Multifunctional Grid Interactive Solar Photovoltaic Systems: A Comprehensive Review

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Abstract- The multifunctional grid-connected inverter (MFGCI's) has drawn a significant attention among researchers because of its ancillary services including active power injection into utility grid while also serving as an active power quality conditioner (APLC) to enhance the power quality (PQ). It should be noted that the application of a multifunctional inverter is specifically increased to integrate renewable and sustainable energy sources like solar photovoltaic (SPV) and wind turbine (WT) in distributed energy resources (DERs) and microgrid (MGs), where the aim is to diminish the transmission and distribution losses considerably by generating power at one place and serving the load requirement of nearby localities. In view of this, various configurations used in MFGCI's are presented along with their detailed comparative study. Furthermore, control strategies employed in single and three-phase MFGCI's are comprehensively reviewed. Additionally, an in-depth explanation, comparison and discussion on MFGCIs are accomplished. Beside this, the author has also made an attempt to provide a detailed explanation on future scopes of MFGCIs in DERs and MGs.

Keywords Multifunctional grid connected inverter, Comparative analysis, Power quality enhancement, Solar photovoltaic system, Distributed energy resources and microgrid

1. Introduction

Renewable and sustainable sources such as SPV systems, WT energy conversion systems are now considered as a promising and growing alternative source of energy considering the fact of global emission and degraded PQ [1]. These problems due to non-renewable sources can be diminished to a great extent by enhancing the use of renewable sources in DERs and MGs [2-4]. These renewable sources possess several features such as emission-free power generation, they are everlasting and most importantly fuel used in generating power from solar and the wind is solar irradiation and moving air masses, which are abundant in amount and also available at free of cost. It is also proven in past studies that the stability of the traditional electric power network can also be augmented by integrating renewable sources to the utility grid through MGs and DERs [5, 6]. In traditional power systems, a power is generated at the far end from the load and further this power is being evacuated from source to load through a long transmission network which will lead to increased transmission and distribution losses. These losses can be alleviated up to a great extent by generating a power at the load end and serving the load requirement of nearby localities. DERs and MGs are considered to be local power systems which possess the above mentioned functionalities which have been looked by power system engineers since past many years [7-10].

Energy storage devices and renewable sources used in DERs and MGs are interfaced to the electric grid through the grid-connected inverter (GCI). But, the use of inverter for only active power injection in the grid will eventually increase the capital investment, maintenance cost, and man-hours. So, to diminish the operation and maintenance cost and also to augment the effectiveness of GCIs in DERs and MGs application, the multifunctional grid-connected inverter (MFGCIs) is proposed in [11-15]. MFGCIs has drawn a significant attention among researchers because it can help to accomplish two major objectives at the same time namely, integration of renewable sources and energy storage devices to the utility grid and enhancement of quality of power supplied to the consumer. This feature of MFGCI has made it the best choice for MGs and DERs application to improve the power factor, to enhance the PQ, to compensate the load reactive power demand as well as to inject the active power into the electric grid [16, 17].

This paper presents a comprehensive review of the grid interactive multifunction inverter based SPV systems. A detailed comparative analysis of single-stage and double-stage system is presented in this paper. Additionally, from the views of single-phase and three-phase electric grid, a detailed explanation, comparison and discussion of MFGCIs control strategies are summarized. Beside, some future framework of MFGCIs in DERs and MGs are presented. Furthermore, various single-phase and three-phase control strategies are extensively reviewed and categorized into four major categories. Widespread concepts of multifunctional grid interfered SPV systems has been investigated into first category [1-17]. Power quality issues in DERs and MGs along with power line quality conditioners are discussed in the second category [18-34]. The third category presents various configurations used with MFGCI's, which is further classified as a single-stage and two-stage [28, 35-37]. The fourth category presents information about various control algorithms [38-54], which are further classified as control algorithms for single-phase grid interfaced SPV systems [55-72] and control algorithms for three-phase grid interfaced SPV systems [73-106].

A comprehensive review of the control algorithms for single-phase and three-phase MFGCI's are carried out in this paper. This paper is presented in six sections. Issues associated with power quality along with some possible control techniques has been presented in Section 2. Single-stage and double-stage configuration of MFGCI's have been demonstrated in Section 3. Tabular comparison based on available control algorithm for single-phase and three-phase grid interfaced SPV systems are presented in Section 4. Future research scope of SPV in DERs and MGs applications are narrated in Section 5 and finally, some conclusions are drawn in Section 6.

2. Power Quality Issues in DERs and MGs

In a traditional power system network, a number of solid states and non-linear loads have been used to get faster control which further influences the performance of the power system very adversely. These non-linear loads inject harmonics in the power system network and they are also having an adverse influence on the adjacent linear loads. Active power line conditioner such as shunt/or series active power filter (SAPF), passive filter, power factor correction meters (PFC), unified power quality conditioner (UPQC) and static VAR generators are drawing more and more attention because of their efficient performance and simpler control techniques. At the same time, it is worth noted that the use of all these devices to augment the quality of power increases the weight, cost and size of overall power system network, which is not imperative from the perspective of the efficient and congestion free power system [18-21]. In addition, the charges of electricity sold to the utility grid in the competitive electricity market are completely negotiated by its quality. Therefore, it is recommended to supply the quality of power order to increase the economic benefit [22-24].

It has been observed from the past studies that, if the quality of power is not injected at the Point of Common Coupling (PCC) then it will influence the stability of GCI's adversely [25, 26]. The nonlinear loads which are connected on the secondary side of the transformer will create the voltage distortion at the PCC voltage. This distorted voltage severely affects the current and voltage control feedback loops of GCI's and further increases the distortion in the injected current at the PCC. Even in some critical cases, it results in the malfunction of the GCI's. On the other hand, if the quality of power injected at the PCC is poor then some extra losses will be incurred due to overheating of power components, torque oscillations in electric machines, interference with the communication lines and creation of humming noises [27, 28].

Research is going on the enhancement of PQ in DERs and MGs mainly emphasizes on the complete solution of power quality, reliability, novel control algorithms of MFGCIs in distorted voltage and current conditions due to the presence of harmonics. Literature [29] proposes a novel control algorithm to address the technical issues associated with MGs and reliability by adopting clustering thinking based on droop controller. GPSO-GM based novel control strategies for the problems of power flow analysis in an islanded microgrid have been proposed in the literature [30]. Literature [31] proposes a repetitive learning based phase lock loop (PLL) to lessen the poor PQ issues of the grid interfaced DC microgrid under non-ideal grid voltage. In a grid-connected SPV system, a new current suppression technique based on a hierarchical theory has been presented in [32] to deal with the issues such as unbalanced and harmonic subjected active current.

Various aspects associated with PQ of a future MGs are analyzed in a testing laboratory and is presented in [33]. Literature [34] has investigated and studied the current control technique for a GCI under unbalanced and non-ideals mains condition. Spontaneously, this is a passive control technique which cannot enhance the quality of power in DERs and MGs. Various compensation techniques such as active and passive power line conditioners are being employed in DERs and MGs to tackle with the poor power quality problem. Capacitors and selected harmonic filter are an example of the passive filter and these filters are considered as a promising and easier choice due to cheaper cost and simple design.

Active power quality conditioner contains same DC to AC conversion stage like GCIs, as depicted in Fig. 1 and thus usually this DC to AC stage is multiplexed while counting a total number of stages considered in MFGCIs. Here, DC to AC stage will remain common for realizing the functionalities of APLC and GCI.

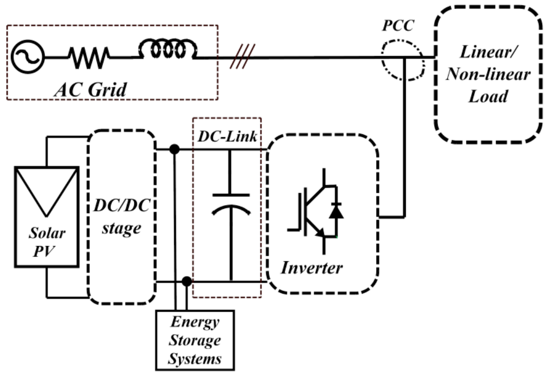

Fig. 1. Active power line conditioner equipment is compared with a grid-connected inverter

3. MFGCI's Configuration

In real practice, grid-interfaced solar power generating systems can be classified on a ground of the number of stages used in it. Generally, there are two types of GCIs are used in SPV application namely single-stage and two-stage. Single-stage and two-stage structures of GCIs are having their own advantages and disadvantages. It is to be noted that, more stages will reduce the efficiency of the overall inverter system and hence the efficiency of two-stage GCI is less, when compared to a single-stage structure of GCI [28].

3.1. Single-stage Configuration

Single-stage GCI has an only DC to AC stage, where the power generated by the solar array is directly transferred from DC to AC through an inverter as shown in Fig. 2.

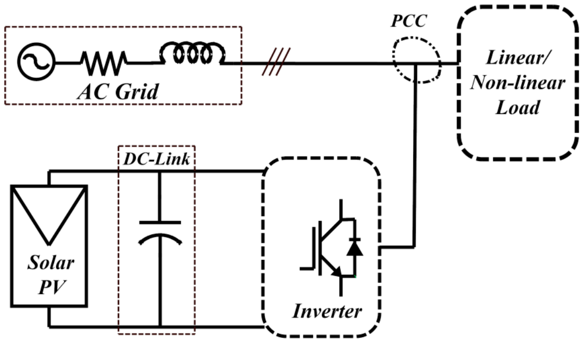

Fig. 2. Single-stage structure of grid interfaced inverter for PV integration

3.2. Double-Stage/Two-Stage Configuration

The two-stage structure of GCI is depicted in Fig. 3. This kind of configuration contains two stages namely DC to DC and DC to AC. The main purpose of adopting DC to DC stage is to extract the maximum power from the solar array and to control the bidirectional power between the energy storage device i.e. battery and SPV [35-37].

The DC to AC stage is nothing but the inverter which controls the power and current injected at the PCC. The two-stage or double stage structure of grid interfaced inverter used for PV application has been depicted in Fig. 3.

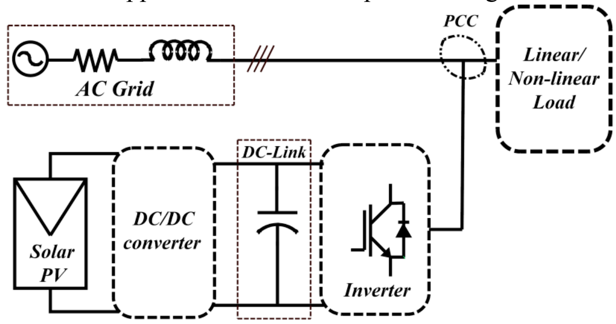

Fig. 3. Two-stage structure of grid interfaced inverter for PV integration

The number of electronics components used in this kind of structure is relatively higher and due to this, it has a bigger size, lower efficiency, higher cost and lower reliability when compared to single-stage structure. The control algorithm used in the two-stage structure is quite simpler when compared to single-stage structure because various functionalities are separated from each other by two stages.

In practice, the DC to DC stage is termed as voltage boost stage because the voltage coming out from the solar array is boosted in order to meet the requirement of the DC-AC stage or DC link. Nowadays, the two-stage structure of GCI is used in three-phase application; however, this two-stage structure suffers from lower efficiency issues. Various parameters of single-stage and double-stage configuration of MFGCIs are compared and further tabulated in Table 1. The comparison indices include a number of stages, efficiency, control algorithm, size, cost, reliability and application. This comparison will help the researchers in selecting suitable configuration based on their application.

Apparently, from Table 1, it can be concluded that single-stage structure is the preferred choice when it comes to efficiency, reliability, size and cost. However, in the single-stage structure, all the parameters are controlled and modulated by inverter only, which makes its control algorithm quite complex. Conversely, in two-stage structure, separate controllers are being used to control the two different quantities and hence the control algorithm is simpler. The single and double-stage configuration of MFGCIs can be selected depending on the application.

Table 1. Comparison of various configurations used in PV application [28]

Configuration	Parameters						
	Number of stages	**Efficiency**	**Control Algorithm**	**Size**	**Cost**	**Reliability**	**Application**
Single-stage	One (Only DC-AC)	Higher	Complex	Compact	Lower	Higher	Preferred in single phase application
Two-stage	Two (DC-DC & DC-AC)	Lower	Simpler	Bigger	Higher	Lower	Preferred in a three-phase application

4. Control Algorithm for MFGCIs

Control algorithm plays a very crucial role in maintaining the efficient operation of MFGCIs. The control algorithms of overall systems can be sub-classified into three major parts namely (a) MPPT controller to extract the maximum power from solar arrays (b) Inverter control comprises the two major controls namely control of real and reactive power injected into the electric grid, and control of DC link voltage (c) Pulse generation techniques.

The operation of MPPT is separately taken care by DC to DC converter. Now a day's use of DC to DC isolated boost converter is increased to reduce the voltage stress on power switches and also to acquire high voltage gain [38, 39]. A number of MPPT algorithms have been quoted in the publications [40-42] and their comparative analysis is presented in [43-45, 116]. However, extraction of maximum power through perturbs and observes (P & O), incremental conductance (INC) control strategy is easy and efficient among all the available techniques of MPPTs and thus these two techniques are used very frequently [46, 47].

The control of active power injection and reactive power compensation into the utility grid is mainly ensured by the inverter controller. The *abc*-control, *αβ*-control, and *dq*-control are the commonly used control strategies for MFGCIs successful operation [48]. The DC-link voltage is generally controlled by using proportional integral (PI), proportional integral derivative (PID) and proportional resonant (PR) based controllers. It is worth noting that the use of PI to regulate the DC-link voltage will decrease the rise time and steady-state error but increases overshoot and settling time [49]. However, it is not possible to eliminate steady-state error completely with PI controller. Contrastly, the use of PID controller for regulating DC-link voltage will make a minor change in rising time, decreases overshoot and settling time [49]. In PID controller, increasing derivative gain will lead to improved stability. However, practitioners have often found that the derivative term can behave against anticipatory action in case of transport delay. It is to be noted that, the steady-state error can be eliminated completely by tuning the PR controller at pertucular frequency [50]. The use of artificial intelligence based techniques such as PSO (particle swarm optimization) and fuzzy have been increased to accomplish the same objective [51].

Based on the application, suitable pulse generation techniques such as hysteresis current control, sinusoidal pulse width modulation control (SPWM) and space vector pulse width modulation (SVPWM) are adopted [52-54]. Still, research is progressively growing for finding new/modified control strategy in order to enhance the operational performance and overall reliability of the grid interfaced SPV systems. A comparative analysis of control algorithms for single-phase MFGCIs has been accomplished based on critical reviews of publication reported in [55-72].

4.1. Control Algorithm Implemented in Single-phase Utility-Based MFGCI's

Control algorithm used for extracting maximum power and also to generate the reference current signal should be easy to implement. In addition, the control algorithm must offer fast and dynamic response during a steady-state and transient condition of the sudden change in load and even during non-ideal supply voltage. All these functionalities can be fulfilled by using MFGCIs.

DC-link voltage control and extraction of maximum power in different weather conditions are two main encountered problems while interfacing single-phase or three-phase inverter system with the utility grid. These challenges associated with single-phase MFGCIs can be tackled by applying different control algorithms as discussed in the following part of this paper.

The single-stage MPPT control scheme is presented in [55]. The control algorithm depicted in Fig. 4(a) diminishes oscillation and also enhances the tracking of maximum power. However, this control algorithm cannot simultaneously cater the two purposes at a time namely active power injection or else active power line conditioning. Error in DC bus voltage is minimized by a proportional-integral (PI) and phase lock loop (PLL) is used for synchronization purpose. The control algorithm presented in [56, 57] deals with harmonic elimination, SPV power injection into the utility grid and enhancement of power factor simultaneously. The nonlinear effect of filter inductor is taken into consideration and also identified by applying a self-learning algorithm and gaussian distribution as shown in Fig. 4(b).

Artificial neural network (ANN) with notch and band filter based approach has been used in [58] to extract the harmonic contents presents in load current and fundamental component of grid voltage at the PCC respectively. Here, the closed loop controller based repetitive controller has been investigated and modified using a zero crossing detector (ZCD) to enhance the tracking accuracy and stability of the overall inverter system. A multi-resonant based current controller approach has been adopted to determine components of current at different frequencies as shown in Fig. 4(c). In this control scheme, proportional-resonant (PR) based controller is used whose transfer function is easy to determine and it also helps in eliminating steady-state error. ANN can also help in minimizing the switching losses up to a possible extent. Battery energy storage based residential PV energy system is implemented in [59] with the help of novel MPPT technique and a DC to DC boost converter. The control scheme is depicted in Fig. 4(d). In this control strategy, two different PIs are being used to control the voltage and power which makes the control algorithm more complex.

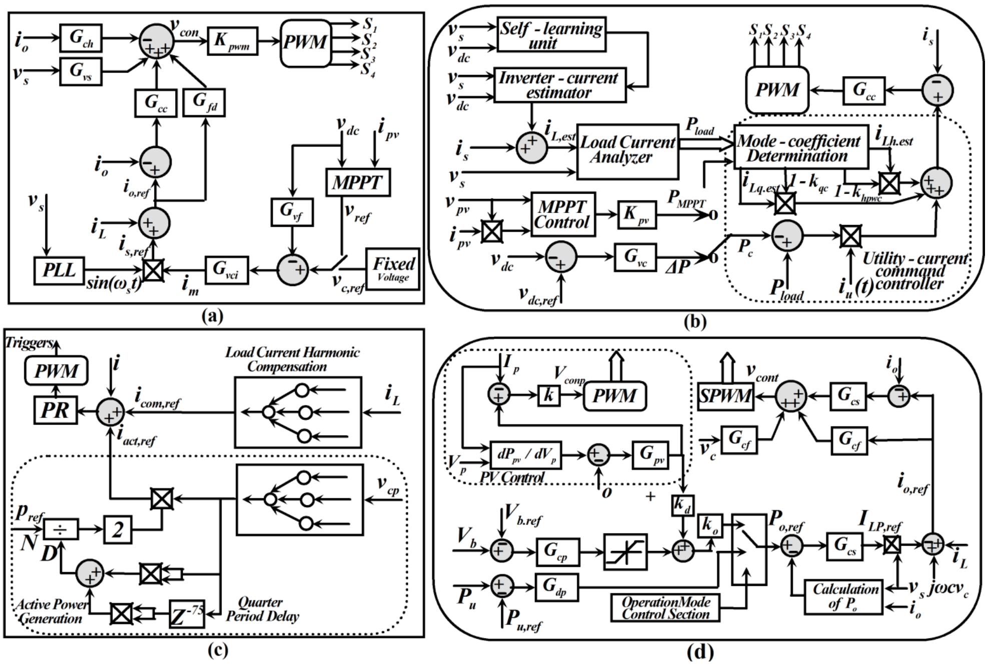

Fig. 4. Different control algorithm used for single phase MFGCIs: (a) single stage MPPT control (b) self-learning based control algorithm (c) multi-resonant based current controller and (d) a novel MPPT control for battery energy storage application

The active power filter functionality in single-phase PV-AF system is realized by using a rotating reference frame based virtual three-phase algorithm as depicted in Fig. 5(a) [60]. The effectiveness of bi-directional power conditioner and SPV system with battery bank storage is evaluated in [61] for switching mode in between utility interactive mode and stand-alone mode as shown in Fig. 5(b). This control scheme can be modified for the standalone mode to cater the local DC load requirement through battery energy storage.

Instantaneous reactive power (IRP) and sinusoidal signal integrator (SSI) based reference current generation control technique as shown in Fig. 5(c) is presented in [62] for real power injection into the electric grid, reactive power control and harmonic mitigation of source. However, the IRP based control strategy doesn't have full control over the power factor. The control strategy proposed in [63] tackles with grid integration of SPV system, power factor improvement and electronic ballast feature.

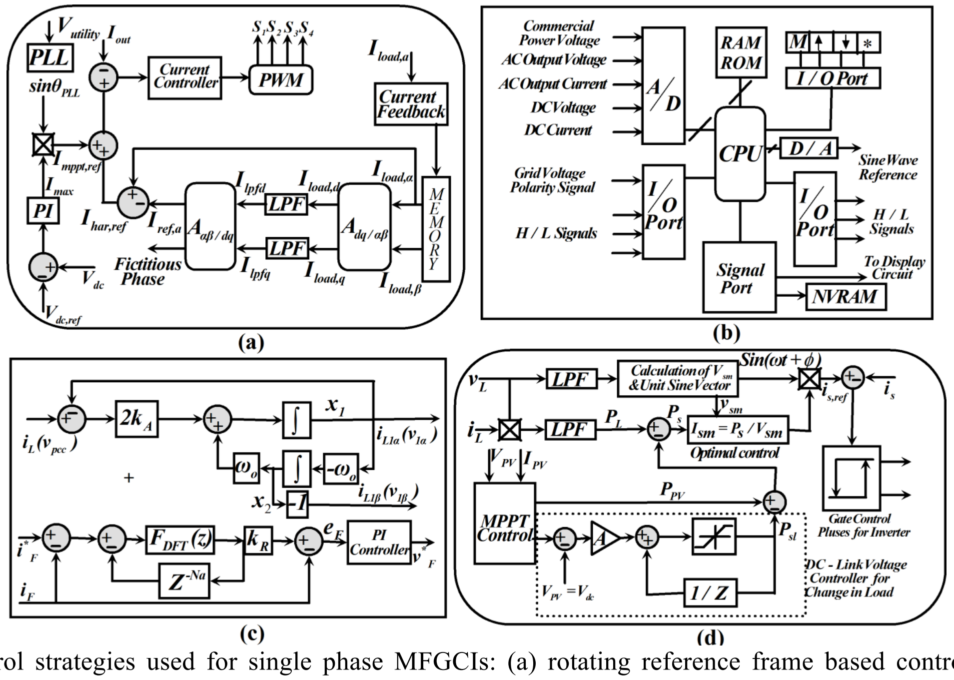

Fig. 5. Various control strategies used for single phase MFGCIs: (a) rotating reference frame based control technique (b) battery bank energy storage control (c) IRP and SSI based control and (d) unit sine vector (UVT) based control

Controller proposed in [64] deals with an injection of active power to the electric grid and also caters the requirement of reactive power by load under non-ideal grid voltage situation. Unit sine vector (UVT) based approach has been adopted to get the voltage (V_{sm}). The control scheme is depicted in Fig. 5(d). The main purpose of adopting UVT based approach is to have unity power factor because in such kind of control the voltage firstly converted into it's per unit value and then it is multiplied with the output of PI controller, which gives the magnitude of current. This voltage and current both are in phase which results in a unity power factor. Further, in this control technique, the hysteresis-based current controlled scheme is implemented to generate the firing pulses. The advantages of hysteresis control are rapid development and higher dynamics.

Amplitude scaling algorithm (ASA) and amplitude clamping algorithm (ACA) based control technique are proposed in [65] for real power injection at PCC and harmonic compensation through a half-bridge inverter system. Another purpose of adopting ACA and ASA based approach is to eliminate even order harmonics generated by the half-bridge inverter. Single-phase three-wire control scheme is proposed in [66, 67], which offers several features such as real power injection, suppression of current harmonics and power factor correction. The control strategy proposed in the literature [68] enhances the voltage support capability and injects reactive power into the utility grid by using droop controller. This control technique does not feed the active power back to the electric grid, however; it does serve the load requirement of local loads. Single-phase two-stage grid interfaced SPV system is proposed in [69] for real power feeding into utility grid and also to acquire the functionalities of APLC and voltage and current control loop for DC to DC boost converter are explained in [70].

Control of parallel and series connected inverter is presented in [71] and [72], respectively. The author has replaced the traditional PI controller with a Lyapunov function to attain simple nonlinear control. Finally, the various parameters of each of the investigated control strategy are tabulated in Table 2 and the comparison indices include control theory, pulse generation technique, DC-link controller, sensors requirement and synchronization technique, number of stages, efficiency, complexity and reference used to fetch the necessary information.

4.2. Control Algorithms Implemented in Three-phase Utility-Based MFGCIs

Harmonic detection and reactive current compensation based approach are presented in [73, 74] and depicted in Fig. 6(a). Sinewave table has been used to get the compensating current. The commonly used control algorithms for three-phase grid interfaced inverter are abc-control, *αβ*-control, and *dq*-control. In *a-b-c* control of three-phase GCIs, a separate current controller has been used for determining each phase grid current as depicted in Fig. 6(b). In addition to *a-b-c* structure, a non-linear controller such as PI, PR, deadbeat and hysteresis current controllers are preferred because of their higher dynamics [75]. In the *αβ*-control algorithm, the grid currents are converted into a stationary reference frame using clerk transformation as depicted in Fig. 6(c). This controller offers higher dynamic characteristic of PI or PR, very high-level current gain around the resonant frequency and very small steady-state error between the reference value and measured signal [76, 77].

The grid current and voltages are converted into a rotating reference frame with the help of parks transformation as shown in Fig. 6(d). It is also known as *a-b-c* to *dq* transformation. The purpose of transformation is to decouple the real and reactive components of currents I_d and I_q, respectively, where I_d controls the active power and I_q control the reactive power.

Table 2. Comparison of a control algorithm used for single-phase utility based multifunctional inverter

Control Theory	Pulse Generation Technique	DC-Link Controller	Sensors Required		Synchronization Technique	Number of Stages	Efficiency	Complexity	Reference
			MPPT	Inverter control					
-	SPWM	PI	2	3	PLL employed	Single	High	**	[55]
IRP	SPWM	PI	2	3	PLL less	Single	High	***	[56, 57]
-	SPWM	PR	-	3	PLL/ZCD employed	Single	Moderate	**	[58]
-	SPWM	PI	2	3	PLL less	Two	Low	**	[59, 66]
IRP +SRF	SPWM	PI	2	3	PLL employed	Single	High	*	[60]
-	SPWM	-	2	3	PLL less	Single	Moderate	**	[61]
IRP	SPWM	Repetitive	-	3	PLL less	Single	High	**	[62]
-	SPWM	-	2	3	PLL less	Single	Moderate	*	[63]
UVT	Hysteresis	PI	2	2	PLL less	Single	High	*	[64]
ACA+ASA	SPWM	PI	2	3	PLL less	Single	High	*	[65]
Droop Control	SPWM	PI	-	3	PLL less	Single	Moderate	**	[68]
-	SPWM	PI	2	3	PLL employed	Two	Low	*	[69]
IRP	SPWM	Lyapunov	-	3	PLL less	Single	Moderate	**	[71, 72]
IRP+SSI	SPWM	PI	2	3	PLL less	Single	High	***	[74]

Note: More * represents more complex system

These components are further regulated to limit the steady-state error between the reference value and the controlled signal. This d-q control can be realized by employing PI, PR and PID along with fuzzy logic [78-80]. A comparative analysis of control algorithms for three-phase MFGCIs has been accomplished based on critical reviews of publication reported in [68, 75-106].

Based on the Widrow-Hoff delta rule, the MO-ADALINE structure is proposed in [81] to estimate symmetrical components and harmonic components. The proposed control strategy as shown in Fig. 7(a) has low computational complexity and it is insensitive to the parameter variation of the DER system because it is adaptive in nature. A control strategy proposed in [82, 83] can be used for three-leg, split capacitor topology, and four-leg converter topology. The proposed technique is shown in Fig. 7(b). Beside this, a *p-q-r* based reference current generating control technique has been used. Mitigation of voltage flicker problem in DERs is realized by using Hilbert transform based control strategy in [84]. The purpose of employing Hilbert transform is to track the voltage envelope as shown in Fig. 7(c). The droop control based control scheme is presented in [85] to mitigate imbalanced compensation issues within three-phase DERs as shown in Fig. 7(d). The proposed control technique can be used for both grids connected as well as islanded operating mode.

A novel control algorithm is presented in [86] for power production through SPV at UPF and with uninterruptible power supply facility. The power switches are controlled by an appropriate current and voltage control technique to extract the maximum power from the solar array and reactive power compensation. Two deadbeat control laws with Leuenberger observer is used to determine and predict the value of the utility grid current in [87]. The deadbeat control is typically employed for getting simpler current regulation control. The proposed controller offers ruggedness against the computational delay which is intrinsic property in digital implementation. This robustness offered by controller results in improved stability margin of the conventional predictive controller.

H^{∞} repetitive control strategy for enhancing voltage track is presented in [88]. The proposed control scheme is tested and also validated under different modes such as grid-connected mode and standalone mode. In addition to this, fluctuation in grid frequency can be cop up by adopting frequency adaptive mechanism. Calculation of reference grid current and voltage is proposed in [89, 90]. Beside this, the absence of PLL and Park's transformation blocks in control loop will substantially improve the control of real and reactive power. Feedforward decoupling based control technique for three-phase GCIs is proposed in [91]. Active and reactive power decoupling has been realized through control strategy. A novel transformerless hybrid SAPF is proposed in [92] to mitigate power quality issues in weak DERs. It is to be noted that the proliferation of more DERs in weak grid increases power quality issues and resonance phenomena.

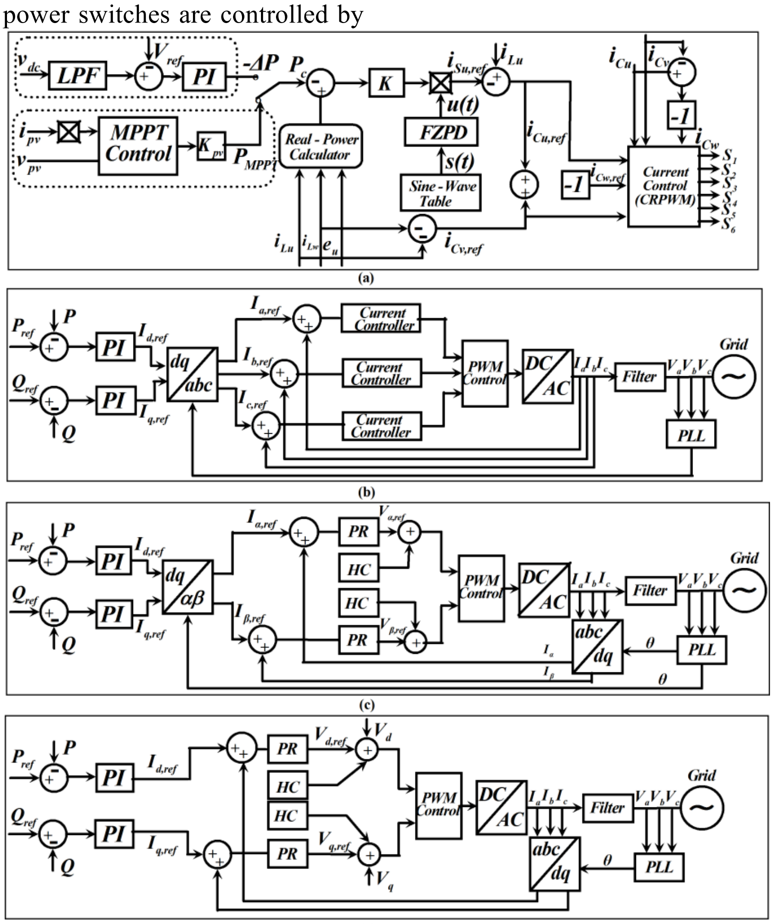

Fig. 6. Various control algorithms used for three-phase MFGCIs: (a) harmonic detection and reactive current compensation based approach, (b) *a-b-c* based control, (c) *αβ*-control algorithm and (d) *abc-dq* based control approach

Both the real power injection and reactive power compensation purposes are simultaneously realized through the control technique presented in [93]. A reactive power controlled can be achieved by monitoring bus voltage. A novel frequency-independent control scheme is proposed in [94] to control both real and reactive power injected by DERs at PCC.

A three-phase three-level neutral point clamped (NPC) inverter based control algorithm is presented in [95-99] for active power injection, reactive power control and load current balancing simultaneously. However, NPC has inherent voltage deviation problems and hence balancing of DC-link capacitors is highly essential. This balancing of the DC-link capacitor in NPC can be accomplished through proper switching control and thus the author has used the SVPWM technique instead of using conventional PWM or hysteresis. Another three-level neutral point clamped inverter based control strategy with LCL filter output is presented in [100]. Here, the main objective of employing an LCL filter is to attenuate the switching frequency of harmonics generated by the grid-integrated inverter systems.

The performance of resistive APF (R-APF) and shunt APF are investigated in [101]. It is found that shunt APF offers better control in DERs over R-APF as it suffers from the poor compensation and also tuning of parameters. An advanced space vector pulse width modulation (SVPWM) based predictive current controller is proposed in [102] to provide protection in DGs and mitigate the harmonic disturbances. A wide range of voltage perturbation and capacitor switching disturbances mitigation is possible by control scheme proposed in [103]. In addition, deadbeat current control strategy has also been implemented for accurate monitoring of active and reactive current trajectories. The control strategy proposed in [104] is used to realize the various functions such as energy supply and harmonic elimination simultaneously.

Various control algorithms for a unified power quality conditioner (UPQC) is presented in [105, 106]. The flow of large current between DERs and electric grid during voltage sags can be limited by using a proposed flux charge current limiting control technique. The control algorithm for three-phase four wire systems under both ideal and non-ideal grid voltage situation is presented in [107]. Both real and reactive power flow in the utility grid is investigated through this multifunctional control strategy. Another three-phase four-wire based UPQC is proposed in [108] for mitigating voltage quality problems in microgrid application. The IPT based control theory is presented in [109] for three-phase four-wires APLC integrated with renewable sources.

Furthermore, a control scheme based on instantaneous symmetrical component theory (ISCT) has been proposed in [110] to feed the generated active power as well as to supply the oscillatory component of power demanded by the unbalanced and nonlinear load at PCC. An ISCT based control strategy has been utilized in [111] to generate the instantaneous reference current waveforms to balance the load.

On the other hand, a novel smart inverter based PV-STATCOM has been presented in [112] to provide voltage control during critical system needs. The proposed inverters discontinue the real power generation function temporarily and provide its full inverter capacity for STATCOM operation in order to control grid voltage. Another optimal reactive power based control is proposed in [113] by curtailing real power. Beside this, the ongoing IEEE Standard P1547 Full Revision is contemplating that DERs shall be capable of injecting a finite amount of reactive power (usually 44%) even at 100% of nameplate real power rating (kW) [112, 114]. However, it is worth noted that, according to present revision of draft IEEE standard P1547 real power curtailment is forbidden.

At last, the various parameters of each of the investigated control strategy is tabulated in Table 3 and the comparison indices include control theory, pulse generation technique, DC-link controller, sensors requirement, synchronization technique (PLL employed or without using PLL), number of stages, efficiency, complexity and reference used to fetch the required information.

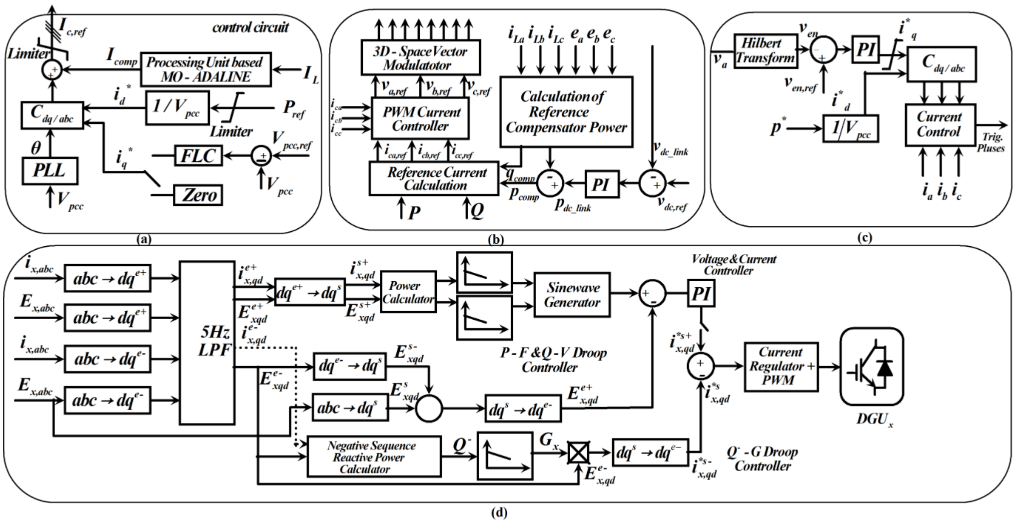

Fig. 7. Different control strategies used for three-phase MFGCIs: (a) widrow-Hoff delta rule-based MO-ADALINE control (b) control strategy for three-leg, split capacitor topology (c) hilbert transform based control strategy and (d) droop control.

Table 3. Comparison of control strategies used for a three-phase utility based multifunctional inverter

Control Theory	Pulse Generation Technique	DC-Link Controller	Sensors Required		Synchronization Technique	Number of stages	Efficiency	Complexity	Reference
			MPPT	Inverter control					
SRF+Widrow hoff delta rule	SPWM	PI	-	7	PLL employed	Single	High	**	[81]
IPT+ deadbeat controller	SVPWM	PI	-	8	PLL less	Single	High	*	[82, 83]
SRF+Hilbert transform	SPWM	PI	-	7	PLL less	Single	High	**	[84]
P-F + Q-V droop controller	SPWM	PI	-	7	PLL less	Single	Moderate	***	[85]
-	SPWM	PI	2	7	PLL employed	Two	Moderate	***	[86]
SRF+deadbeat controller + Leuenberger observer	SPWM	PI	-	7	PLL employed	Single	Moderate	**	[87]
SRF	SPWM	H^{∞} Repetitive	-	7	PLL employed	Single	High	*	[88]
IPT	SPWM	PI	2	7	PLL less	Two	Moderate	**	[89, 90]
SRF + Feedforward decoupling	SPWM	PI	2	7	PLL employed	Two	Moderate	*	[91]
SRF + IPT	SPWM	PR+PI	-	7	PLL employed	Single	High	**	[92]
SRF	SPWM	PI	2	7	PLL employed	Two	Moderate	*	[93]
IPT + SRF	Hysteresis	PI	-	7	PLL employed	Single	High	*	[94]
SRF	SVPWM	PI	2	10	PLL employed	Two	Moderate	***	[95]
-	SPWM	PI	-	7	PLL less	Single	Moderate	**	[97]
SRF	SVPWM	PI	-	7	PLL employed	Single	High	**	[98]
IPT + SRF+ deadbeat controller	SPWM	PI	-	4	PLL less	Single	Moderate	**	[99]
SRF	SPWM	PI	-	7	PLL employed	Single	High	**	[100]
IPT + SRF	SPWM	PI	-	8	PLL less	Single	Low	***	[101]
IPT	SPWM	PI	-	7	PLL employed	Single	Low	***	[102]
IPT + CPT	SPWM	PI	-	8	PLL less	Single	High	**	[103]
-	SPWM	PI	-	-	PLL less	Single	Low	***	[115]

Note: More * represents more complex system

5. Future Scopes of Solar PV in DERs and MGs

The demand for energy is increasing at an alarming rate. This thrust for energy can be catered by enhancing proliferation of RE sources into the electric grid through DERs and MGs. However, indecisive nature problem associated with these RE sources are required to be solved to acquire better security, stability and reliability of the power system network. Investigation of power electronics based converter to integrate RE sources with the electric grid is required to be emphasized so that quality power can be fed back into the utility grid. Further, the efficiency of SPV array can be increased from 20% to 30% by using third generation solar cell made up of organic materials. However, these solar cells will add more cost to the capital investment. Few other aspects are associated with the traditional inverter system which plays a vital role in controlling system parameters such as real power, reactive power, frequency and power factor.

The control algorithm implemented in the traditional grid interfaced inverter system generates active power typically at unity power factor. Thus, the real-time reactive power control, as well as power factor control, is not possible through this implemented control algorithm. Even the response of these inverters is not adequate according to system condition and in the event of a fault. All these problems associated with a traditional inverter as well as the implemented control algorithm can be solved using the equipment called ‘smart inverter’. This smart inverter generates and modulates active power; exchanges (inject/absorb) reactive power with the electric grid. There are utilities which have started using smart inverter instead of using conventional inverter system to interface the SPV with the utility grid.

This smart inverter offers several features such as non-unity power factor, volt/var function, volt/watt function, low/high voltage and frequency ride through, ramp rate, peak power limiting, and dynamic reactive current support. Having considering all the above functions of using a smart inverter, it can be said that the smart inverter performs in response to system conditions. There are utilities like Germany, California which have changes their grid codes to replace all the traditional inverter with the smart inverter to get benefited from the smart inverter functionalities. On a contrary, there are utilities like India which has not yet changed their grid codes which will create more issues in near future. It is worth noted that, the smart inverter is highly capable and beneficial device, but associated challenges with it must be understood very clearly to get full benefits from them.

6. Conclusion

This review provides a broad perspective to researchers and engineers who deal with PV penetration and power quality issues in DERs and MGs. Additionally, the present control strategies used in MFGCIs for PV integration and power quality solutions are investigated, analysed in detail and compared on a ground of control theory, pulse generation technique, DC-link controller, number of sensor requirement, synchronization technique, number of stages, efficiency and complexity. It is also demonstrated that problems associated with a traditional grid-connected inverter can be effectively alleviated by means of smart inverter control. However, the associated challenges with it need to be addressed to get full benefits from them. Finally, a brief description of the future scope of SPV in DERs and MGs are presented. The author hoped that this critical comparison of control algorithm will help the researcher to select the particular control technique of the constituent elements of GCI based on the application.

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