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# **An Overview of Power Quality Enhancement Techniques Applied to Distributed Generation in Electrical Distribution Networks**

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**Abstract** – It is obvious that power quality is an important characteristic of today's distribution power systems as loads become more sensitive on the other hand nonlinear loads are increasing in the electrical distribution system. Considering the distributed nature of harmonic loads, the need for distributed power quality improvement (PQI) is inevitable. From years ago, researchers have been working on various kinds of filters and devices to enhance the overall power quality of power system, but today the nature of distribution system has been changed and power electronic based DGs play an important role in distribution grids. In this paper, a thorough survey is done on power quality enhancement devices with emphasis on ancillary services of multi-functional DGs. A literature review is also done on microgrids concept, testbeds and related control methods. Although there were some applications of DGs for PQI improvement these applications were not defined multi-functional DGs. Various control methods are studied and categorized regarding different viewpoints in the literature. Finally, a couple of thorough comparisons are done between the available techniques considering the nature, capabilities, advantages and implementation costs.

**Index Terms** \_ Power Quality, Distributed Generation, Multifunctional DGs, Microgrids, Renewable energy sources

## **1. Introduction**

The concept of power quality is defined as the capability of the electricity grid to provide costumers reliable, ideal and non-tolerant electricity. In details power quality issues can be classified into several levels. Initially, it was just referring to the availability of electrical power, voltage and frequency regulation within a specific range [1]. As electrical devices are getting more sensitive, costumers are becoming more aware, and power quality pollutions are increasing in the system, power quality is gaining increasing attention and it has to include some other aspects like harmonic distortion, short time transients, unbalances, interruptions and flickers in addition to initial requirements [2, 3].

There are some IEEE and IEC standards such as IEC 61000, En 50160, IEEE 519, about power quality [1, 4, 5]. Nevertheless, IEEE standards do not provide structured and comprehensive discussions on power quality in comparison to IEC standards, but IEEE and IEC both have standards for this special topic, and it is a proof to the importance of power quality issues in modern power systems [1, 4, 6, 7]. A comparison between IEEE and IEC standards for power quality topics is presented in [8, 9].

Power electronic devices as a part of today's grid may have some undesirable effects on grid parameters, power quality, and system reliability. These devices that are commonly used in modern networks have a direct impact on power quality of the distribution networks [10, 11]. An example of these pollutants is inverter-based DGs, which use power electronic devices as an interface to connect to the grid. The important point is the increasing growth of DG implementation both by individuals and electrical utilities. Nevertheless, in standalone usages the output voltage and current of DGs could be improved in the source of generation by means of some inverter switching methods, it is worth noting that because of these capabilities, multilevel inverters are one of the most interesting inverters for applying these switching methods, such as harmonic elimination methods [12-16]. By the increasing penetration of DGs in today's grid, power quality issues become more important and paying attention to this topic is inevitable. Several researches are done on minimizing the negative effects of power electronic based DGs in microgrids using DGs, although this seems to be the first versions of the multi-functional DGs concept, still much improvement has to be done in this area [17-21]. During the years, many devices are suggested as PQI devices, though each one is having some disadvantages, then the research has to continue on this topic yet. Although the integration of power electronic based converters and nonlinear loads may also deteriorate the power quality on the other hand multifunctional DGs are one of the new solutions for power quality enhancement challenge [22]. The microgrid gives us the opportunity to deal with some system problems, making the grid more reliable and secure. The concept of microgrid was first introduced in the 1990s, and then it got more attention from researchers [23]. It has special characteristics that will lead to power quality improvements; one of these characteristics is including several units of DG with different natures to increase the overall system reliability. Since most of the employed DG units use power electronics based converters, these energy sources could be utilized for power quality enhancement [24]. Each power electronics based converter used in microgrids is a potential of power quality improvement device, even though it has some other functions as an ordinary converter. Several researches are done in the field of power quality improvement in distributed power systems by date but mostly in a particular field and not comprehensive [2, 3, 9, 25-34]. Power quality includes several aspects,

in some of the papers researchers are trying to control voltage in a centralized and decentralized way using DG inverters locally [35, 36]. Different converter topologies and control methods are applied to microgrids to enhance power quality[37, 38]. Since not all of them could be referred in this part, these methods will be explained more in the other sections. To verify the proposed control methods an standard and a testbed for microgrid was needed, then the first version of microgrid testbed was formed to test the control strategies [39, 40]. Since it is a popular research field, there are several well-known testbeds made by several research groups all over the world for microgrid tests [41-44]. In this paper, almost all of these methods have been classified, while paying special attention to multifunctional DGs, both in the local and regional state. First of all these devices will be classified based on the capabilities, to make it comprehensive a brief discuss is done on each device including its operation, advantages,disadvantages, and new applications of each one. Finally, a thorough comparison is done between all these methods taking every aspect into account to make a clear overview of power quality improvement devices

## **2. Classification of PQI devices**

PQI devices could be categorized to three main generations that are developed during last fifty years, the first generation of PQI devices, is simple and reliable in structure and usually do not cost so much, these devices include passive, active and hybrid power filters and will be discussed in section 2.1. The second section of this paper is explaining the working principles,advantages, and disadvantages of the second generation of PQIs which are the most favorite PQIs used in power systems up to now. Finally, the most detailed discussion in this paper is oriented around multi-functional PQIs including smart impedance, electrical springs and multi-functional DGs. Several comparison tables are presented, to show the superiority of each device to the others.

### **2.1 The first generation of PQI Devices**

The first generation of PQI devices mainly focuses on intercepting harmonics from spreading to the grid or being injected to a load or compensating the harmonics mainly on the consumer side. This classification includes passive and active power filters which originated the hybrid power filters, which will be discussed in section 2.1.3

#### **2.1.1 Passive Power Filters**

Passive power filters were developed by a combination of inductances and capacitances, to reduce or eliminate current harmonics and compensate reactive power. Fig. 1- c displays a simplified scheme of passive power filters.

Passive filters are categorized in two kinds of parallel and series. These Filters are installed in parallel with loads to make a Detour for the harmonic currents, by setting the inductance and capacitance value as shown in Fig. 1-c, such that in fundamental frequencies the filter has a high impedance and in desired harmonic frequencies it has a very low impedance to absorb the harmonic currents [45, 46]. The other kind of passive power filters is installed in series with load to stop the harmonic current to enter the load. Besides the advantage of being simple and cheap and highly reliable, there is the disadvantage of the need for a new design for every new case, the filters should be tuned to a specific harmonic to act correctly and may lead to over voltage during low power demand. It is worth noting that these filters are used nowadays in some application beside disadvantages because of being simple design and cost-effective. Research in the application and novel methods to design of this filter is still going on in three phase and single phase power systems, although most of them are some hybrid applications of filters to reduce the costs and increase the reliability of the system [33, 47-56].

### **2.1.2 Active Power Filters (APF)**

Since tuned passive filter efficiency is highly dependent on the tuned factor, quality factor and source equivalent impedance, active power filters are a good alternative for them. Active power filters were developed to overcome passive filters drawbacks, APFs can reduce harmonics, compensate and improve power factor, compensate unbalances and flicker and regulate voltage. APFs have been used as PQI devices with different topologies and control strategies, [57-62]. There is some detailed comparison between various APFs and the applications of each one, while most of the comparisons are from topology aspect [26, 27, 29]. Active power filters are divided into two main groups, shunt active power filters and series active power filters [63, 64]. The new generation of APFs which deals with the idea of resistive APF (R-APF), will be discussed more in section 2.3.4.1. It is worth noting that a comprehensive comparison is done between advantages and disadvantages of each of these devices in Tables 4 and 5.

#### **2.1.2.1 Shunt active power filter**

It compensates current harmonics by injecting a harmonic current with the same magnitude but with 180 degrees phase in difference with the harmonic current. Hence, harmonic current is compensated and grid current is nearly sinusoidal and in phase with source [65]. Furthermore, active power filter can be used to compensate reactive power if proper control methods are used. From the viewpoint of grid, a parallel active power filter with nonlinear load seems like a linear load. Fig. 1-b is a simple display of shunt active power filters, as it is shown APF is compensating the

nonlinear load current by injecting the same nonlinear current that load absorbs from the grid, so that the grid current will be sinusoidal [66, 67] Ongoing researches in this field are concentrated over novel control methods of shunt active power filters and also new applications for shunt APFs [68-80]. More detailed analysis of main topologies of shunt active power filters is done in [81].

#### **2.1.2.2 Series active power filter (SAPF)**

Although series active power filter (SAPF) was developed longtime ago, it is popular nowadays. It compensates the voltage harmonics by adding a harmonic voltage to the grid in series, with opposite phase with voltage harmonic and acts like a controlled voltage source. It can also compensate voltage unbalances. The main disadvantage of SAPF is that, since series active power filter needs to produce the same power to compensate harmonics, it becomes rather expensive in high power applications. As it can be seen in Fig. 1-a, a series active filter usually connects to the grid by means of a transformer. A series active filter can be used with a shunt passive filter to lower the costs to form hybrid active power filter which will be discussed in detail in 2.1.3. [67, 82, 83]. Deployment of SAPF in various new applications is one of the popular research fields in SAPF [84-87]. Moreover, research on different control strategies for SAPF is going on yet [88-90].

#### **2.1.3 Hybrid active power filters**

The hybrid filters have advantage of both active and passive filters in many aspects such as price, efficiency and reliability. Hybrid active power filters offer a method to overcome the physical limits of tuned passive filters and at the same time, reduce cost of using an expensive high capacity active power filter [91-93]. The main categories of hybrid filters are shunt active series passive filters [67, 94-101], shunt active shunt passive filters [26], and series active shunt passive filters [96, 97]. A simple configuration of hybrid APF is presented in Fig.1-d. Each of these categories has its advantage, disadvantage, application and several detailed studies have been done on this subject [102-104]. The main advantage of these filters in comparison with passive filters is introduction of virtual active resistance and virtual active inductance concept, which can be defined as “virtual active impedance” concept and is discussed in details in [105]. Defining new applications for hybrid filters always has been popular [85, 90, 106]. Some researchers are interested in virtual hybrid APFs, that is an APF between an AC and DC micro-grid [107]. To research

finding novel control strategies to improve the performance of hybrid filters has always been popular for researchers [108-113].

## **2.2 The second generation of PQI Devices**

Some other methods of harmonic compensation are used in literature; these methods are kind of active power filters using ultra capacitors or renewable energy sources as power sources for controlling power flow to grid. These methods can be classified as the second generation of PQI devices including dynamic voltage restorer (DVR), static VAR compensator (SVC), static compensator (STATCOM), automatic voltage restorer (AVR) and uninterruptible power supply (UPS). There is a slight difference between the operation of these devices, a brief discussion about the operation and capabilities of these devices are provided in each section.

### **2.2.1 Dynamic Voltage Restorer (DVR)**

Dynamic Voltage Restorer (DVR) is a power electronic based device that protects critical loads from voltage unbalances and as shown in Fig. 1-e, it is connected in series with the sensitive load and can absorb or get P and Q from the grid. The working principle of DVR is such that it senses a voltage unbalance in the grid and adds a voltage to grid to compensate it, so it needs an energy storage source that can be a battery, capacitor, ultra capacitor, super conductive energy storage (SMES) and flywheel [114]. Nowadays in many applications RES plays the role of storage sources, in this case not only it can improve the power rating of DVR but also it will decrease the storage source cost. It is worth noting that there is a slight different between these devices and the multi-functional DGs that will be discussed in 2.3.3 that can do both of the roles of power delivery source and PQI device. An isolated transformer is inevitable in DVR structure to isolate the DC and AC side and to protect the device over fault conditions of the grid [115]. While some researchers try to present novel DVRs with different transformer topologies, others research on transformer fewer DVR topologies [116, 117]. Researchers try to improve the performance and rating of DVR by using some kind of novel multilevel inverters and new control strategies in DVR topologies because of the unique characteristics that multilevel inverters will bring to power systems [118-121].

### **2.2.2 Automatic Voltage Regulator (AVR)**

The automatic voltage regulator is a device that is changing the output voltage to keep the critical load voltage at a sufficient level, and it does it by changing the transformer tap or other methods, mechanically or electronically [122].

There are two major groups of AVRs, static AVR and rotary (servo motor AVRs) that tracks the voltage tolerances continuously. The response time of AVR in rotary ones is not so little to give the AVR ability to track every change in voltage and on the other hand, static AVRs that are power electronic based devices and faster than servo motor AVRs, having less precession on tracking voltage tolerances because of the discrete voltage change of these AVRs. Nowadays different algorithms are used to design the AVRs and improve the performance of these devices, some of these algorithms and a comparison between classic design methods and new design methods are explained in more details in [123-128].

### **2.2.3 DSTATCOM**

Distribution static VAR compensator is a kind of device that is widely used in industry and distribution system, capable of regulating load voltage by absorbing or giving reactive power to it. There are two different VAR compensators, TCR and TSC that are thyristor-controlled reactors and thyristor-switched capacitors. DSTATCOM is a kind of static VAR compensator (SVC) that is equipped with a voltage source inverter to regulate the output voltage continuously unlike SVC that is regulating the output voltage discontinuously. As the configuration of SVC is shown in Fig. 1-f, it can inject or absorb reactive power from loads [129].

### **2.2.4 UPS**

The uninterruptible power supply is a power electronic based device that can sense voltage and frequency unbalance, under or over voltages and supply the critical load by itself with a pure sinusoidal voltage and a fixed frequency. Due to physical classification of UPS, there are two major types; static and dynamic UPSs, static UPSs are made up of power electronic switches while the other group may have some rotary parts like a flywheel, there is also a combination of these two types that is called hybrid UPS. Based on international standards IEC 62040-3 and ENV 500091-3 and application point of view, there are three types of UPSs, offline (passive standby or line preferred) UPSs, line-interactive UPS, and online (double conversion or inverter preferred) UPSs [130-133]. To understand the main difference between these UPSs, a comparison is presented in Table 1. As it can be seen from the table Online UPS are capable of solving all the mentioned problems, while line-interactive UPSs are only able to deal with brown out and long time over voltages, and finally, off-line UPSs can deal with short time (>10ms) sag, swell and total black-outs. The main drawback of static UPSs is the need for large energy storage, though it feeds the whole load in the case of unbalance, not a part of it like DVR [131-134]. Nowadays some researches are going on application of UPS as an

active power filter to overcome storage size problem of UPSs. Some other researchers are trying to develop improved control strategies for UPS systems [135-137]. Other researches are done on improving design concept of modern UPS systems[138-140]. Research on standards, qualifications and reliability of UPS systems has always been popular, e.g. IEEE has recently published an updated version of UPS and battery charger standard [141, 142].

## **2.3 The third generation of PQI Devices**

Next generation of power quality improvement equipment is mostly multi-functional, which are capable of doing more than one task at the same time with the same hardware that will lead to increased cos-effectiveness, besides being reliable and effective. Characteristics of all aforementioned topologies could be gathered in a novel topology called “smart impedance” [143-145]. Electrical spring is another device of this group that performs voltage regulation while improving the stability of grid and also takes part in demand response program [146-149]. The most improved class of these devices is multi-functional DGs which are getting more and more attentions nowadays and researchers are proposing novel control methods to improve the functionality of these devices.

### **2.3.1 Smart impedance**

As it was mentioned earlier, hybrid and active power filters helped on improving the physical parameters of tuned passive filters just in one aspect. By combination of an active converter, a coupling transformer, a capacitor bank and an appropriated control strategy, in single phase or three phase topology the concept of “Smart Impedance” is formed. It can solve the tuning process of passive filters since all the tuning process is done automatically. It can compensate harmonic current, harmonic unbalances, improve quality factor, tuned factor and displacement power factor [143, 145]. In weak systems like microgrids that source impedance is not negligible, the smart impedance can also help improving voltage regulation and stability. Its control strategy is based on proportional resonant controller, by means of which, power system synchronization is possible in the absence of phase locked loops. As it is obvious, smart impedance firstly was formed as an improved tuned passive filter that leads to optimal tuning factor and quality factor [143] but its working principles are different. It can behave as different equivalent impedances due to its working mode both in fundamental and harmonic frequencies. Smart impedance can perform as a shunt active filter, series active filter, a tuned passive filter, a capacitor bank and a combination of an active and passive filter to reduce the capacity of filters moreover it can mitigate selected harmonics of interest. For example, smart impedance can act like a short circuit (zero impedance) for load current harmonics, or it can act like infinite impedance against undesired

harmonics, at the same time in fundamental frequency it can act the actual needed impedance to improve load displacement power factor [150]. It can be told that smart impedance is a variable impedance and can take different values due to system needs and power quality improvement.

Fig. 2 describes a simple smart impedance topology, as it can be seen, power circuit is composed of a capacitor bank connected to a power converter via a transformer, and three control blocks are formed on the basis of the proportional resonant (P + Resonant) converter to alleviate system current harmonics without need for PLL. The harmonic control block is used to eliminate harmonics using P+Resonant controller, while Displacement power factor (DPF) block can control injected reactive power by capacitor bank and DC voltage control block regulates DC link voltage of each converter [151, 152].

### 2.3.2 Electrical springs

Concept of electrical spring was developed on the basis of mechanical spring principles; it can also be used as a voltage regulator and in the case of integrating into electrical appliances, it can act as a smart load (as it is shown in Fig. 3) [153], which can follow the power generation profile. By means of the distributed smart loads in electrical power system, stability of power system will increase independently of the communication system and information [146]. If a power system could be imagined as a mattress, and subsidence of mattress as voltage drops all over the network, using mechanical springs to avoid mattress subsidence is somehow identical to using electric springs to avoid voltage drops and help improving voltage stability, this concept could be better understood by details in [147, 148, 153, 154]. Its most important advantage is that by the failure of few springs systems stays stable. Electrical spring would store energy and pay it back to the power system in the case of need, and therefore it can alleviate stability problems of renewable energy sources.

Like mechanical springs, electrical springs can do these three tasks in a power system, 1) to store (electrical) energy; 2) to support voltage regulation; 3) to abate electrical system oscillations and act as inductance and capacitance as presented in equations (1) and (2). In equation (1),  $q$  is the amount of stored electrical charge in capacitor,  $V_a$  is the voltage on Capacitor, and  $i_c$  is the current following through capacitor. Electrical springs have been improved and new generations of ESs named ES2 and ES3 are presented in [153, 154] with some novel capabilities such as P & Q compensation and harmonic reduction.

Equation (1) presents that voltage regulation process is affected by the amount of stored charge in capacitor and equation (2) reveals the direct relation between stored charge and current and the fact that stored charge can be managed by a controlled current source.

$$q = \begin{cases} q = CV_a & \text{Inductive mode } e \\ q = -CV_a & \text{capacitive mode } e_a \end{cases} \quad (1)$$

$$q = \int i_c dt \quad (2)$$

To damp the electrical oscillations a non-critical electrical load (such as water heating or refrigerator) should be connected in series with lossless spring to form a “smart load”, it can dissipate electrical energy for damping objective, and also it can help the spring follow the generation profile of power system. This feature of electrical spring is useful in improving voltage stability of future adaptive power system that deals with intermittent renewable energy sources [148].

Fig. 4 represents a simplified power distribution system with critical and non-critical loads, electric springs and the simulated mechanical behavior of springs to lift the voltage dips is also shown in Fig. 4. What a mechanical spring does in a mattress is to support the subsides, electrical springs do the same to a power system by supporting the power system with regulating the voltage and preventing under voltages and over voltages. Unlike non-critical loads, critical loads are loads requiring regulated voltage such as control boards and medical equipment.

Electrical spring is like a reactive power controller that controls input voltage instead of output voltage, and in contrast with other reactive power controllers such as FACTS or SVCs that only take part in reactive power compensating, it can manage both reactive and active power. It can produce a sinusoidal voltage named  $V_a$  that is perpendicular with  $I_o$ , and it can be controlled 90 degrees lagging or leading to  $I_o$ . As shown in equation (3) sum of  $V_a$  and  $V_o$  is equal to main voltage  $V_s$  [149].

$$\vec{V}_a + \vec{V}_o = \vec{V}_s \quad (3)$$

Fig.5 is an example of vector diagram of an electric spring that operates in inductive mode, and it can be concluded that  $V_o$  is controlled by increasing and decreasing of  $V_a$ , so it is capable of controlling the amount of reactive power that non-critical load consumes, then it can also be called as a demand response solution [155].

Recently feasibility of using ES in DC microgrids has also been reported in [154, 156] Previous solutions were not suitable for DC microgrid problems. DC-ES is serially connected to non-critical load forming the smart load and it has a bi-directional DC-DC power converter and storage elements such as batteries in its structure. Power system oscillations can be damped by means of non-critical load and storage sources and therefore demand response becomes operational in DC microgrids [154].

### **2.3.3 Multifunctional DGs**

Nowadays, demands for renewable energy sources are increasing for different reasons, most of these energy sources output DC Voltage and this source of power needs to be converted to AC in order to be used. Although there are some researches on control, management, development, power quality improvement, utilization of DC microgrids and some home appliances compatible with DC electricity has been developed but it is not as inclusive as AC grids [157-161]. Power electronic converters are an inevitable part of these systems but there is a problem, and it's the overall cost of these systems that creates doubt in cost-effectiveness of power electronic based RESs. To make these sources cost-effective it is possible to add ancillary services for converters in power systems such as being an active power filter or an energy storage source for different smart grid applications. Therefore these kinds of RESs are called multifunctional RESs (MFRES) and will have great part in future smart grids. MFRESs can be categorized by the effecting domain or by some objects to be controlled. Both of these categories will be discussed and different control methods will be presented for different objectives [162-164].

### **2.3.4 Control methods of MFRESs**

Some of the MFRESs can influence just a part of power system locally, while others can affect more than a part or region. There are little differences in the control methods, in a way that local systems only consider the output current of RES to be harmonic free, while regional MFRES may consider the whole area as a unique region and treat it as a linear load, in this case, objective will be the voltage of PCC or grid current. For this reason, multiple control methods can be used to control the inverters of MFRES, including current control method (CCM) [165-169], voltage control method (VCM) [162, 170, 171] and hybrid control method (HCM) [38, 172, 173] that will be discussed further. The Overall scheme of harmonic compensation in micro-grids is shown in Fig. 6 and it will be explained more in 2.3.4.1.

As it was mentioned above, to control the MFRES, multiple methods are implemented in the microgrids, and usually these methods are hierarchical [43, 174-180]. Multiple levels of control are applied to the microgrids, including energy management, load supervision, voltage and current control in primary control level, power quality issues including power flow control and synchronization with grid in secondary control level and finally in tertiary control level, economic dispatch, DSM and microgrid supervision are the focus areas [181]. The other popular control method in this area is Model predictive control or direct control that could be utilized in harmonic compensation and power quality improvement and active power filter applications because of its good dynamic response and simplicity of the controller [70, 182-184]. In the next section, there will be a detailed discussion of the two control levels [185] as the third control level is not the focus area in the field of this paper. MFRES are considered to participate in load sharing as well as PQI roles, and the main objectives related to PQI services are harmonic compensation of PCC voltage, local load current, and DG output current compensation. How to fulfill these objectives in the microgrids are discussed in detail by three different control methods in the following sections.

#### **2.3.4.1 Current control method**

The current control method is the most common method to control grid connected DGs, and it has an increasing penetrate in grid-connected microgrids, Fig. 7 explains the control strategy for CCM, it is obvious that, DG unit in this method, compensates current harmonics as well as participating in load sharing of the microgrid. It compensates the line current harmonic as default compensating object of CCM and two other compensation modes to be discussed are PCC voltage harmonic compensation and local harmonic compensation. The main control scheme of CCM is shown in Fig 8.

In PCC voltage harmonic compensation, the basic idea is to provide nonlinear load current by DG and grid current will only include sinusoidal currents and as a result PCC voltage will be harmonic free since the nonlinear load current is provided by DG [37, 165-168, 186].

Because of the distributed nature of the nonlinear loads, it is difficult to directly compensate the nonlinear load, another method based on measurement of local current uses the resistive active power filter (R-APF) concept {Akagi, 1997 #123; Bai, 2018 #438} in which DG unit works like a small damping resistor at the selected harmonic frequencies. As it is obvious in Fig 7, there are two different control levels, controlling fundamental power and Harmonic power delivered to microgrid.

To fulfill Local load harmonic compensation, the DG unit should absorb the local load current harmonics, when this method of compensation is applied, microgrid including DG unit and the nonlinear load is seen as a linear load source from the grid point of view. The difference between how to implement PCC voltage harmonic compensation and local load harmonic compensation lays in setting the DG unit current reference for CCM controller that is shown in Fig 9 .In PCC voltage harmonic compensation, a current reference is calculated as follows.

$$\begin{aligned} I_{ref} &= I_{ref\_f} + I_{ref\_h} \\ &= I_{ref\_f} - H_D(s) \cdot V_{PCC} / R_V \end{aligned} \quad (4)$$

In which,  $I_{ref\_f}$  is the fundamental DG current reference that controls  $P$  and  $Q$  and how to calculate it is explained in fig 7,  $R_V$  is the equivalent DG resistor at harmonic frequencies and  $H_D(s)$  is the harmonic detector to extract PCC harmonic voltage.

For the local load harmonic compensation, current reference is set to:

$$\begin{aligned} I_{ref} &= I_{ref\_f} + I_{ref\_h} \\ &= I_{ref\_f} + H_D(s) \cdot I_{local} \end{aligned} \quad (5)$$

In which  $I_{Local}$  is the local load current, it's obvious that for DG line current harmonic rejection, the reference current is;

$$I_{ref} = I_{ref\_f} \quad (6)$$

It should be mentioned that when compensating PCC voltage, some other disturbances may be added to system. Since the objective is to have a harmonic free PCC voltage, it can be ignored. It is correct for other kinds of compensations, and this is called the whack-a-mole effect, then a tradeoff should be done due to optimization of harmonics in a microgrid and all aspects of power quality should be taken into account [188].

#### 2.3.4.2 Voltage control method

Nowadays most grid-connected inverters use CCM to control power flow, but VCM is also popular for some reasons. Since it can mimic the behavior of a synchronous generator [162, 189-191] and on the other hand for independent microgrids, VCM is a proper choice to control frequency and voltage. By means of droop control and deriving a suitable voltage reference, VCM enables decentralized control of multiple DGs for demand sharing without need to communication systems [171, 172, 192-195]. It would hardly control the output current harmonics of a DG

since it does not have a closed loop line current regulation so the output current is highly sensitive to PCC voltage disturbances and local load harmonics. It can be enhanced by means of virtual harmonic impedance. An overall view of VCM based DG control schematic is shown in Fig. 10, here droop control is used to derive the instantaneous voltage reference. As for CCM method, several objectives can be obtained by VCM as well, which are discussed in the following.

For PCC harmonic compensation, voltage reference should be calculated as (7), where  $H_D(s)$  is the harmonic detector,  $\tau$  is the feed forward gain, and  $V_{Ref}$  is the modified voltage reference.

$$\begin{aligned} V_{ref} &= V_{ref\_f} + V_{ref\_h} \\ &= V_{ref\_f} - H_D(s) \cdot V_{PCC} \end{aligned} \quad (7)$$

And the corresponding equivalent impedance  $Z_{DG,eq}$  is calculated by equation (8).

$$Z_{DG,eq} = Z_{DG} / (1 + \tau) \quad (8)$$

Where  $Z_{DG} = SL_2 + R_2$  is the LCL filter grid-side inductance. DG acts as a small impedance at selected harmonics.

Like a resistive active power filter (R-APF) with a small impedance of  $Z_{DG,eq}$  and a high feed-forward gain, PCC harmonic specifications could be improved. Virtual harmonic impedance that is shown in the equations (7) and (8) can take inductive or resistive values due to Selected feed forward gain  $\tau$ , such that  $Z_{DG,eq}$  can be inductive when  $\tau$  is a real number and it has resistive nature when supposing  $\tau$  as a complex number, to accurately control the amount of virtual impedance, grid-side information is needed and it is a drawback for this control system.

Local load harmonic compensation cannot be realized by the references provided in (7) and to compensate local load harmonic a harmonic current feed forward term should be added to the inner control loop reference. On the other hand, it needs a high-bandwidth inverter output current tracking and the inner controller of VCM  $G_{Inner}$  should be changed to a method such as the Hysteresis control, model predictive control or multiple harmonic resonant controllers but it may increase the complexity of control method and bring some drawbacks to VCM [196, 197]. To overcome some of these drawbacks, researches are going on to decrease the computational burdens of the inner control loop.

To apply DG line current harmonic rejection when using VCM, value of  $\tau$  should be considered -1, So that DG acts like a big virtual harmonic impedance in harmonic frequencies, rejecting harmonic currents from  $I_{DG}$  and flowing

harmonic currents to the grid, It is somehow similar to what is done in CCM controlled DG without any harmonic compensation system, so thanks to series virtual harmonic impedance, line current of DG can be harmonic free, a detailed explanation of this system can be seen in Fig. 11 [195].

#### 2.3.4.3 Hybrid control method

There is another method of control for DG inverters called as HCM, in this method both fundamental capacitor voltage and line harmonic current is controlled. Like VCM, the output power of DG is controlled by regulating the fundamental capacitor voltage in HCM and ; line current harmonics can be controlled by means of a closed-loop harmonic current compensator. Control diagram of HCM is shown in Fig 12. Fig 13 also explains the main control unit of HCM, multiple control terms are included in this controller, the first term is a resonant controller in fundamental frequencies controlling fundamental capacitor voltage, the second one is the line current harmonic controller that is composed of multiple resonant controllers that work in different harmonic frequencies, and finally the third one is an active damping term that is made up of a proportional controller and can provide a damping path for both capacitor voltage control and line harmonic current control. Equation (9) shows the reference voltage to control the DG inverter, and it is obvious that by this reference voltage and other arrangements done in this control method, the output voltage of DG, and line current harmonics can be controlled separately [172, 195, 198]. It is easy to compensate the PCC voltage harmonics by just setting the current reference of DG inverter to (4), just like what is done in CCM method.

$$\begin{aligned}
 V_{out}^* &= G_{power}(s).(V_{ref\_f} - V_C) \\
 &+ G_{harmonic}(s).(I_{ref\_h} - I_{DG}) \\
 &+ G_{damping}(s) I_{Ind}
 \end{aligned} \tag{9}$$

In this case, DG acts like a small virtual impedance at the selected harmonic frequencies to absorb the harmonic currents, making PCC voltage harmonic free. As the current reference for HCM is the same as for CCM, then  $I_{ref\_h}$  is calculated just as the one explained about CCM in Fig. 7, even though there are some advantages in using HCM method that will be mentioned in next section.

When HCM is used to compensate local load harmonics, it is able to provide some unique benefits, if  $I_{ref\_h}$  in (9) is replaced by harmonic content of local load currents, most of the harmonics produced by local loads can be

compensated and a harmonic free  $I_{MG}$  will be delivered to PCC. Since the harmonic current control loop has a small gain for fundamental frequencies, measured local load  $I_{Local}$  by itself can be considered as  $I_{ref\_h}$  for controlling harmonic current without using harmonic extractor block  $H_D(s)$  in HCM. Harmonic compensation by this method has a great benefit over CCM and VCM, and it makes HCM attractive and cost-effective for controlling medium scaled DG units' inverters with limited computational power. It should be noticed that, active damping element has only a proportional controller that influences both the fundamental voltage control path and the harmonic current control path. The detailed operation of each compensation method is given in the following sections.

To compensate PCC voltage harmonics with HCM, harmonic current reference should be set as in (4) ( $I_{ref\_h} = H_D(s) \cdot (V_{PCC} / R_V)$ ). In this case, DG unit works as a small virtual resistive impedance at the selected harmonic frequency and can easily compensate PCC voltage harmonics in a similar way like CCM method.

To locally compensate the load current with HCM, it is possible to set the  $I_{ref\_h}$  in (9) to local load harmonic current.

This term will control the DG unit to compensate local load current harmonics leaving an improved  $I_{MG}$  to the PCC.

Since the local load harmonic compensation loop has a small gain in fundamental frequency, there is no need to use a harmonic extractor block to obtain harmonic load current and the measured line current  $I_{Local}$  can represent the harmonic current. Then it can be used as the current reference  $I_{ref\_h}$  in (9), this is an outstanding characteristic of this method that gives preference to HCM in comparison with other methods.

It is possible to reject DG harmonic current by setting a proper reference current for DG controller. If  $I_{ref\_h}$  is set to zero, most of the DG harmonic current is rejected. It is somehow like CCM, where DG current is fully sinusoidal and main grid provides all harmonic current of the nonlinear loads.

The other advantage of HCM is that it can be used instead as CCM by simply replacing the first term (9) with the fundamental current. So the fundamental and harmonic currents can be controlled separately but in this case, as a characteristic of HCM there is no need for harmonic extraction block in local load harmonic compensation. Finally, a brief comparison is presented in Table. 2 to verify the capabilities of each method in satisfying the objectives of controlling DG units. Afterward, a brief comparison of advantages and disadvantages of each method is presented in Table. 3. Each of control methods has benefits over the others but there should always be a tradeoff between complexity of control, easy implementation and costs. When there is no need to have control over voltage there is no

need to handle control complexity of HCM instead of using simple CCM, or when it is related to stand alone microgrids, maybe VCM is the best option. Fig 14 presents a classification of PQI devices by considering the functionality and development year also.

### **2.3.5 Harmonic current sharing among DGs**

For harmonic sharing between multiple DGs, when multiple DG units are responsible for harmonic compensation, it should be divided between DGs in relation based on the DG compensation capacity. For example, when compensating PCC voltage harmonic by means of several DG units, the virtual impedance of each DG should be in reverse proportion to its available current for compensating. It is simple to use the virtual resistor to share harmonic currents between multiple DGs by means of the hierarchical controller. Although this method needs a low band-width communication system to transmit data such as the value of the virtual resistor and therefore it is somehow unreliable in the case of communication unavailability [152, 173, 175]. There is an alternative for this method to use droop control in steady state control of harmonic current sharing as a secondary control which is needless of communication system [199, 200].

When it is up to practical use of these compensation methods to share harmonic currents between multiple DGs, some other important factors have an effect on the harmonic sharing process, such as location of sensitive loads, feeder power losses, economical dispatch, existing active/passive harmonic filters and voltage regulators. To have the best harmonic current sharing between multiple DGs, considering these factors, an optimization in setting value of virtual impedance is essential [201, 202]. Although some other consideration should be taken into account. For example, it is important that in the case virtual impedance is not supposed fully resistive, the phase angle of multiple virtual impedances should be equal to avoid circulating current between DGs [171, 203].

A thorough comparison of different PQI devices introduced up to date is presented in Table. 4. Almost all of these devices can regulate the grid voltage and some harmonic compensation besides P and Q compensation but some of these capabilities are unique between PQIs such as Selective harmonic compensation (SHE) and load feeding. Finally, it should be noted that using multifunctional DGs will increase the cost efficiency of using DGs, on the other hand, it helps improving distribution system power quality without the need to add other utilities to the grid. In the future, it will be essential to create conditions that not only the grid side but also the utility and DG owners benefit from using DGs for improving distribution system power quality.

Another detailed comparison between PQI devices is presented in Table. 5, in this table two aspects are added in comparison columns, as distributed PQI nature and cos-effectiveness. Distributed PQI nature refers to the case that a PQI device is distributed all over the grid, this state not only depends on its capability and size but also depends on its cost. Hybrid filter can be installed all over the grid but it may cost a lot and it is not effective, so hybrid filter does not qualify as a distributed PQI device, as a contrary MFDGs will be an inevitable part of future grids, and because almost no hardware is installed other than the RES control converters, it seems to be more cos-effective than devices like APF, STATCOM and SVC. In this table cos-effectiveness index 1 refers to the cheapest PQI device in comparison to its capabilities, So MFDGs may have the highest cos-effectiveness index due to not adding expensive hardware to microgrid and many capabilities these devices will add to a microgrid.

### **3. Conclusion and Future Trends**

In this paper, in-depth analysis and comparison is done between different methods of distribution power system power quality improvement methods that have been introduced till now. To do so, a timeline figure of these devices is provided that is categorized into three main generations, every generation of PI devices include several devices for which applications, advantages and disadvantages are explained. Because of the growing popularity of renewable energy sources main concentration of this paper was on reviewing the methods which have been applied to control the multi-functional DG units. In this regard, different control methods of inverter-based renewable energy sources are studied in detail by considering the effecting domain and application. Advantages and disadvantages of each method are exposed. Finally, a thorough comparison is done between DPQI (distributed power quality improvement) methods introduced up to now.

Since the future power electrical grids are moving toward smaller, renewable energy based microgrids, the concentration on the power quality issues of these microgrids is inevitable, so far several of these devices has been introduced and used but as the costs increase, power electronic converters play an important role in decision making for the future grid technologies. For cost affordable PQI in distribution level, maybe the best option is to use some multi-functional devices such as MFDGs, but there are several issues to be considered, like communication and online metering as an important part of control methods, or maybe trying some new control methods independent or at least, less dependent on communication and online metering. So improvements in infrastructures of smart electricity grid such as communication devices with online metering and monitoring will take a great amount of researchers'

concentration. Another concern could be the computational limit of PQI devices in the past, but as the computational limits of controllers are going up by time, it may seem reasonable to get much of the computational capabilities of controllers to improve the operation of the microgrids without considering it as a limit, an example of this is the application of model predictive control in power electronics in last years. To add some levels of extra reliability to microgrids and PQI issues, adding some storage devices or UPS systems will be a good idea, since maintaining these storage sources will be costly, so storage device operation improvement could be also a future trend. New generations of UPS systems which can help improve the power quality without feeding total load power may be a possible solution.

## References

- [1] EN B. 50160: Voltage Characteristics of Electricity Supplied by Public Distribution Systems. British Standards Institution. 2000.
- [2] Agarwal A, Kumar S, Ali S. A Research Review of Power Quality Problems in Electrical Power System. MIT International Journal of Electrical and Instrumentation Engineering. 2012;2:88-93.
- [3] Chauhan RK, Pandey J. Mitigation of Power Quality Problems Using FACTS Devices: A Review.
- [4] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems - Redline. IEEE Std 519-2014 (Revision of IEEE Std 519-1992) - Redline. 2014:1-213.
- [5] Sakthivel K, Das SK, Kini K. Importance of quality AC power distribution and understanding of EMC standards IEC 61000-3-2, IEC 61000-3-3 and IEC 61000-3-11. Electromagnetic Interference and Compatibility, 2003 INCEMIC 2003 8th International Conference on: IEEE; 2003. p. 423-30.
- [6] IEEE Draft Guide for Testing the Electrical, Mechanical, and Durability Performance of Wildlife Protective Devices on Overhead Power Distribution Systems Rated up to 38kV. IEEE P1656/D10, August 2010. 2010:1-14.
- [7] Compatibility E. Part 4-30: Testing and Measurement Techniques—Power Quality Measurement Methods. IEC Standard. 2008:61000-4.
- [8] Halpin SM. Comparison of IEEE and IEC harmonic standards. IEEE Power Engineering Society General Meeting, 2005:2005. p. 2214-6 Vol. 3.
- [9] Balasubramaniam P, Prabha S. Power Quality Issues, Solutions and Standards: A Technology Review. Journal of Applied Engineering Sciences 2015;18:371-80.
- [10] Wyk JDV. Power quality, power electronics and control. 1993 Fifth European Conference on Power Electronics and Applications 1993. p. 17-32 vol.1.
- [11] Mauthe G, Heinemann L, Westermann D. Economical power quality enhancement in MV distribution networks by power electronics solutions. 16th International Conference and Exhibition on Electricity Distribution, 2001 Part 1: Contributions CIRED (IEE Conf Publ No 482)2001. p. 5 pp. vol.2.
- [12] Dahidah MSA, Agelidis VG. Selective Harmonic Elimination PWM Control for Cascaded Multilevel Voltage Source Converters: A Generalized Formula. IEEE Transactions on Power Electronics. 2008;23:1620-30.
- [13] Ebadpour M, Sharifian MBB, Hosseini SH. A new structure of multilevel inverter with reduced number of switches for electric vehicle applications. Energy and Power Engineering. 2011;3:198.
- [14] Naderi Y, Hosseini SH, Mahari A, Naderi R. A new strategy for harmonic minimization based on triple switching of multilevel converters. Electrical Engineering (ICEE), 2013 21st Iranian Conference on: IEEE; 2013. p. 1-6.
- [15] Hosseini SH, Ravadanegh SN, Karimi M, Naderi Y, Oskuee MRJ. A new scheme of symmetric multilevel inverter with reduced number of circuit devices. Electrical and Electronics Engineering (ELECO), 2015 9th International Conference on: IEEE; 2015. p. 1072-8.
- [16] Savaghebi M, Vasquez JC, Jalilian A, Guerrero JM, Lee T-L. Selective harmonic virtual impedance for voltage source inverters with LCL filter in microgrids. Energy Conversion Congress and Exposition (ECCE), 2012 IEEE: IEEE; 2012. p. 1960-5.
- [17] Temerbaev S, Dovgun V. Improvement of power quality in distributed generation systems using hybrid power filters. Harmonics and Quality of Power (ICHQP), 2014 IEEE 16th International Conference on: IEEE; 2014. p. 694-8.
- [18] Lee T-L, Yang S-S, Hu S-H. Design of decentralized voltage control for pv inverters to mitigate voltage rise in distribution power system without communication. Power Electronics Conference (IPEC-Hiroshima 2014-ECCE-ASIA), 2014 International: IEEE; 2014. p. 2606-9.
- [19] Elbaset AA, Hassan M. Design and Power Quality Improvement of Photovoltaic Power System. Springer; 2016.
- [20] Tiwari AK, Jhala A. Improvement of Power Quality in Distribution System with Grid Connected RES.
- [21] Zin AAM, Naderipour A, Habibuddin MB, Khajehzadeh A. DESIGN A NEW COMPENSATION CONTROL STRATEGY FOR GRID-CONNECTED WT AND MT INVERTERS AT THE MICROGRID. 2006.
- [22] Singh M, Khadkikar V, Chandra A, Varma RK. Grid interconnection of renewable energy sources at the distribution level with power-quality improvement features. Power Delivery, IEEE Transactions on. 2011;26:307-15.
- [23] Smallwood CL. Distributed generation in autonomous and nonautonomous microgrids. Rural Electric Power Conference, 2002 IEEE: IEEE; 2002. p. D1-.

- [24] Wang X, Guerrero JM, Blaabjerg F, Chen Z. A review of power electronics based microgrids. *Journal of Power Electronics*. 2012;12:181-92.
- [25] Utama NPS, Hartati RS, Ariastina WG, Swamardika IBA, Penangsang O. A Review on Model of Integrating Renewable Distributed Generation into Bali's Power Distribution Systems: Issues, Challenges, and Possible Solutions. *Indonesian Journal of Electrical Engineering and Computer Science*. 2016;4:245-55.
- [26] Akagi H. New trends in active filters for improving power quality. *Power Electronics, Drives and Energy Systems for Industrial Growth, 1996, Proceedings of the 1996 International Conference on: IEEE; 1996*. p. 417-25.
- [27] Waware M, Agarwal P. Power quality survey and harmonic compensation in high power system.
- [28] Tembhurnikar G, Chaudari A, Wani N, Gajare A. A review on Reactive Power Compensation Techniques using FACTS devices. *International Journal of Engineering and Management Research*. 2014;4:76-80.
- [29] Singh B, Al-Haddad K, Chandra A. A review of active filters for power quality improvement. *IEEE transactions on industrial electronics*. 1999;46:960-71.
- [30] Dixon J, Moran L, Rodriguez J, Domke R. Reactive power compensation technologies: State-of-the-art review. *Proceedings of the IEEE*. 2005;93:2144-64.
- [31] Vivek M, Srividhya DP. Power Quality Improvement Techniques in Hybrid Systems—A Review. *International Journal of Advanced Technology & Engineering Research (IJATER)*. 2013;3.
- [32] Arulkumar K, Vijayakumar D, Palanisamy K. Recent advances and control techniques in grid connected PV system—A review. *International Journal of Renewable Energy Research (IJRER)*. 2016;6:1037-49.
- [33] Yang-Wen W, Man-Chung W, Chi-Seng L. Historical review of parallel hybrid active power filter for power quality improvement. *TENCON 2015 - 2015 IEEE Region 10 Conference 2015*. p. 1-6.
- [34] Singh B, Singh BN, Chandra A, Al-Haddad K, Pandey A, Kothari DP. A review of three-phase improved power quality AC-DC converters. *IEEE Transactions on industrial electronics*. 2004;51:641-60.
- [35] Cagnano A, De Tuglie E. A decentralized voltage controller involving PV generators based on Lyapunov theory. *Renewable energy*. 2016;86:664-74.
- [36] Cagnano A, De Tuglie E. Centralized voltage control for distribution networks with embedded PV systems. *Renewable Energy*. 2015;76:173-85.
- [37] Hosseini YNSH, Zadeh SG, Mohammadi-Ivatlo B, Vasquez JC, Guerrero JM. Distributed power quality improvement in residential microgrids. *Electrical and Electronics Engineering (ELECO), 2017 10th International Conference on: IEEE; 2017*. p. 90-4.
- [38] Mousavi SYM, Jalilian A, Savaghebi M, GE JMG. Autonomous Control of Current and Voltage Controlled DG Interface Inverters for Reactive Power Sharing and Harmonics Compensation in Islanded Microgrids. *IEEE Transactions on Power Electronics*. 2018.
- [39] Lasseter RH, Eto JH, Schenkman B, Stevens J, Vollkommer H, Klapp D, et al. CERTS microgrid laboratory test bed. *IEEE Transactions on Power Delivery*. 2011;26:325-32.
- [40] IEEE Draft Standard for the Testing of Microgrid Controllers. *IEEE P20308/D11, February 2018*. 2018:1-44.
- [41] Bracco S, Brignone M, Delfino F, Procopio R. An Energy Management System for the Savona Campus Smart Polygeneration Microgrid. *IEEE Systems Journal*. 2017;11:1799-809.
- [42] Cagnano A, De Tuglie E, Dicorato M, Forte G, Trovato M. PrInCE Lab experimental microgrid Planning and operation issues. *Environment and Electrical Engineering (EEEIC), 2015 IEEE 15th International Conference on: IEEE; 2015*. p. 1671-6.
- [43] Meng L, Luna A, Diaz ER, Sun B, Dragicevic T, Savaghebi M, et al. Flexible system integration and advanced hierarchical control architectures in the microgrid research laboratory of aalborg university. *IEEE Transactions on Industry Applications*. 2016;52:1736-49.
- [44] Jiang T, Costa L, Tordjman P, Venkata S, Siebert N, Kumar J, et al. A Microgrid Test bed in Singapore: An electrification project for affordable access to electricity with optimal asset management. *IEEE Electrification Magazine*. 2017;5:74-82.
- [45] Saha SS, Suryavanshi R. Power system harmonic mitigation of an offshore oil rig using passive shunt filter. *2010 Annual IEEE India Conference (INDICON)2010*. p. 1-5.
- [46] Fang J, Li X, Tang Y. A review of passive power filters for voltage-source converters. *2016 Asian Conference on Energy, Power and Transportation Electrification (ACEPT)2016*. p. 1-6.
- [47] Kumar D, Zare F. Analysis of harmonic mitigations using hybrid passive filters. *2014 16th International Power Electronics and Motion Control Conference and Exposition 2014*. p. 945-51.

- [48] Li D, Yang K, Zhu ZQ, Qin Y. A Novel Series Power Quality Controller With Reduced Passive Power Filter. *IEEE Transactions on Industrial Electronics*. 2017;64:773-84.
- [49] Beres RN, Wang X, Blaabjerg F, Liserre M, Bak CL. Optimal Design of High-Order Passive-Damped Filters for Grid-Connected Applications. *IEEE Transactions on Power Electronics*. 2016;31:2083-98.
- [50] Beres RN, Wang X, Liserre M, Blaabjerg F, Bak CL. A Review of Passive Power Filters for Three-Phase Grid-Connected Voltage-Source Converters. *IEEE Journal of Emerging and Selected Topics in Power Electronics*. 2016;4:54-69.
- [51] Mboving CSA, Hanzelka Z. Different approaches for designing the passive power filters. 2015 International School on Nonsinusoidal Currents and Compensation (ISNCC)2015. p. 1-6.
- [52] Yang NC, Le MD. Multi-objective bat algorithm with time-varying inertia weights for optimal design of passive power filters set. *IET Generation, Transmission & Distribution*. 2015;9:644-54.
- [53] Rizk G, Salameh S, Kanaan HY, Rachid EA. Design of passive power filters for a three-phase semi-controlled rectifier with typical loads. 2014 9th IEEE Conference on Industrial Electronics and Applications2014. p. 590-5.
- [54] Li S, Yongan L, Xiaodong L, Lilin Z, Zhengping H. Multi-objective optimal design for passive power filters in hybrid power filter system based on multi-island particle swarm optimization. *Proceedings of The 7th International Power Electronics and Motion Control Conference*2012. p. 2859-63.
- [55] He N, Xu D, Huang L. The application of particle swarm optimization to passive and hybrid active power filter design. *Industrial Electronics, IEEE Transactions on*. 2009;56:2841-51.
- [56] Patil GA, Bhosale YN, Bolaj VS. Passive filter design to mitigate harmonics in three phase induction furnace. 2017 International Conference on Circuit ,Power and Computing Technologies (ICCPCT)2017. p. 1-6.
- [57] Xiaozhi G, Linchuan L, Wenyan C. Power Quality Improvement for Microgrid in Islanded Mode. *Procedia Engineering*. 2011;23:174-9.
- [58] Lee T-L, Cheng P-T, Akagi H, Fujita H. A dynamic tuning method for distributed active filter systems. *Industry Applications, IEEE Transactions on*. 2008;44:612-23.
- [59] Lee T-L, Hu S-H. An active filter with resonant current control to suppress harmonic resonance in a distribution power system. *IEEE Journal of Emerging and Selected Topics in Power Electronics*. 2016;4:198-209.
- [60] Dash R, Paikray P, Swain SC. Active power filter for harmonic mitigation in a distributed power generation system. 2017 Innovations in Power and Advanced Computing Technologies (i-PACT)2017. p. 1-6.
- [61] Bai H, Wang X, Blaabjerg F. A Grid-Voltage-Sensorless Resistive-Active Power Filter With Series LC-Filter. *IEEE Transactions on Power Electronics*. 2018;33:4429-40.
- [62] Morán L, Dixon J, Torres M. 41 - Active Power Filters A2 - Rashid, Muhammad H. *Power Electronics Handbook (Fourth Edition)*: Butterworth-Heinemann; 2018. p. 1341-79.
- [63] Tang Y, Loh PC, Wang P, Choo FH, Gao F, Blaabjerg F. Generalized design of high performance shunt active power filter with output LCL filter. *Industrial Electronics, IEEE Transactions on*. 2012;59:1443-52.
- [64] Angulo M, Ruiz-Caballero DA, Lago J, Heldwein ML, Mussa SA. Active power filter control strategy with implicit closed-loop current control and resonant controller. *Industrial Electronics, IEEE Transactions on*. 2013;60:2721-30.
- [65] Hirofumi A, Edson Hirokazu W, Mauricio A. Shunt Active Filters. *Instantaneous Power Theory and Applications to Power Conditioning*: Wiley-IEEE Press; 2007. p. 109-220.
- [66] Campanhol LBG, Silva SAOd, Goedel A. Application of shunt active power filter for harmonic reduction and reactive power compensation in three-phase four-wire systems. *IET Power Electronics*. 2014;7:2825-36.
- [67] Salmeron P, Litran SP. Improvement of the Electric Power Quality Using Series Active and Shunt Passive Filters. *IEEE Transactions on Power Delivery*. 2010;25:1058-67.
- [68] Ketzer MB, Jacobina CB. Sensorless current shaping control technique for shunt active filters. 2014 11th IEEE/IAS International Conference on Industry Applications2014. p. 1-7.
- [69] Gotherwal N, Ray S, Gupta N, Saxena D. Performance comparison of PI and fuzzy controller for indirect current control based shunt active power filter. 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)2016. p. 1-6.
- [70] Tarisciotti L, Formentini A, Gaeta A, Degano M, Zanchetta P, Rabbeni R, et al. Model Predictive Control for Shunt Active Filters With Fixed Switching Frequency. *IEEE Transactions on Industry Applications*. 2017;53:296-304.
- [71] Biricik S, Komurcugil H. Three-level hysteresis current control strategy for three-phase four-switch shunt active filters. *IET Power Electronics*. 2016;9:1732-40.
- [72] Tilli A, Conficoni C. Control of Shunt Active Filters With Actuation and Current Limits. *IEEE Transactions on Control Systems Technology*. 2016;24:644-53.

- [73] Ronchi F, Tilli A, Marconi L. Control of shunt active filter based on the internal model principle: Tuning procedure and experimental results. 2003 European Control Conference (ECC)2003. p. 2327-32.
- [74] Panigrahi R, Subudhi B. Performance Enhancement of Shunt Active Power Filter Using a Kalman Filter-Based  $H_{\infty}$  Control Strategy. IEEE Transactions on Power Electronics. 2017;32:2622-30.
- [75] Bhattacharya S, Cheng P-T, Divan DM. Hybrid solutions for improving passive filter performance in high power applications. Industry Applications, IEEE Transactions on. 1997;33:732-47.
- [76] Shukla S, Mishra S, Singh B, Kumar S. Implementation of Empirical Mode Decomposition Based Algorithm for Shunt Active Filter. IEEE Transactions on Industry Applications. 2017;PP:1-.
- [77] Ko WH, Gu JC. Impact of Shunt Active Harmonic Filter on Harmonic Current Distortion of Voltage Source Inverter-Fed Drives. IEEE Transactions on Industry Applications. 2016;52:2816-25.
- [78] Mane M, Namboothiripad MK. Current harmonics reduction using sliding mode control based shunt active power filter. 2016 10th International Conference on Intelligent Systems and Control (ISCO)2016. p. 1-6.
- [79] Hao S, Fu Z, Wang Q, Zheng J, Zhang M. A Novel Control Strategy for Shunt Active Power Filter under Nonlinear and Unbalanced Three Phase Load Conditions. 2016 International Symposium on Computer, Consumer and Control (IS3C)2016. p. 96-8.
- [80] Gowtham N, Shankar S. PI tuning of Shunt Active Filter using GA and PSO algorithm. 2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB)2016. p. 207-13.
- [81] Fabricio ELL, Júnior SCS, Jacobina CB, Corrêa MBdR. Analysis of Main Topologies of Shunt Active Power Filters Applied to Four-Wire Systems. IEEE Transactions on Power Electronics. 2018;33:2100-12.
- [82] Tian J, Chen Q, Xie B. Series hybrid active power filter based on controllable harmonic impedance. IET Power Electronics. 2012;5:142-8.
- [83] Mulla MA, Rajagopalan C, Chowdhury A. Hardware implementation of series hybrid active power filter using a novel control strategy based on generalised instantaneous power theory. IET Power Electronics. 2013;6:592-600.
- [84] Javadi A, Hamadi A, Ndtoungou A, Al-Haddad K. Power Quality Enhancement of Smart Households Using a Multilevel-THSeAF With a PR Controller. IEEE Transactions on Smart Grid. 2017;8:465-74.
- [85] Javadi A, Hamadi A, Woodward L, Al-Haddad K. Experimental Investigation on a Hybrid Series Active Power Compensator to Improve Power Quality of Typical Households. IEEE Transactions on Industrial Electronics. 2016;63:4849-59.
- [86] Aravind S, Vinatha U, Jayasankar VN. Wind-solar grid connected renewable energy system with series active self tuning filter. 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)2016. p. 1944-8.
- [87] Krishna AM, Prasad KNV, Kumar GR. Realization of cascaded H-bridge 5-level multilevel inverter as Series Active Filter. IET Chennai 3rd International on Sustainable Energy and Intelligent Systems (SEISCON 2012)2012. p. 1-8.
- [88] Reddy TD, Barai M. A novel configuration to eliminate dominant Harmonic frequency (DHF) by using FFT in series active filters. 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)2016. p. 1-5.
- [89] Nasiri M, Doroudi A, Sheikholahi H. A new control circuit for series active filters to eliminate voltage flicker and harmonics. 2012 Proceedings of 17th Conference on Electrical Power Distribution2012. p. 1-4.
- [90] Swain SD, Ray PK, Mohanty KB. Improvement of Power Quality Using a Robust Hybrid Series Active Power Filter. IEEE Transactions on Power Electronics. 2017;32:3490-8.
- [91] Akagi H, Fujita H, Nabae N. A combined system of shunt passive and series active filters-An alternative to shunt active filters. EUROPEAN CONFERENCE ON POWER ELECTRONICS AND APPLICATIONS: PROCEEDINGS PUBLISHED BY VARIOUS PUBLISHERS; 1992. p. 012-.
- [92] Shuai Z, Liu D, Shen J, Tu C, Cheng Y, Luo A. Series and parallel resonance problem of wideband frequency harmonic and its elimination strategy. Power Electronics, IEEE Transactions on. 2014;29:1941-52.
- [93] Lu J, Fu P, Li J, Mao H, Shen X, Xu L, et al. A new hybrid filter based on differential current control method for low-order harmonic suppression in Tokamak power system. International Journal of Energy Research. 2018;42:82-90.
- [94] Hasan KNM, Romlie MF. Comparative study on combined series active and shunt passive power filter using two different control methods. 2007 International Conference on Intelligent and Advanced Systems2007. p. 928-33.
- [95] Litran SP, Salmeron P, Vazquez JR, Herrera RS. A New Control for a Combined System of Shunt Passive and Series Active Filters. 2007 IEEE International Symposium on Industrial Electronics2007. p. 2463-8.

- [96] Al-Zamil AM, Torrey DA. A passive series, active shunt filter for high power applications. *IEEE Transactions on Power Electronics*. 2001;16:101-9.
- [97] Peng FZ, Akagi H, Nabae A. A new approach to harmonic compensation in power systems-a combined system of shunt passive and series active filters. *Industry Applications, IEEE Transactions on*. 1990;26:983-90.
- [98] Aliouane K, Saadate S, Davat B. Analytical study and numerical simulation of the static and dynamic performances of combined shunt passive and series active filters. *1994 Fifth International Conference on Power Electronics and Variable-Speed Drives*1994. p. 147-51.
- [99] Fujita H, Akagi H. Design strategy for the combined system of shunt passive and series active filters. *Conference Record of the 1991 IEEE Industry Applications Society Annual Meeting*1991. p. 898-903 vol.1.
- [100] Tanaka T, Akagi H. A new combined system of series active and shunt passive filters aiming at harmonic compensation for large capacity thyristor converters. *Industrial Electronics, Control and Instrumentation, 1991 Proceedings IECON '91, 1991 International Conference on*1991. p. 723-8 vol.1.
- [101] Tareen WUK, Mekhief S. Three-Phase Transformerless Shunt Active Power Filter With Reduced Switch Count for Harmonic Compensation in Grid-Connected Applications. *IEEE Transactions on Power Electronics*. 2018;33:4868-81.
- [102] Demirdelen T, İnci M, Bayındır KÇ, Tümay M. Review of hybrid active power filter topologies and controllers. *4th International Conference on Power Engineering, Energy and Electrical Drives*2013. p. 587-92.
- [103] Patel P, Mulla MA. A comparative study on different types of hybrid active power filters. *2012 IEEE International Conference on Engineering Education: Innovative Practices and Future Trends (AICERA)*2012. p. 1-6.
- [104] Hirofumi A, Edson Hirokazu W, Mauricio A. Hybrid and Series Active Filters. *Instantaneous Power Theory and Applications to Power Conditioning: Wiley-IEEE Press*; 2007. p. 221-63.
- [105] Silva CHd, Pereira RR, Silva LE, Torres GL, Pinto JOP. Modified synchronous reference frame strategy for selective-tuned single phase hybrid active power filter. *Industry Applications Society Annual Meeting, 2009 IAS 2009 IEEE: IEEE*; 2009. p. 1-5.
- [106] Ghandehari R, Jalil M, Naderi P. A novel structure for parallel hybrid active power filters with series resonant circuits. *The 5th Annual International Power Electronics, Drive Systems and Technologies Conference (PEDSTC 2014)*2014. p. 529-34.
- [107] Khederzadeh M, Sadeghi M. Virtual active power filter: a notable feature for hybrid ac/dc microgrids. *IET Generation, Transmission & Distribution*. 2016;10:3539-46.
- [108] Wang L, Lam CS, Wong MC, Dai NY, Lao KW, Wong CK. Non-linear adaptive hysteresis band pulse-width modulation control for hybrid active power filters to reduce switching loss. *IET Power Electronics*. 2015;8:2156-67.
- [109] Luo Z, Su M, Sun Y, Zhang W, Lin Z. Analysis and control of a reduced switch hybrid active power filter. *IET Power Electronics*. 2016;9:1416-25.
- [110] Wang L, Lam CS, Wong MC. Modeling and Parameter Design of Thyristor-Controlled LC-Coupled Hybrid Active Power Filter (TCLC-HAPF) for Unbalanced Compensation. *IEEE Transactions on Industrial Electronics*. 2017;64:1827-40.
- [111] Oruganti VSRV, Bubshait AS, Dhanikonda VSSSS, Simões MG. Real-time control of hybrid active power filter using conservative power theory in industrial power system. *IET Power Electronics*. 2017;10:196-207.
- [112] Wang L, Lam CS, Wong MC. Selective Compensation of Distortion, Unbalanced and Reactive Power of a Thyristor Controlled LC-Coupling Hybrid Active Power Filter (TCLC-HAPF). *IEEE Transactions on Power Electronics*. 2017;PP:1-.
- [113] Lam CS, Wong MC, Han YD. Hysteresis current control of hybrid active power filters. *IET Power Electronics*. 2012;5:1175-87.
- [114] Gee AM, Robinson F, Yuan W. A Superconducting Magnetic Energy Storage-Emulator/Battery Supported Dynamic Voltage Restorer. *IEEE Transactions on Energy Conversion*. 2017;32:55-64.
- [115] Kara A, Dahler P, Amhof D, Gruning H. Power supply quality improvement with a dynamic voltage restorer (DVR). *Applied Power Electronics Conference and Exposition, 1998 APEC '98 Conference Proceedings 1998, Thirteenth Annual*1998. p. 986-93 vol.2.
- [116] Carlos GAdA, Santos ECd, Jacobina CB, Mello JPRA. Dynamic Voltage Restorer Based on Three-Phase Inverters Cascaded Through an Open-End Winding Transformer. *IEEE Transactions on Power Electronics*. 2016;31:188-99.
- [117] Komurcugil H, Biricik S. Time-Varying and Constant Switching Frequency Based Sliding Mode Control Methods for Transformerless DVR Employing Half-Bridge VSI. *IEEE Transactions on Industrial Electronics*. 2016;PP:1-.

- [118] Jiang F, Tu C, Shuai Z, Cheng M, Lan Z, Xiao F. Multilevel Cascaded-Type Dynamic Voltage Restorer With Fault Current-Limiting Function. *IEEE Transactions on Power Delivery*. 2016;31:1261-9.
- [119] Galeshi S, Iman-Eini H. Dynamic voltage restorer employing multilevel cascaded H-bridge inverter. *IET Power Electronics*. 2016;9:2196-204.
- [120] Shahabadini M, Iman-Eini H. Improving the Performance of a Cascaded H-Bridge-Based Interline Dynamic Voltage Restorer. *IEEE Transactions on Power Delivery*. 2016;31:1160-7.
- [121] Babaei E, Kangarlu MF, Sabahi M. Dynamic voltage restorer based on multilevel inverter with adjustable dc-link voltage. *IET Power Electronics*. 2014;7:576-90.
- [122] Hietpas SM, Naden M. Automatic voltage regulator using an AC voltage-voltage converter. *IEEE Transactions on Industry Applications*. 2000;36:33-8.
- [123] Gozde H, Taplamacioglu MC, Ari M. Automatic Voltage Regulator (AVR) design with Chaotic Particle Swarm Optimization. *Proceedings of the 2014 6th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)2014*. p. 23-6.
- [124] Priyambada S, Mohanty PK, Sahu BK. Automatic voltage regulator using TLBO algorithm optimized PID controller. *2014 9th International Conference on Industrial and Information Systems (ICIIS)2014*. p. 1-6.
- [125] Majumdar S, Mandal K, Chakraborty N. Performance study of Mine Blast Algorithm for automatic voltage regulator tuning. *2014 Annual IEEE India Conference (INDICON)2014*. p. 1-6.
- [126] Ting-Chia O, Ta-Peng T, Chih-Ming H, Chiung-Hsing C. Hybrid control system for automatic voltage regulator in smart grid. *2013 International Conference on Machine Learning and Cybernetics2013*. p. 1103-8.
- [127] Khedr SFM, Ammar ME, Hassan MAM. Multi objective genetic algorithm controller's tuning for non-linear automatic voltage regulator. *2013 International Conference on Control, Decision and Information Technologies (CoDIT)2013*. p. 857-63.
- [128] Khalid A, Shahid AH, Zeb K, Ali A, Haider A. Comparative assessment of classical and adaptive controllers for Automatic Voltage Regulator. *2016 International Conference on Advanced Mechatronic Systems (ICAMEchS)2016*. p. 538-43.
- [129] Hosseini SH, Ajami A. Transient stability enhancement of AC transmission system using STATCOM. *TENCON '02 Proceedings 2002 IEEE Region 10 Conference on Computers, Communications, Control and Power Engineering2002*. p. 1809-12 vol.3.
- [130] Karve S. Three of a kind. *IEE Review*. 2000;46:27-31.
- [131] Bekiarov SB, Emadi A. Uninterruptible power supplies: classification, operation, dynamics, and control. *Applied Power Electronics Conference and Exposition, 2002 APEC 2002 Seventeenth Annual IEEE: IEEE; 2002*. p. 597-604.
- [132] Solter W. A new international UPS classification by IEC 62040-3. *Telecommunications Energy Conference, 2002 INTELEC 24th Annual International: IEEE; 2002*. p. 541-5.
- [133] Guerrero JM, Vicuna LGD, Uceda J. Uninterruptible power supply systems provide protection. *IEEE Industrial Electronics Magazine*. 2007;1:28-38.
- [134] Knight B. Uninterruptible-power-supply systems. *Electronics and Power*. 1982;28:529-31.
- [135] Bendrat F, Chhor J, Sourkounis C. Cascaded operation-mode-adaptive control for power conditioning systems with uninterruptible power supply capability. *Control and Automation (MED), 2017 25th Mediterranean Conference on: IEEE; 2017*. p. 774-80.
- [136] Rymarski Z, Bernacki K. Different approaches to modelling single-phase voltage source inverters for uninterruptible power supply systems. *IET Power Electronics*. 2016;9:1513-20.
- [137] Pichan M, Rastegar H. Sliding-Mode Control of Four-Leg Inverter With Fixed Switching Frequency for Uninterruptible Power Supply Applications. *IEEE Transactions on Industrial Electronics*. 2017;64:6805-14.
- [138] Aamir M, Mekhilef S. An online transformerless uninterruptible power supply (UPS) system with a smaller battery bank for low-power applications. *IEEE Transactions on Power Electronics*. 2017;32:233-47.
- [139] Amira IB, Lahyani A, Guermazi A. Fuel cell/supercapacitors combination in Uninterruptible Power Supply (UPS). *Sciences and Techniques of Automatic Control and Computer Engineering (STA), 2015 16th International Conference on: IEEE; 2015*. p. 707-14.
- [140] Bendrat F, Chhor J, Sourkounis C. LCL filter design for a modular power conditioning system with uninterruptible power supply capability. *Industrial Electronics Society, IECON 2017-43rd Annual Conference of the IEEE: IEEE; 2017*. p. 303-9.

- [141] Rahmat MK, Karim AZA, Salleh MNM. Sensitivity analysis of the AC uninterruptible power supply (UPS) reliability. Engineering Technology and Technopreneurship (ICE2T), 2017 International Conference on: IEEE; 2017. p. 1-6.
- [142] IEEE Standard for Qualification of Class 1E Static Battery Chargers, Inverters, and Uninterruptible Power Supply Systems for Nuclear Power Generating Stations. IEEE Std 650-2017 (Revision of IEEE Std 650-2006). 2018:1-61.
- [143] Da Silva CH, Pereira R, Silva L, Lambert-Torres G, Gonzatti R, Ferreira S, et al. Smart impedance: Expanding the hybrid active series power filter concept. IECON 2012-38th Annual Conference on IEEE Industrial Electronics Society: IEEE; 2012. p. 1416-21.
- [144] Gonzatti RB, Ferreira SC, da Silva CH, Pereira RR, da Silva LEB, Lambert-Torres G. Smart Impedance: A New Way to Look at Hybrid Filters.
- [145] Gonzatti RB, Ferreira SC, Silva CHd, Silva LEBd, Lambert-Torres G, Silva LGF. Smart impedance application on unbalanced harmonic mitigation in three-phase four-wire systems. 2013 IEEE Energy Conversion Congress and Exposition 2013. p. 1978-83.
- [146] Hui SY, Lee CK, Wu FF. Electric Springs-A New Smart Grid Technology. IEEE Transactions on Smart Grid. 2012;3:1552-61.
- [147] Kanjiya P, Khadkikar V. Enhancing power quality and stability of future smart grid with intermittent renewable energy sources using electric springs. Renewable Energy Research and Applications (ICRERA), 2013 International Conference on: IEEE; 2013. p. 918-22.
- [148] Lee CK, Chaudhuri B, Hui SY. Hardware and control implementation of electric springs for stabilizing future smart grid with intermittent renewable energy sources. Emerging and Selected Topics in Power Electronics, IEEE Journal of. 2013;1:18-27.
- [149] Lee CK, Cheng KL, Ng WM. Load characterisation of electric spring. Energy Conversion Congress and Exposition (ECCE), 2013 IEEE: IEEE; 2013. p. 4665-70.
- [150] Ferreira S, Gonzatti R, Silva C, Silva L, Lambert-Torres G, Silva L. Adaptive Notch filter applied to hybrid active var compensator under nonsinusoidal and unbalanced conditions. Energy Conversion Congress and Exposition (ECCE), 2013 IEEE: IEEE; 2013. p. 2264-9.
- [151] Zmood DN, Holmes DG, Bode GH. Frequency-domain analysis of three-phase linear current regulators. Industry Applications, IEEE Transactions on. 2001;37:601-10.
- [152] Savaghebi M, Jalilian A, Vasquez JC, Guerrero JM. Secondary control for voltage quality enhancement in microgrids. Smart Grid, IEEE Transactions on. 2012;3:1893-902.
- [153] Yan S, Tan SC, Lee CK, Chaudhuri B, Hui SY. Use of Smart Loads for Power Quality Improvement. IEEE Journal of Emerging and Selected Topics in Power Electronics. 2017;5:504-12.
- [154] Mok KT, Wang M, Tan SC, Hui SY. DC Electric Springs - A New Technology for Stabilizing DC Power Distribution Systems. IEEE Transactions on Power Electronics. 2016;PP:1-.
- [155] Heffner GC, Goldman C, Moezzi MM. Innovative approaches to verifying demand response of water heater load control. Power Delivery, IEEE Transactions on. 2006;21:388-97.
- [156] Mok KT, Wang MH, Tan SC, Hui SY. DC electric springs - An emerging technology for DC grids. 2015 IEEE Applied Power Electronics Conference and Exposition (APEC) 2015. p. 684-90.
- [157] Lin P, Jin C, Xiao J, Li X, Shi D, Tang Y, et al. A Distributed Control Architecture for Global System Economic Operation in Autonomous Hybrid AC/DC Microgrids. IEEE Transactions on Smart Grid. 2018;PP:1-.
- [158] Saleh M, Esa Y, Mohamed A. Communication Based Control for DC Microgrids. IEEE Transactions on Smart Grid. 2018;PP:1-.
- [159] Sahoo S, Prakash S, Mishra S. Power Quality Improvement of Grid-Connected DC Microgrids Using Repetitive Learning-Based PLL Under Abnormal Grid Conditions. IEEE Transactions on Industry Applications. 2018;54:82-90.
- [160] Wang MH, Tan SC, Lee CK, Hui SY. A Configuration of Storage System for DC Microgrids. IEEE Transactions on Power Electronics. 2018;33:3722-33.
- [161] Hosseini-pour A, Hojabri H. Virtual inertia control of PV systems for dynamic performance and damping enhancement of DC microgrids with constant power loads. IET Renewable Power Generation. 2018;12:430-8.
- [162] He J, Li YW, Munir MS. A flexible harmonic control approach through voltage-controlled DG-grid interfacing converters. Industrial Electronics, IEEE Transactions on. 2012;59:444-55.
- [163] Zeng Z, Yang H, Guerrero JM, Zhao R. Multi-functional distributed generation unit for power quality enhancement. IET Power Electronics. 2015;8:467-76.

- [164] Olek B, Wierzbowski M. Local Energy Balancing and Ancillary Services in Low-Voltage Networks With Distributed Generation, Energy Storage, and Active Loads. *Industrial Electronics, IEEE Transactions on*. 2015;62:2499-508.
- [165] Trinh QN, Lee HH. An Advanced Current Control Strategy for Three-Phase Shunt Active Power Filters. *IEEE Transactions on Industrial Electronics*. 2013;60:5400-10.
- [166] He J, Li YW, Blaabjerg F, Wang X. Active harmonic filtering using current-controlled, grid-connected DG units with closed-loop power control. *Power Electronics, IEEE Transactions on*. 2014;29:642-53.
- [167] Shitole A, Suryawanshi HM, Talapur G, s s, Ballal M, Borghate VB, et al. Grid Interfaced Distributed Generation System with Modified Current Control Loop using Adaptive Synchronization Technique. *IEEE Transactions on Industrial Informatics*. 2017;PP:1-.
- [168] Castilla M, Miret J, Camacho A, Matas J, Vicuna LGd. Reduction of Current Harmonic Distortion in Three-Phase Grid-Connected Photovoltaic Inverters via Resonant Current Control. *IEEE Transactions on Industrial Electronics*. 2013;60:1464-72.
- [169] Xing X, Zhang C, He J, Chen A, Zhang Z. Model predictive control for parallel three-level T-type grid-connected inverters in renewable power generations. *IET Renewable Power Generation*. 2017;11:1353-63.
- [170] Vasquez JC, Guerrero JM, Luna A, Rodríguez P, Teodorescu R. Adaptive droop control applied to voltage-source inverters operating in grid-connected and islanded modes. *Industrial Electronics, IEEE Transactions on*. 2009;56:4088-96.
- [171] He J, Li YW. Analysis, design, and implementation of virtual impedance for power electronics interfaced distributed generation. *Industry Applications, IEEE Transactions on*. 2011;47:2525-38.
- [172] He J, Li YW. Hybrid voltage and current control approach for DG-grid interfacing converters with LCL filters. *Industrial Electronics, IEEE Transactions on*. 2013;60:1797-809.
- [173] Wang X, Blaabjerg F, Chen Z, Guerrero JM. A centralized control architecture for harmonic voltage suppression in islanded microgrids. *IECON 2011-37th Annual Conference on IEEE Industrial Electronics Society: IEEE*; 2011. p. 3070-5.
- [174] Guerrero JM, Chandorkar M, Lee T-L, Loh PC. Advanced control architectures for intelligent microgrids, part I: decentralized and hierarchical control. *IEEE Transactions on Industrial Electronics*. 2013;60:1254-62.
- [175] Guerrero JM, Vasquez JC, Matas J, Vicuna D, García L, Castilla M. Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization. *Industrial Electronics, IEEE Transactions on*. 2011;58:158-72.
- [176] Savaghebi M, Jalilian A, Vasquez JC, Guerrero JM. Secondary control scheme for voltage unbalance compensation in an islanded droop-controlled microgrid. *IEEE Transactions on Smart Grid*. 2012;3:797-807.
- [177] Zhao X, Meng L, Guerrero JM, Savaghebi M, Vasquez JC, Xie C, et al. An Embedded Voltage Harmonic Compensation Strategy for Current Controlled DG Interfacing Converters. *Proceedings of 8th Annual IEEE Energy Conversion Congress & Exposition: IEEE*; 2016.
- [178] Meng L, Tang F, Savaghebi M, Vasquez JC, Guerrero JM. Tertiary control of voltage unbalance compensation for optimal power quality in islanded microgrids. *IEEE Transactions on Energy Conversion*. 2014;29:802-15.
- [179] Guerrero JM, Loh PC, Lee T-L, Chandorkar M. Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids. *IEEE Transactions on Industrial Electronics*. 2013;60:1263-70.
- [180] Li YW, He J. Distribution system harmonic compensation methods: An overview of DG-interfacing inverters. *IEEE industrial electronics magazine*. 2014;8:18-31.
- [181] Han Y, Li H, Shen P, Coelho EAA, Guerrero JM. Review of Active and Reactive Power Sharing Strategies in Hierarchical Controlled Microgrids. *IEEE Transactions on Power Electronics*. 2017;32:2427-51.
- [182] Falkowski P, Sikorski A. Finite Control Set Model Predictive Control for Grid-Connected AC&#8211;DC Converters With LCL Filter. *IEEE Transactions on Industrial Electronics*. 2018;65:2844-52.
- [183] Lei M, Yang Z, Wang Y, Xu H, Meng L, Vasquez JC, et al. An MPC-Based ESS Control Method for PV Power Smoothing Applications. *IEEE Transactions on Power Electronics*. 2018;33:2136-44.
- [184] Aguilera RP, Acuña P, Lezana P, Konstantinou G, Wu B, Bernet S, et al. Selective harmonic elimination model predictive control for multilevel power converters. *IEEE Transactions on Power Electronics*. 2017;32:2416-26.
- [185] Kouro S, Cortes P, Vargas R, Ammann U, Rodriguez J. Model Predictive Control&#x2014;A Simple and Powerful Method to Control Power Converters. *IEEE Transactions on Industrial Electronics*. 2009;56:1826-38.

- [186] Zarnaghi YN, Hosseini SH, Zadeh SG, Mohammadi-Ivatloo B, Quintero JCV, Guerrero JM. Distributed Power Quality Improvement in Residential Microgrids. Eleco 2017 10th International IEEE Conference on Electrical and Electronics Engineering: IEEE; 2017.
- [187] Akagi H. Control strategy and site selection of a shunt active filter for damping of harmonic propagation in power distribution systems. Power Delivery, IEEE Transactions on. 1997;12:354-63.
- [188] Wada K, Fujita H, Akagi H. Considerations of a shunt active filter based on voltage detection for installation on a long distribution feeder. IEEE Transactions on Industry Applications. 2002;38:1123-30.
- [189] Li Y, Vilathgamuwa DM, Loh PC. Design, analysis, and real-time testing of a controller for multibus microgrid system. Power electronics, IEEE transactions on. 2004;19:1195-204.
- [190] Gao F, Irvani MR. A control strategy for a distributed generation unit in grid-connected and autonomous modes of operation. Power Delivery, IEEE Transactions on. 2008;23:850-9.
- [191] Zhong QC, Weiss G. Synchronous inverters: Inverters that mimic synchronous generators. Industrial Electronics, IEEE Transactions on. 2011;58:1259-67.
- [192] Li Y, Vilathgamuwa DM, Loh PC. Design, analysis, and real-time testing of a controller for multibus microgrid system. IEEE Transactions on Power Electronics. 2004;19:1195-204.
- [193] Li YW, Kao C-N. An accurate power control strategy for power-electronics-interfaced distributed generation units operating in a low-voltage multibus microgrid. Power Electronics, IEEE Transactions on. 2009;24:2977-88.
- [194] Guerrero JM, De Vicuna LG, Matas J, Castilla M, Miret J. Output impedance design of parallel-connected UPS inverters with wireless load-sharing control. IEEE Transactions on industrial electronics. 2005;52:1126-35.
- [195] He J, Li YW. Generalized closed-loop control schemes with embedded virtual impedances for voltage source converters with LC or LCL filters. Power Electronics, IEEE Transactions on. 2012;27:1850-61.
- [196] Yao Z, Xiao L. Control of single-phase grid-connected inverters with nonlinear loads. Industrial Electronics, IEEE Transactions on. 2013;60:1384-9.
- [197] He J, Li Y, Bosnjak D, Harris B. Investigation and active damping of multiple resonances in a parallel-inverter-based microgrid. Power Electronics, IEEE Transactions on. 2013;28:234-46.
- [198] Li Z, Li Y, Wang P, Zhu H, Liu C, Gao F. Single-loop digital control of high-power 400-Hz ground power unit for airplanes. Industrial Electronics, IEEE Transactions on. 2010;57:532-43.
- [199] Cheng P-T, Lee T-L. Distributed active filter systems (DAFSs): A new approach to power system harmonics. Industry Applications, IEEE Transactions on. 2006;42:1301-9.
- [200] Olivares DE, Cañizares C, Kazerani M. A centralized energy management system for isolated microgrids. Smart Grid, IEEE Transactions on. 2014;5:1864-75.
- [201] Munir S, Li YW. Residential distribution system harmonic compensation using PV interfacing inverter. Smart Grid, IEEE Transactions on. 2013;4:816-27.
- [202] Munir MS, Li YW, Tian H. Improved Residential Distribution System Harmonic Compensation Scheme Using Power Electronics Interfaced DGs. IEEE Transactions on Smart Grid. 2016;7:1191-203.
- [203] Vandoorn T, Meersman B, De Kooning J, Vandeveld L. Controllable harmonic current sharing in islanded microgrids: DG units with programmable resistive behavior toward harmonics. Power Delivery, IEEE Transactions on. 2012;27:831-41.