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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.

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

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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 cos-effectiveResearch 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 Section 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].