT) [74] states that they stay connected during grid abnormalities [75, 76]. Fig. 10 shows the classified islanding detection methods [77 - 79]. If grid voltages become unbalanced, islanding detection methods should take place within few milli seconds.

6.1. Passive islanding method

Islanding detection monitors changes in inverter output parameters or any other system parameters that indicates islanding. The changes in electrical parameter determine the occurrence of islanding commonly known as passive islanding [80]. This technique does not require any controller and easy to implement. Fig. 11. a) depicts interconnection of power inverter and load and Fig.11 b) the balance of power system. The primary drawbacks are large non detection zone (NDZ) and helpless in multiple PV inverter systems. The most familiar passive technique for islanding detection are,

- Under/over voltage (UV/OV)
- Under/over frequency (UF/OF)
- Voltage harmonics
- Phase jump detection

Due to large non detection zone (NDZ), UV/OV and UF/OF methods are employed rarely. However, in grid connected system, it is used for monitoring purpose. Active techniques inject smaller disturbance on the output of PV inverter to detect islanding [81-83]. It has smaller NDZ than passive methods that makes the system instability to the PV inverters thus it requires addition controllers. Active techniques include impedance measurement, active phase shift and sandia frequency shift [84]. The condition for grid voltage and frequency limits as per EN 50160 is listed in Table 4.

From the Fig. 11. a). the power balance equation is framed as in equation (5) and (6) P_{load} is the real power of the load, Q_{load} is the reactive power of the load, Q_{DG} is the reactive power output of the PV, P_{DG} is the real power output of PV, ΔP is the real power output of the grid, ΔQ is the reactive power output of the grid. The NDZ depends on load conditions as in Fig. 11. b).

Hence the power balance is,

$$P_{load} = P_{DG} + \Delta P \qquad (5)$$

$$Q_{load} = Q_{DG} + \Delta Q \qquad (6)$$

Table 4. Standard grid parameters limits of EN 50160

Value	Minimum	Maximum
Frequency	F_{min} = 49 Hz	F_{max} = 51 Hz
Voltage	V_{min} = 0.9 p.u	V_{max} = 1.1 p.u

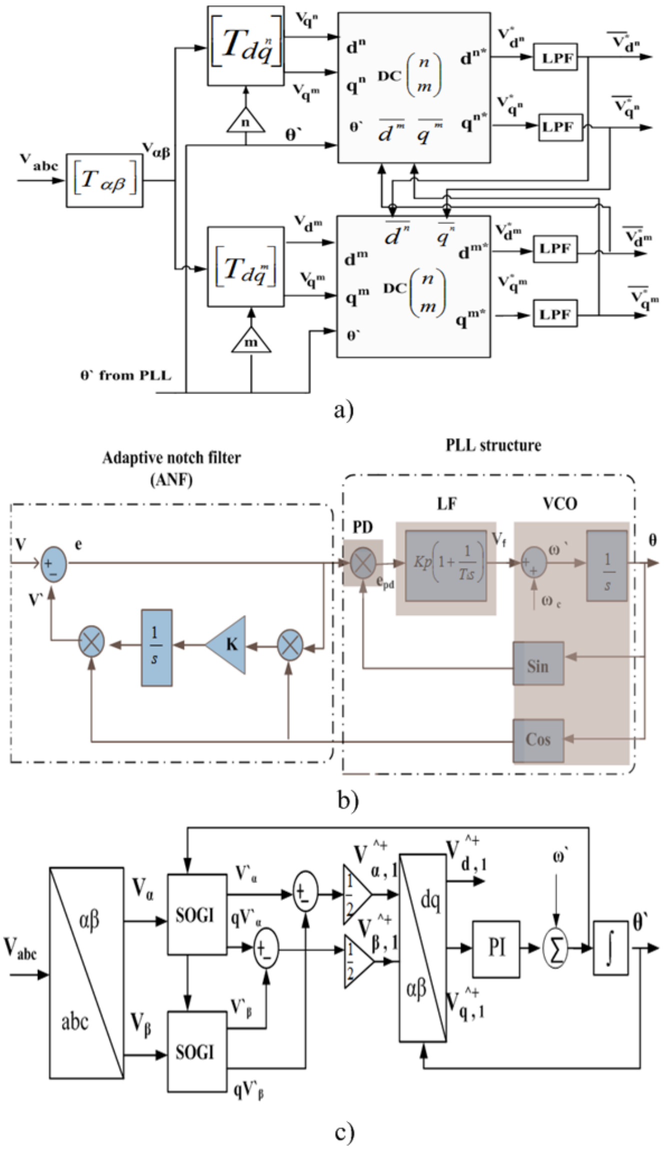


Fig. 8. Control structure of different PLL techniques. a).DDSRF, b).EPLL, c)DSOGI

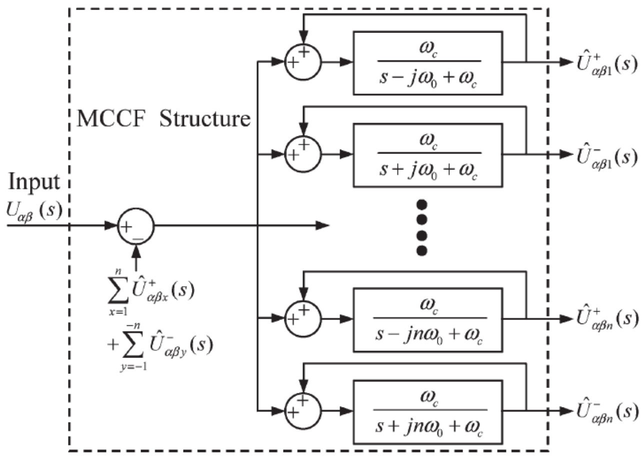


Fig. 9 Basic structure of MCCF

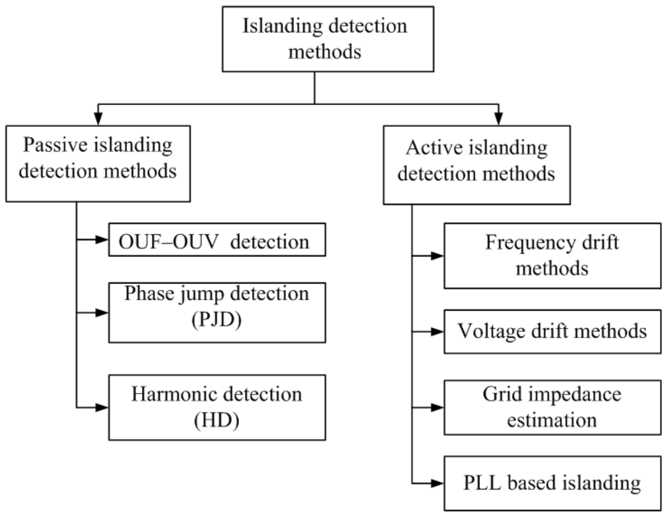


Fig. 10. Classification of islanding detection methods

6.2. Active islanding method

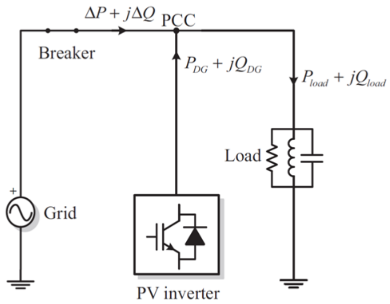
The active method depends on the output of PV inverter generating small changes in frequency, phase, harmonics, active and reactive power [84]. It is divided into two groups defined as transient active and steady state active. Active islanding methods are serious due to reduced NDZ and disturbance introduced in the grid. When large numbers of inverters are interconnected to the same point of common coupling (PCC) interferences occur. To prevent this active methods are proposed. Inconvenience of this method is that they produce disturbances in the grid for obvious reason. Fig. 12 shows the closed loop control system of a PV system, an effective power calculation method in terms of accurate computation and fast dynamic response with an advanced synchronization unit enhances the LVRT performance of the system. The overall performance of active methods is differentiated as in Table 5.

7. Advances in PV inverter

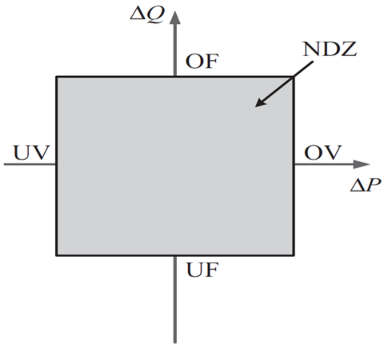
The idleness of solar farm in night leads poor asset management. In [85] a new approach on power inverter as PV-STATCOM, which uses solar farm at night time for the regulation of voltage variations at the point of common coupling. STATCOM control functionality [86-88] is implemented in PV inverter during night time for enhancing the transient stability of the system. It is also noted that the recent grid code recommend the solar PV farm to help the voltage regulation of grids by supplying / absorbing appropriate reactive power. This operation makes revenues to the investors. However, this is achieved by appropriate agreements between regulators, changes in grid code and inverter manufacturers.

Table 5. Overall performance comparisons of active methods

	Active methods				
Performances	Active frequency drift [77]	Sandia frequency shift [77,80]	Reactive power variation [81]	Grid impedance estimation-harmonic injection [83]	Grid Communication [85]
Reliability	Medium	High	Moderately high	High	Very high
	Reason: not capable to remove NDZ	Reason: It removes NDZ	Reason: It can remove NDZ	Reason: It can eliminate NDZ	Reason: As it does not depend on PQ, communication is good
Power quality	Low	Medium	High	Medium	High
	Reason: Lower order harmonics are introduced	Reason: power factor is affected, but no harmonics are injected	Reason: As no harmonics are injected, only the PF can be reduced.	Reason: It depends on injections.	Reason: No influence on PQ
Applicable for Parallel inverter operation	Low	Medium	Low	Low	Very high
	Reason: It does not handle continuous detection	Reason: Its able to work with parallel inverters but power quality is affected	Reason: Variation of frequency at PCC due to the other inverter	Reason: Readings get to be influenced in parallel injection	Reason: Depending on communication reliability
Advisable for standardization	Low	Medium	Low	Low	Very high



a)



b)

Fig. 11. a). Connectivity of inverter to the grid and the load b). Nondetection zone

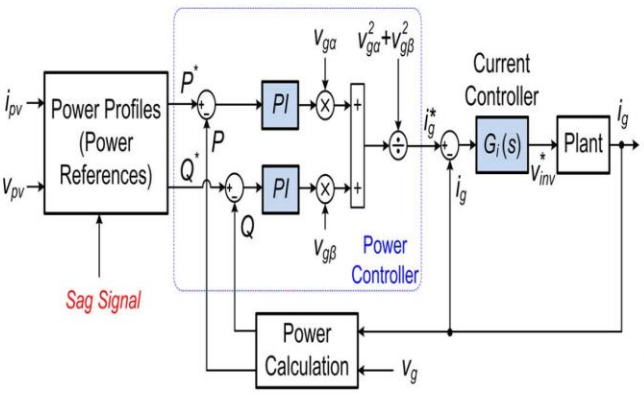


Fig. 12. Closed-loop control system of grid power converter with LVRT capability based on PQ theory and PR + HC current controller

8. Conclusion

The outlook of recent standard grid codes and regulation of interconnecting PV inverter to the grid have covered in detail, which focuses on the performance requirement and power quality. The advanced material of SiC and GaN based power converter shows enhanced future performance in PV inverter technology. Further, detailed study on current control strategy and grid synchronization method for single phase and three phase have been differentiated with analysis. The robustness of PV control strategy believes to with-stand in grid abnormalities by the advanced synchronization method. Compared to passive islanding detection methods, in active islanding many innovative methods have been analysed based on frequency drift, voltage drift, and PLL. Recent advances of STATCOM control functionality of grid connected PV inverter is also discussed.

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