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Harmonic Control Strategies of Utility-Scale Photovoltaic Inverters

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Abstract- Installation of utility-scale photovoltaic power systems (UPVPSs) is continually increasing throughout the world. This leads to increasing number of utility-scale PV inverters (UPVIs) being connected to the grid both at transmission and distribution networks. The amplitudes of harmonics generated by these inverters are becoming important issues of concerns. Manufacturers of these inverters specified 3% current THD. Also, most researches on performance analysis of the current control strategies of these inverters put their current THD at 3%. At utility-scale level, the 3% current THD has large amplitude values which can have significant consequences especially on the distribution networks. This paper statistically relates the percentage current THD of some common industrial UPVIs to their equivalent amplitude current THD. The paper also reviews the existing current control strategies of UPVIs in terms of their performances in optimizing the control of harmonics generated by the UPVIs. Various current control strategies, their mode of operation, advantages, disadvantages and limitations to harmonic reduction are discussed. Several current controllers are compared and evaluated for harmonic emission and control. The current control strategies of the existing inverters are not effective enough to optimize the control of harmonics generated by UPVIs as the amperage magnitude of current THD is high. Further study is necessary to improve on the existing current control strategies or incorporate new ones to optimally control THD of the UPVIs and make them more effective in controlling harmonics at utility-scale level.

Keywords-Utility-scale; photovoltaic; inverters; total harmonic distortion (THD); current control strategies.

1. Introduction

Energy is the force that drives sustainable development, socio-economic growth, ecological restoration and modernization. However, energy usage and demand are increasing globally and energy demand projections indicate that current and expected energy resources cannot meet up [1-3]. Exploiting renewable energy resource is, therefore, an effective approach to cope with the ecological environment and satisfy increasing energy demand. Photovoltaic (PV) power generation provides an acceptable option due to its inexhaustible nature, environmental friendliness, technological maturity and economic profitability [4-6]. The PV systems connected to the grid are of various sizes and capacities for various applications and needs. They range from a PV module of 200W to millions of PV modules for plants of 100MW and above. Based on their power rating, grid-connected PV system can be categorized into small scale (10kW to 100kW), medium scale (10kW to 1MW) and large-scale or utility-scale (>20MW) [7-9]. The installation and integration of several utility-scale PV (UPV) plants into the grid in some parts of the world is aimed at replacing the fossil fuels kinds of energy generation with renewable energy sources like PV systems [10, 11]. Thus, the future of commercial utilities generation depends on the implementation of UPV plants. Figure 1 shows the capacities of utility-scale PV plants installed worldwide by the ten leading countries up to 2017 to attest to this fact [12]. A total of at least 303GW have been installed globally in 2016 at an annual growth of 48% over 2015 amounting to at least 75GW additions in 2016. China leads in this development at total installed capacity of 77.4GW and 2016 annual addition of 34.5GW which up 2015 additions by 126% [12].

The UPVPSs are interfaced with the grid through high power DC/AC inverters (UPVIs) that transform DC power into AC and integrate into the grid. There are four configurations of PV inverters of which Central inverters are mainly used for utility-scale generation due to their high power ratings. Multistring types are at their developmental stage to be introduced to utility-scale generations. Some of the common commercially available UPVIs being used in the practical activities of UPVPSs are reported to have higher current THD values [13, 14]. However, the UPVIs generate harmonics that negatively affect the power quality and the power system stability. Harmonics arise due to conversion operation of grid-connected inverters. The current harmonics generated by the PV inverters depend on the effectiveness of the current control techniques being used. The magnitudes of current harmonics depend on the active power output of the PV inverters. This means that at utility-scale PV inverters, the magnitudes of current harmonics are high.

Various researchers have proposed a large number of strategies for controlling harmonics of PV grid-connected inverters. This paper seeks to statistically relate the percentage (%) current THD of some common industrial UPVIs to their equivalent magnitude current THD. The relation is to know the amperage magnitude of harmonics that is being generated by these inverters vis-à-vis the effectiveness of their current control strategies on harmonic generation and control. This paper, therefore, aims to review the performance of current control strategies of PV inverters in terms of their applicability in the UPVIs bearing harmonic reduction and control in mind. The paper is arranged as follows: Section 2 discusses the types of inverters used in the UPVPSs (Plants) and analyses harmonic injection of some common industrial UPVIs.

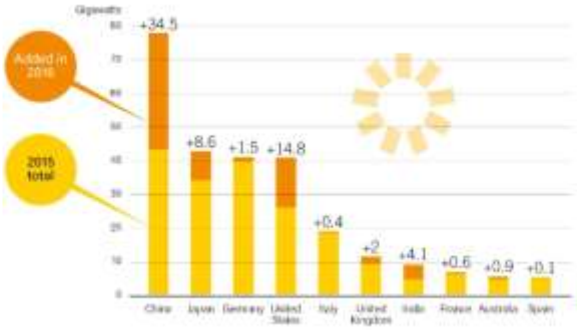


Fig. 1. Solar PV capacity and additions, top 10 countries, 2017 [12]

The sources of harmonic generations in the UPVIs are discussed in section 3. Section 4 lists and explains the groups of current control strategies used in UPVIs stressing their capability to reduce and control harmonics generated by these inverters. Performances of these inverters at reducing and controlling harmonics are expatiated in section 5. Section 6 concludes the paper and recommends the future actions in controlling the harmonics generated by the utility-scale PV inverters.

2. Utility-Scale PV Inverters

The inverter configurations are named as ac module inverters, string inverters, multistring inverters and central inverters based on the PV module arrangement as shown in Fig. 2 [13, 15]. The AC-module configurations employ the use of one inverter to connect each of the PV modules of the system to the grid [13, 16]. These AC-module inverters are used in small-scale PV systems. The string inverters configurations use one inverter to connect a PV string to the grid. String inverters are either single or double-stage conversion arrangement based on whether a DC-DC boost stage is used to increase the output DC-link voltage to grid-connected inverter. String inverters are used in small and medium-scale PV systems. The typical utility-scale PV inverters are central inverters but multistring UPVIs are in their developmental stage.

2.1. Multistring Inverters

The multistring inverter shown in Fig. 2 is developed from string inverters to improve the MPPT performance of the PV systems and make the inverter more flexible. This inverter type interface several strings with its DC-DC converters to a common DC/AC inverter. This makes individual control of every string possible [15, 17-19]. It is cost effective option than using many string inverters. Multistring inverter can be found with or without transformer. It is used in small-scale PV systems and medium-scale PV plants. One of the early multistring inverters for industrial use is the half-bridge inverters with DC booster converters from SMA. Other industrial multistring inverters are the H5, H-bridge, 2L-VSI and 3L-T type [13].

2.2 Central Inverters

The central inverter (Fig 2) uses one inverter to connect a whole PV array to the grid [13, 20]. The MPPT efficiencies of central inverters are the lowest of all the configurations of PV inverters. Due to the fact that a single inverter connects the whole PV array to the grid and thereby provides only a single MPPT operation [17, 18]. A low-frequency transformer is used to interface the central inverter to the grid to step-up the voltage of the power plant. It is the most used inverter for utility-scale PV plants because of its simple structure, high reliability, power efficiency, high voltage and high power applications. It has low voltage (LV) of about 1000V and capacity of up to 850KW. Two central inverters (dual central inverter) can be commercialized and connected to increase the power rating up to 2.5MW. As a result, a utility-scale PV power generation plant can attain hundreds of MW capacity with several hundreds of central inverters

[13]. The 2L-VSI is the most common practical central inverter topology. The three phase 2L-NPC and 3L-T type inverters have been in use recently for this configuration.

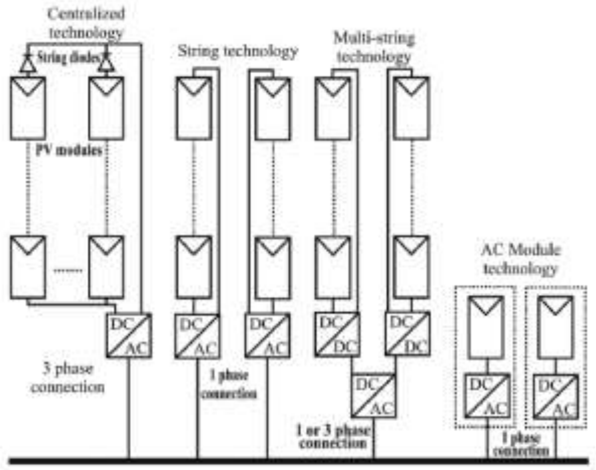


Fig. 2. Types of grid-connected PV inverters, central, string, multistring, and module inverters [15]

2.3 *Harmonic Analysis of UPVIs*

Ref. [14] listed some common industrial utility-scale PV inverters from various manufacturers with different topologies of central inverters [14]. This paper extracts the specification sheets of these central inverters from the manufacturers' sites and based its analysis on the information provided by the manufacturers of those inverters. They have current THD values of about 3% of their ratings as shown in Table 1. These inverters are either connected to transmission or distribution networks. This may implies higher THD values during practical operations and more higher at less than 10% and greater than 95% power output based on the characteristic behaviour of PV inverters [21].

To the best of the authors' knowledge, there exist few literatures on the performance analysis of UPVIs during practical industrial service in terms of harmonics generation. Except few reports that were made by some commissioned committees and the information from the manufacturers' data sheets. From Table 1, it can be seen that the amplitude of one thirty-third (3%) current harmonics on high voltage transmission network is minimal. Though, amplitude and phase angle of harmonics can vary rapidly and their aggregate may have negative effects on the network. The amplitude of one thirty-third current harmonics is very significant in the distribution network which may cause system stability problems. In essence, the current THD value of 3% is rather high considering what its magnitude can be when talking of very high magnitude output current from UPVIs.

Table 1: Magnitude of 3% current THD of some industrial high power UPVIs

Inverters	Network Transmission/ Distribution*	Power Rating (MW)	Output Current (A)	Current Harmonics (%)	Magnitude of Current Harmonics (A)
A. Central					
1. ABB PV800 IS*	400V	2.0	2886	3	86.7
2. DAFOSS CENTRAL PV*	430V	2.4	2014	3	60.0
3. SATCON PRISM PLAYFORM EQUINOX*	320V	1.25	2255	3	67.00
4. SIEMENS SINVERT PVS 600 SERIES TO PVS 400*	370V	2.4	3745	3	112.00
5. ABB PVS 800 MWS	20kV	1.25	36	3	1.08
6. SMA SUNNY CENTRAL	20kV	1.6	46	3	1.39

In addition, Ref. [13] reported some on-service practical industrial inverters listed in Table 1 (2L-VSI topologies of central inverters rated at 1.5MW to 2.5MW). It stated that these inverters produced higher THD than the industry standard limits but the paper was not precise on the actual values of their THDs. They also have poor MPPT during operations [13]. It is a known fact that during practical operations of these inverters, they may generate higher THD than what were written on their data sheets even after some harmonic superimpositions.

The level of harmonics generated potentially leads to the distortions of current and voltage. The addition of different sinusoidal harmonic components at higher frequency from multiple UPVIs can make the network system highly distorted. These harmonics greatly affect the load, protective relay, and operational efficiency, reliability and stability of the power system. The harmonics cause power quality and stability problems that negatively affect proper operation of grid networks, and equipment, devices and loads supplied. Some of the problems associated with harmonics in the power system include reduction of engine life, worsening of the power factor, increase of noise and vibration, unexpected failure of protection devices, premature ageing of insulation and dielectric, and false tripping of circuit breakers [22-25]. Even in some cases, this can also be a threat to people's lives (high harmonics presence causes equipment and devices to overheat and lead to fire hazard) [25, 26].

3. Harmonic Content of UPVIs

Power system harmonics have become a major challenge for power utilities all-over the world. Statistical analysis conducted in recent time reveal that harmonics is one of the most disturbing power quality issues in PV energy generation. They also have reverberating effects in generating most of other power quality issues of UPVPS [21, 27-29]. The sources of harmonics generated by UPVIs can be broadly grouped into (a) DC link voltage harmonics, (b) grid voltage harmonics and (c) switching harmonics [30].

3.1. DC Link Voltage Harmonics

The DC link voltage ripple is one of the sources of harmonics generated by UPVIs. The DC link voltage harmonics are caused from the random and intermittent nature of solar irradiation. They are mostly taken to be constant in the designs and analyses of PV inverters but in practical sense they are not always constant. The DC link voltage ripple is found to be responsible for the odd harmonics that are found in the frequency spectrum of output current of the PV inverter [31]. Also, Ref. [32] investigated harmonic transfer through three-phase inverters and discovered that the third order harmonic present in the AC side was produced by the second order harmonic from the DC link [32]. Various researchers have proposed methods to overcome the current harmonics produced by the DC link voltage ripple [33-37]. Some of the methods proposed degraded the system dynamic performance while others lack qualitative information about the output current harmonics and DC link voltage ripple relationship [30].

3.2. Grid Voltage Harmonics

The output current of PV inverter is generated from the voltage difference between the AC output voltage of the inverter and voltage of the grid. The grid voltage becomes a source of harmonic to the output current when its waveform contains harmonic contents. The research literatures and field measurements showed that grid voltage always contain harmonics but at varying degrees in different location of the system [10]. These harmonics are mostly low orders which are difficult to eliminate by the filters. Different methods of eliminating current harmonics produced by the grid voltage harmonics have been proposed [38-40]. Ref. [10] posited that no relationship exists between the current harmonics caused by the grid background voltage and the level of inverter output power. The grid background voltage only reflect in the amplitude of output current harmonics [10].

3.3. Switching Harmonics

Switching harmonics is another source of inverter output current harmonics. This is as a result of switching pulse generation mismatch. The switching harmonics of the PWM (unipolar) inverters exist at the double of switching frequency [41]. Switching harmonics are more difficult to eliminate and may require a suitable control design else it results in system instabilities and power losses [10, 30, and 42]. Many research works have proposed different methods to eliminate or control the switching harmonics of inverters [41, 43].

Other researchers have mentioned the quantization and resolution effects of measuring instruments of the control systems as causes of harmonics in PV inverters [44, 45]. Equally mentioned are limitations of the current controls of inverters to reduce components of harmonics [46, 47], and the positioning of sensor in the network system. Also, the reference current harmonics can come from the outer voltage control loop of the two cascaded control algorithm and the PLL system. Dead time of the switching pulse is another cause of output current harmonics of the PV inverters [10, 30].

3.4. Current Harmonic Standards for UPVIs

Power quality is a grid requirement common to all standards for the PV systems interconnecting the grid. The IEC 61727 and IEEE1547 standards related to the requirements for current harmonics is tabulated in Table 2 [48, 49]. The total harmonic distortion (THD) of emitted current must be below 5% limit. The various control strategies that are being used to control and mitigate inverters' current harmonics are discussed in the next section.

Table 2: Current harmonic limits by IEC 61727 and IEEE 1547 standards [48]

Order of Harmonics (I_h)	Percentage of Fundamental (%)
A. Odd Harmonics	
3, 5, 7, 9	Less than 4%

11, 13, 15	Less than 2%
17, 19, 21	Less than 1.5%
23, 25, 27, 29, 31, 33	Less than 0.6%
Greater than 33	Less than 0.3%
B. Even Harmonics (All)	Less than 25% of equivalent Odd harmonics
Total Harmonic Distortion (THD)	Less than 5%

Meanwhile, the aggregate harmonics generated by UPVIs during the conversion processes are in high quantity, even when multileveled and parallel-connected [48]. This becomes a significant issue when delivered to the utility grid. The current amplitude from multiple high power inverters with their harmonics can inject high harmonic levels into the grid. Since current harmonic magnitudes depend mainly on the active power output of the inverter [26, 50]. The loss of power in UPVPS is mostly as a result of harmonics generated during the inverter power conversions. Power loss through harmonic generation is recognized as a costly problem worldwide both because of technical damages as well as from an economic point of view. The economic loss, among others, associated with harmonics is increasingly growing at alarming rate in recent years due to large integration of utility-scale PV into the power system. Therefore, reviewing the current control strategies used in PV inverters to ascertain their effectiveness in controlling the harmonics generated by the UPVIs is vital considering the huge amount of economic losses and technical problems caused by these harmonics.

4. Current Control Strategies of UPVIs

Traditional control techniques involve the connection of passive or active or hybrid harmonic filters between the grid-connected inverters (GCI), which serves only synchronization purpose, and the grid. Such a control technique has poor response to harmonic elimination. Consequently, a significant amount of power would have been lost and a large number of equipment and devices damaged due to poor harmonic control. Over the years, different control structures and strategies have been adopted for use in PV inverters for harmonic mitigation and power quality enhancement. The current-controlled grid-connected PV inverter control scheme implements two cascaded control loops. The outer voltage control loop controls the inverter input DC link voltage of the PV system. The inner current control loop regulates the output current of the inverter to the grid and thereby responsible for the output current harmonic control [16, 48, 51-55]. The current control strategies are, therefore, classified based on their technical nature into linear and non-linear control strategies.

4.1 Linear Current Control Strategies

Linear current control strategies use proportional integral (PI), proportional-resonant (PR) or repetitive (RC) controllers in either synchronous reference frame (dq), stationary reference frame (αβ) or natural abc frame to control harmonics generated by the PV inverters.

4.1.1. Proportional Integral (PI) Controller: Current control strategy using proportional integral (PI) controller is normally based on dq control structure as it is superior in DC variable control. Figure 3 shows the current control structure of PI controller in dq frame [16, 48, 51, and 56]. This control transforms the grid voltage and current in abc natural frame into a dq reference frame which rotates synchronously with the grid voltage. As a result, the AC power is decoupled into active (Id) and reactive (Iq) power components. The DC link voltage controller regulates the component of active power by generating the reference current so as to balance the active power that flows in the system. The current controller compares the reference and measured currents to generate the proper switching pulse for the inverter. This will eliminate the current errors and generate the clean AC current waveform. Linear PI controllers associated with the d-q control structure are established for reference tracking due to their good combinational performance [15, 48, and 57].

The matrix transfer function in dq coordinates form defines a PI controller gain as:

$$G_{PI}^{(dq)}(S) = \begin{bmatrix} K_p + \frac{K_i}{s} & 0 \\ 0 & K_p + \frac{K_i}{s} \end{bmatrix} \text{.................................(1)}$$

where K_p and K_i are the proportional and integral gains of the controller

Implementation and portability of PI controller in abc and αβ frames are possible by placing transformation modules between the frames as illustrated in [16, 56]. The matrix transfer function of PI controller in abc frame is derived in [58] as Eq. (2).

However, the compensation capability of PI controller normally used in the control structure of a grid-connected inverter is very poor on low order harmonics and the steady state error elimination. It has complex transfer function when implemented on abc frame due to the complex off-diagonals terms. This is because of the presence of cross coupling terms between the phases.

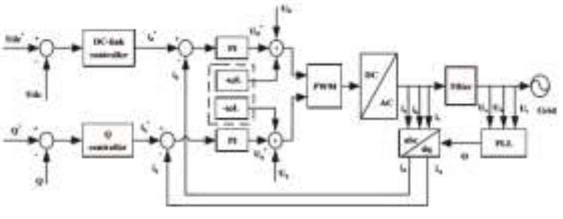


Fig. 3. Typical current control structure of PI controller in dq frame [48]

$$G_{PI}^{(abc)}(S)=\begin{bmatrix} K_p+\frac{K_i s}{s^2+\omega_o^2} & -\frac{K_p}{2}-\frac{K_i s+\sqrt{3}K_i\omega_o}{2(s^2+\omega_o^2)} & -\frac{K_p}{2}-\frac{K_i s-\sqrt{3}K_i\omega_o}{2(s^2+\omega_o^2)} \\ -\frac{K_p}{2}-\frac{K_i s-\sqrt{3}K_i\omega_o}{2(s^2+\omega_o^2)} & K_p+\frac{K_i s}{s^2+\omega_o^2} & -\frac{K_p}{2}-\frac{K_i s+\sqrt{3}K_i\omega_o}{2(s^2+\omega_o^2)} \\ -\frac{K_p}{2}-\frac{K_i s+\sqrt{3}K_i\omega_o}{2(s^2+\omega_o^2)} & -\frac{K_p}{2}-\frac{K_i s-\sqrt{3}K_i\omega_o}{2(s^2+\omega_o^2)} & K_p+\frac{K_i s}{s^2+\omega_o^2} \end{bmatrix} \text{.......}(2)$$

4.1.2. Proportional Resonant (PR) Controller

The proportional-resonant (PR) controller uses an abc-αβ module to transform the grid currents in the natural (abc) frame into a stationary reference (αβ) frame. Figure 4 shows a current control structure of PR controller in αβ frame with harmonic compensator [16, 48, 51, and 56]. PR controller performs better in αβ frame than PI controller due to its ability to track the reference current without considering the phase error and steady state magnitude [59]. PR controller achieves a large gain by introducing an infinite gain on the resonance frequency spectrum which depends on the magnitude of the integral gain Ki [16, 48]. A low value of Ki gives very narrow band, while a high value of Ki gives wider band. The matrix transfer function of PR controller in αβ coordinate is given as;

$$G_{PR}^{(\alpha\beta)}(S)=\begin{bmatrix} K_p+\frac{K_i s}{s^2+\omega^2} & 0 \\ 0 & K_p+\frac{K_i s}{s^2+\omega^2} \end{bmatrix} \text{.......}(3)$$

where ω is the resonance frequency, K_i is the integral gain and K_p is the proportional gain of the controller.

PR controller works on narrow band of its resonant frequency ω. This allows simpler implementation of harmonic compensator on low order harmonics without affecting the controller' behaviour [56, 60].

Implementation and portability of PR controller in abc natural frame is simple since it is already defined in abc frame. The controller matrix transfer function is given in [61] as Eq. (4);

$$G_{PR}^{(abc)}(S)=\begin{bmatrix} K_p+\frac{K_i s}{s^2+\omega^2} & 0 & 0 \\ 0 & K_p+\frac{K_i s}{s^2+\omega^2} & 0 \\ 0 & 0 & K_p+\frac{K_i s}{s^2+\omega^2} \end{bmatrix} \text{.......}(4)$$

There exists no cross coupling terms between the phases in abc platform. So, Eq. (4) is not applicable when the interfacing transformer neutral is isolated. It can also be seen that the complexity of the controller designed from Eq. (4) is reduced compared to the one from equation (3).

This controller has advantage at eliminating the steady state error and has high dynamic response. Several research works have been reported in the literature on good dynamic characteristics of PR controllers [62-66]. The drawbacks are lack of full control on power factor (and indirectly on harmonics) and complex hardware circuitry [15, 16].

4.1.3. Repetitive Current (RC) Controller

This controller uses the internal model principle (IMP) for harmonic elimination. RC controls its parameters periodically to eliminate the steady state error [59]. It achieves high gain at the multiple of fundamental frequency [48]. This controller usually compensates the high order odd harmonics such as 11th and 13th, and tracks the fundamental reference current [67, 68]. However, RC controller is problematic, and exhibits slow dynamic response which has effect on its stability. Figure 5 shows the schematic diagram of RC controller [69]. RC controller transfer function is given as:

$$G_{RC}(S)=\frac{K_{RC}e^{-T_o S}\,Q(S)}{1-e^{-T_o S}\,Q(S)}G_f(S) \text{.......}(5)$$

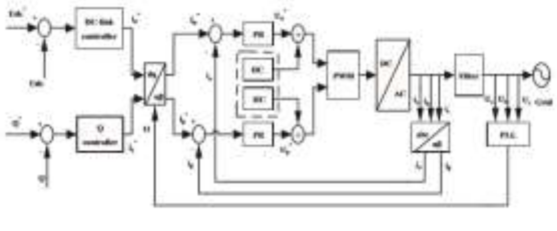


Fig. 4. Typical current control structure of PR controller in αβ frame [48]

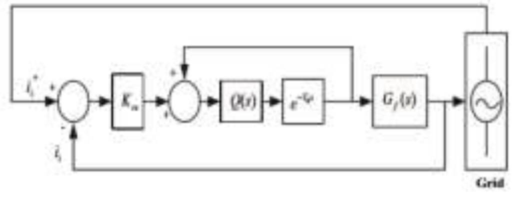


Fig. 5 Schematic diagram of RC controller

4.2 Nonlinear Current Control Strategies

Non-linear control strategies on the other hand, may have independent controllers in the controller design to handle individual control parameters of the system. Natural abc control is preferred in non-linear control strategies because of their needs for high dynamic responses though dq and αβ can also be implemented with them. The rapid advancement in digital signal processors (DSP) and field programmable gate array (FPGA) is a plus for the implementation of nonlinear current controllers since their performance is linked to the sampling frequency. Figure 6 shows a current control structure implemented in abc frame.

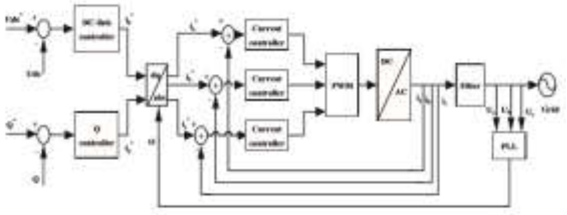


Fig. 6. Typical current control structure of controllers in abc frame [48]

4.2.1. Dead-Beat (DB) Controller

Harmonic control strategy employing dead-beat (DB) controller allows fast transient response when it is tuned [16, 48, and 68]. It is a member of predictive regulators. The dead-beat controller discrete transfer function is given in [51] as:

$$G_{DB}^{(abc)}(S) = \frac{1-az^{-1}}{b(1-z^{-1}} \qquad (6)$$

where a and b are given in equations (7) and (8) respectively as:

$$a = e^{\frac{R_T}{L_T}T s} \qquad (7)$$

and

$$b = -\frac{1}{R}\left(e^{\frac{R_T}{L_T}T s} - 1\right) \qquad (8)$$

where L_T and R_T are the interfacing inductance and resistance of the inverter.

Dead-beat controller uses two switching cycles to regulate the current and achieve its reference. An observer is added to the structure to compensate the time delay in order to achieve the reference current tracking (Fig.7) [51, 70]. The discrete transfer function of the observer is given as

$$F_{DB}^{(abc)} = \frac{1}{1-z^{-1}} \qquad (9)$$

Then, the new reference current is given as,

$$i^{*(ref)} = F_{DB}^{(abc)}(i^{*} - i\ ) \qquad (10)$$

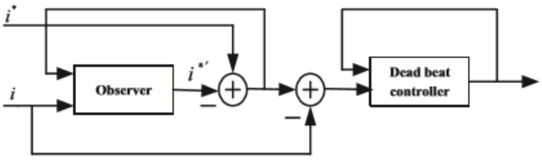


Fig. 7. Block diagram of dead-beat controller [48]

Consequently, fast and simple controller for current regulation and high dynamic is obtained. The algorithms for dead-beat controller and its observer are simple and suitable for use in microprocessor-based applications [71, 72]. The main problem of DB controller is the implementation in high frequency micro-controller [16].

4.2.2. Hysteresis Controller

Employing non-linear method, hysteresis controller, for harmonic mitigation involves comparing the grid and reference current instantaneous values to generate switching pulses for the inverter [48]. The output current of inverter is controlled by the range of error signal called hysteresis band. The error signal is the current difference between reference and grid currents. This makes the current to stay within the hysteresis band limits as shown in Fig.8. Figure 9 shows a schematic diagram of hysteresis current controller. Hysteresis controller has advantages in simplicity, high dynamic response, unconditioned-stability, robustness and independence of load parameters [16, 48, and 73]. Hysteresis controller has high control complexity for current regulation as its drawback. It can also generate high frequency harmonics to the current because of its variable switching frequency [26]. However, researchers have proposed different methods and algorithms for the controller in order to design an adaptive hysteresis band to achieve fixed switching frequencies [74-78]. Though, attempts at obtaining fixed switching frequencies may increase the complexity of the controller considerably.

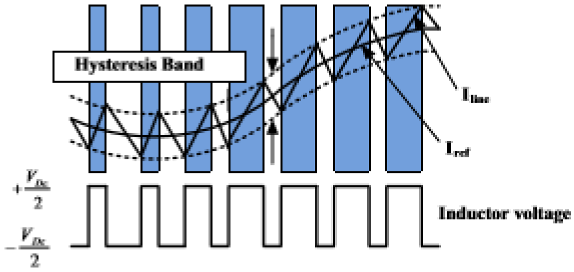


Fig. 8. Hysteresis current controller band limits

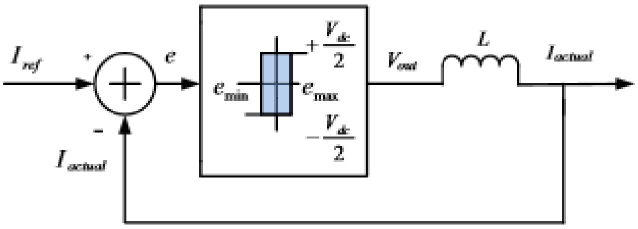


Fig. 9. Schematic diagram of hysteresis current controller [48]

4.2.3. Predictive Controller

Another control strategy for harmonic control in PV system is to use predictive controller. In this strategy, the voltage needed to drive the reference current and the grid current to follow each other is calculated by the controller [79, 80]. Here, the characteristics of the system variables are predicted by the reference and grid currents at each switching state [48]. Figure 10 shows the schematic diagram of predictive current controller [79]. This controller is good in handling systems with nonlinearities [81]. It achieves good current control at the expense of low order harmonics and noise. Also, predictive current control is more difficult to implement. It requires matching it to an exact load [79].

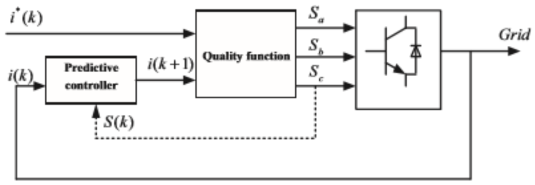


Fig. 10. Schematic diagram of predictive current controller [48]

Table 3: Advantages and limitations of current control strategies for PV inverters

Control strategies	Controller type	Advantages	Disadvantage	Limitation on harmonic control
dq control [15, 16, 48, 51]	PI	• Current control is simple • Dynamic response is good • Hardware implementation is easy	• Harmonic compensation of low order harmonics is very poor • Poor steady-state error elimination	• Increased complexity of control due to need for harmonic compensators of both negative & positive sequences of each harmonic order.
αβ control [16, 48, 51, 56, 60]	PR	• Current harmonic compensation (low order harmonics)is good • Good steady-state error elimination • High gain at resonant frequency	• Complex hardware implementation • Lacks full control on power factor	• Introduces high computational burden when compensating high order (11th and 13th) harmonics
	RC	• High dynamic response • High order harmonic compensator • Gain at multiples of fundamental frequency is high	• Selective harmonic compensation • Dynamic response is slow	
abc control [15, 16, 48, 51, 56, 60, 70, 75]	PI		• Transfer function is complex	
	PR	• Simpler transfer function	• Transfer function is complex for high sampling rate	
	DB	• Easy control for current regulation • Dynamic response is high	• Implementation in high frequency DSP • Sensitive to parameter variations	• Switching and sampling frequency harmonics are not controlled
	Hysteresis	• Control structure is simple • High dynamic response • Insensitive to load parameters • Good transient response	• Complex current control • Sampling rate is high	
	Predictive	• Precise current	• Complex current	

	control • Good dynamic response • Optimized switching frequency	control • High sampling rate • Low order harmonic distortion • Implementation involves matching to an exact load • Difficulty of implementation	

5 Performance of Different Controllers on Harmonic Control of UPVIs

5.1. Linear Current Control Strategies

Ref. [82] compared the performances of three linear current control strategies; (a) PI controller implemented in dq frame, (b) PR controller in αβ frame and (c) RC controller in abc frame, at stead state and transient conditions as shown in Fig. 11 and Fig.12 [82].

5.1.1. Performance in Steady State Condition

The steady state analysis of linear current controllers is based on the current harmonics analysis using the current total harmonic distortion THD as the basis for comparison.

5.1.1.1. PI Controller in dq Frame

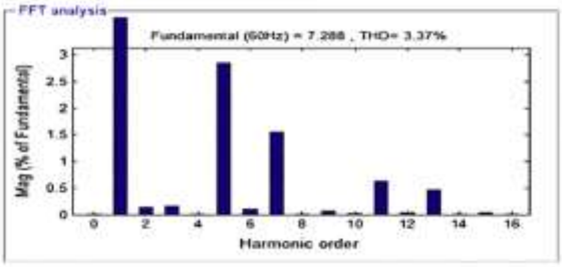
The current THD was 3.37% when PI controller is employed in dq frame as shown in Fig 11a where individual harmonic up to 16th order is considered.

5.1.1.2. PR Controller in αβ Frame

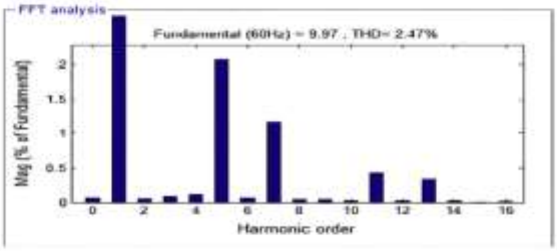
As shown in Fig 11b, the PR implemented in αβ frame with harmonic compensator has 2.47% THD value of current harmonics.

5.1.1.3. RC Controller in abc *Frame*

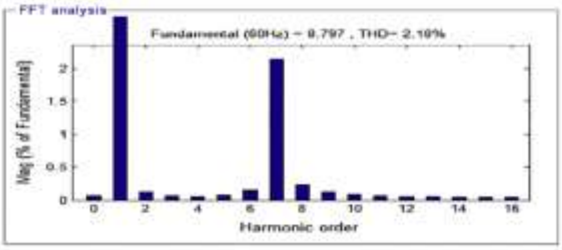
The harmonic spectrum of an improved RC controller is shown in Fig 11c. The improved RC controller performs better than the classical PI and PR controllers with a THD of 2.18%.



(a)



(b)

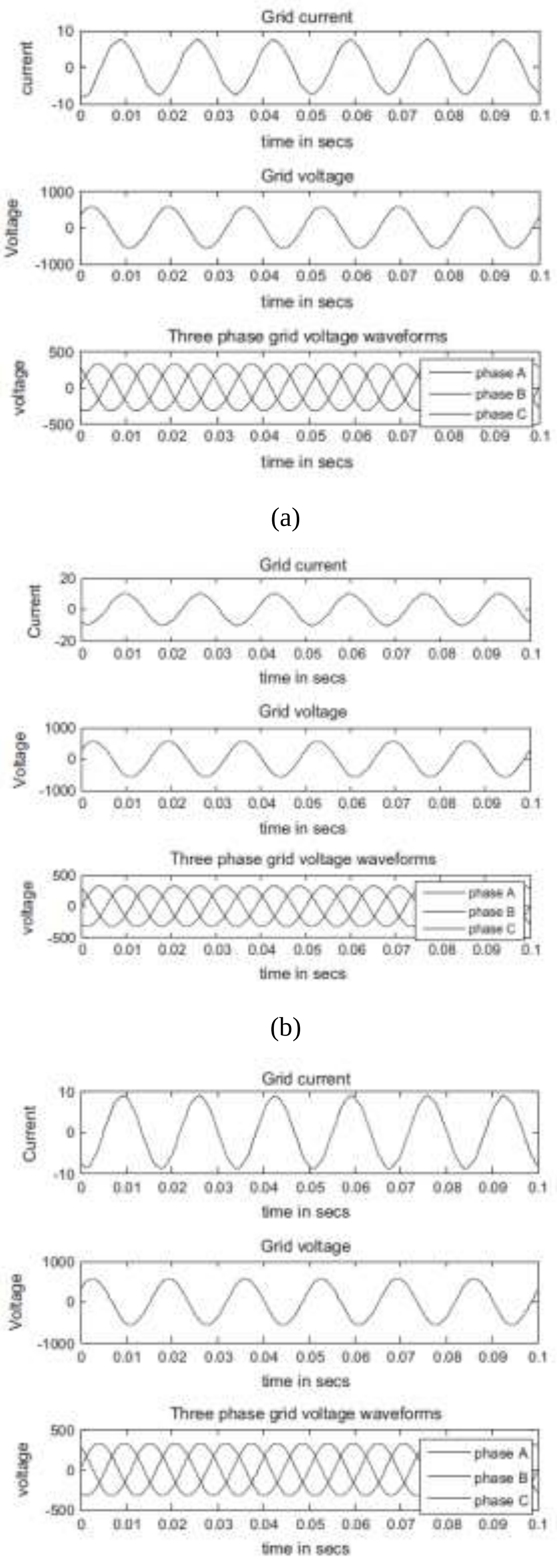


(c)

Fig. 11. Experimental results showing the current harmonic spectral for (a) PI controller in dq, (b) PRcontroller in αβ, and (c) RC controller in abc frame [82]

5.1.2. Performance in Transient Condition

The performance during transient operation can be determined by studying sinusoidal current reference tracking during normal operation and during abrupt changes in the current reference [82]. Figure 12 is the experimental results showing the grid current response of different controllers implemented in various reference frames. It is shown from the experimental results that all the controllers can track the sinusoidal reference current and exhibit good dynamic response.



(a)

(b)

(c)

Fig. 12. Experimental results showing current controllers transient responses in tracking sinusoidal current reference for (a) PI controller implemented in dq, (b) PR controller in αβ, and (c) RC controller in abc frames [82]

5.2. Nonlinear Current Control Strategies

Also, Ref. [83] proposed a nonlinear predictive current controller for three phase grid-connected inverters interfacing PV system. It compared the performance of the proposed controller with hysteresis current controller at steady state conditions in terms of current THD and dynamic state responses

5.2.1. Performance in Steady State Condition:

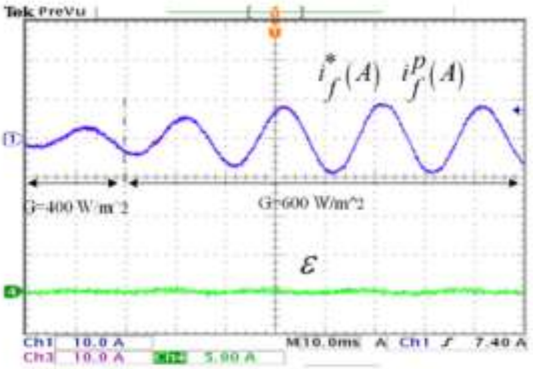
Table 4 shows the performance comparison between the predictive current controller and hysteresis current controller in abc frames. The predictive current controller has a current THD of 1.8% while hysteresis current controller exhibit current THD of 3.4% which are lower than 5% limit of IEEE standard 519-1992.

Table 4: Experimental results in terms of current THD for predictive and hysteresis current controller.

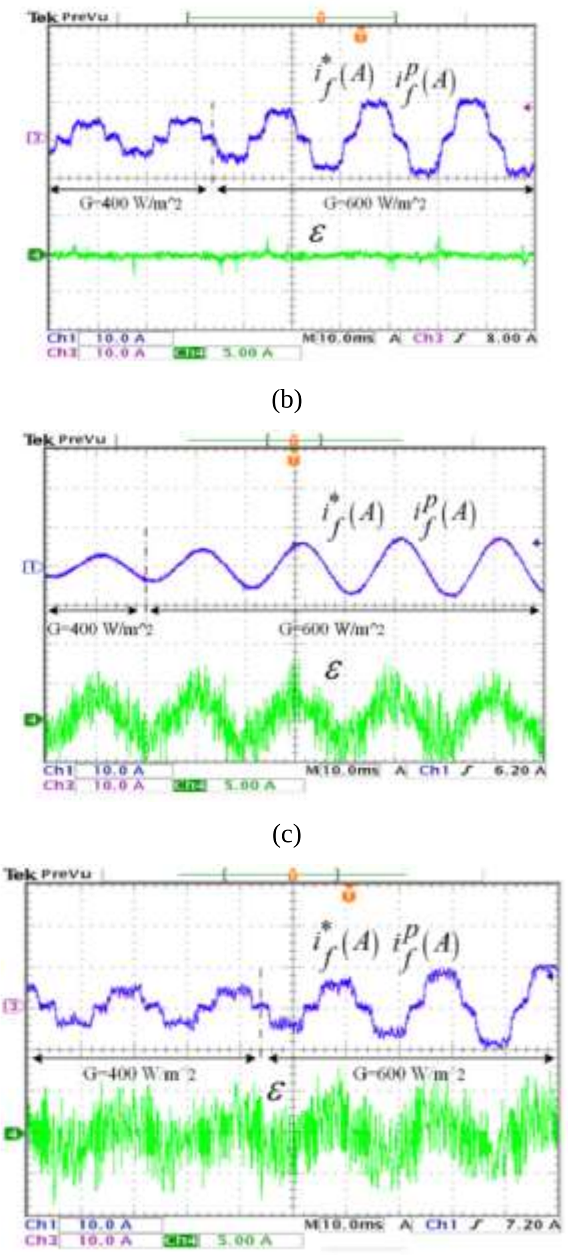
Control strategies	**THDi (%)**
Predictive current controller	1.8
Hysteresis current controller	3.4

5.2.2. Performance in Dynamic Condition:

The dynamic performance was examined under irradiation step change. Figure 13 shows the experimental results regarding dynamic behaviour of predicted and reference currents and the error between them for predictive and hysteresis current controllers [83]. The predictive current controller provides more stability and better prediction at the instant of changing in operation mode. Meanwhile, hysteresis current controller provides good performance in terms of power quality improvement but the error between measured and reference current is more [83].



(a)



(b)

(c)

(d)

Fig. 13. Dynamic behavior of predicted and filter current at step irradiation (G=400 W/m^2 to G=600 W/m^2): (a), (b) predictive current controller and (c), (d) hysteresis current controller [83]

The power ratings of the PV inverters reviewed above are between 10kW to 30kW. The performance of the current controllers mentioned above in terms of current THD is averaged at less than 3%. This is below the IEEE standard 519-1992 harmonic limit of 5% at their power ratings of between 10kW and 30kW. Meanwhile at a utility-scale PV generation with a single central inverter of 2.5MW power rating, the magnitude of the current THD will be very high even at that 3% THD. Consequent upon the fact that the magnitude of the current THD depends on the magnitude of active power output of the inverter.

6 Comparison of Current Controllers of PV Inverters

In UPVPS, low steady state error, low harmonic distortions, good stability, and high dynamic response are some of the desired characteristics required for viable power systems [48]. Table 3 summarizes the strengths and weaknesses of various current control strategies applicable to PV inverters. Considering harmonics control of PV inverters which is the strong point of this review, an optimum harmonic control strategy has not been fully achieved for UPVIs. The average current THD value of 3% on rated power output of UPVIs is rather high comparing its equivalent magnitude to the magnitude of the output current of the UPVIs. The linear current controllers either exhibit slow dynamic responses, poor harmonic compensations or poor steady state error eliminations. Also, the requirements for high switching and sampling frequencies result in switching and sampling frequency harmonics and complex hardware implementations in the nonlinear control strategies.

7 Conclusion

This paper has presented various types of inverters and reviewed the current control strategies of inverters used in the PV power systems connected to the utility grid. Harmonic analysis of various configurations of industrial inverters, from different manufacturers, used in utility-scale PV power systems was addressed. This is done based mainly on the available information from the manufacturers of the inverters. The probable sources and causes of harmonic generations in UPVIs were equally discussed. The control strategies implemented in the three reference frames such as dq, αβ, and natural abc were presented and compared with respect to their major characteristics. Experimental results to make fair comparison of their performances on harmonic control are limited. Based on the available data in the literatures, PI controllers are mostly implemented in dq frame, and PR and RC controllers are widely implemented in αβ frame. The nonlinear control strategies (dead-beat, hysteresis and predictive controllers) are implemented in natural abc frame since abc frame is a nonlinear control platform itself.

The performances of all the controllers at average of 3% current THD are good for small and medium scales PV power systems but the current harmonics magnitude at 3% current THD for utility-scale PV power systems is too significant to be ignored especially on the distribution networks. Both linear current control strategies (PI, PR and RC controllers) and nonlinear current control strategies (dead-beat, hysteresis and predictive controllers) need constant and continuous research to improve on their performances on harmonic control and reduction of utility-scale photovoltaic inverters interfacing the grid system. The amplitude of current THD as a percentage of the output current depends significantly on the real power output of the inverter. This affects utility-scale PV system.

Conflict of Interest

None

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