CHALLENGES AND DESIGN CONSIDERATIONS OF PV INVERTERS IN THE FUTURE SMART GRIDS

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ABSTRACT

Decentralisation of power generation is generally acknowledged one of characteristics of future smart grids. Different conventional and renewable energy sources will be installed in different locations but supporting the common grid network. The energy sources will work separately but with communication to optimize the power flow in the grids. Currently, solar energy is the most commonly used among the renewable energy sources, since installation of PV panel is very flexible, it can be down to few kilowatts for residential applications or up to tens Megawatts for solar farms. However, the disadvantage is that solar energy harvesting only operates during day time, and the amount of extracting energy highly depends on the weather conditions. It creates power quality issues for the future smart grids due to this unpredictable energy flows. Furthermore, emerging semiconductors is getting close to the market. The design of PV inverters will be a new era to achieve high energy efficiency and reliable. The paper will present the challenges of the future PV inverter design based on the grid-environment, the regulations and the applications. Moreover, the technology trend of improving system performance of PV inverters, including semiconductors, magnetic materials and converter topology, will be reviewed and discussed.

1 INTRODUCTION

A look back at the last two decades of technology development, Information Technology (IT) was the main subject in 90s. Different products, such as cell phones, internet, network games, e-commerce etc., have appeared in our daily life based on the research results of IT. In the beginning of 21st century, renewable energy sources have drawn the attentions of researchers due to the shortage of traditional energy sources. Meanwhile, Power Electronics (PE) has taken an important role for converting and controlling the energy from the sources to the grids. It is well known that the renewable energy conversion process does not generate any toxic gases plus the energy is renewable, thus the sources are generally classified as environment-friendly energy. Thus, some countries and regions have already started the program to achieve high percentage of renewable energy supplying in the future [1]-[3]. Unfortunately, the renewable energy generation is non-scheduled, it highly depends on weather conditions, locations and seasons. For example solar energy, it only can generate electrical power during the sunny day time. And in some regions of the world, the day time is very short during the winter time. It leads traditional energy sources are still being the main stream in the energy supply at this moment in order to stabilize the energy flow in the grids. Therefore, a new grid structure which has been proposed to achieve minimum traditional energy production by means of IT and PE [4]. This grid structure and optimization method is generally named as “Smart Grids”. And it will be a large research topic in the coming 20 years.

Decentralisation of power generation is generally acknowledged one of the characteristics of future Smart Grids. An imagined structure of future Smart Grids is shown in Figure 1 [5]. The energy sources, such as the wind power, the hydro power, the solar power and the nuclear power, support to the same grid. The grid connects to power consumers by ring connection and the energy flow is bi-directional [6]. Consumers can have their own power generators, e.g. Photovoltaic (PV) energy generators. The generators do not only supply for their own use, but also contribute to the grids when the supply energy is higher than the own demands. Therefore, the theories of communication, metering, power conversion, power flow control and power stability are the core subjects in the future Smart Grids.

The contributions of Power Electronics in the future Smart Girds will be mainly in the subjects of power flow control and power conversion. PE systems will manage the energy flowing-in as a consumer, or flowing-out as a supplier, or buffering the energy in storage elements for later consuming. Thus, the power optimization can be done by this process. Besides, power quality compensators, such as Dynamic Voltage Restorers (DVR) [7] and Active Power Filters (APF) [8], will be applied to ensure high quality power within the complex and dynamic grid network. PE energy interfaces will be found in the transforming between Medium Voltage (MV) grid and Low Voltage (LV) grid [9]. The process of energy conversion of renewable energy sources also requires efficient PE systems to inject energy to the grids. Thus, technology development of PE is playing extremely important role for realizing the future Smart Grids.
Among the renewable energy sources, solar energy is the most commonly used, since installation of PV panel is very flexible, it can be down to few kilowatts for residential applications or up to tens Megawatts for solar farms. Thus, 7.5GWp PV inverter installation has been done in Germany in 2011 [10]. However, the design of this PE converter is facing a couple of challenges, including changes of regulation, component revolution and additional features for the purpose of grid-friendly. All of them will lead the technology development in PV inverters.

Following this introduction, this paper is organized in three sections. In Section 2, configurations and the state-of-the-art technologies in PV energy conversion systems are presented. Furthermore, Section 3 discusses the design considerations and system features of PV inverters for the future Smart Grids. Finally, in Section 4, conclusions are given.

2 REVIEW OF PV INVERTERS

PV inverters are mainly classified as four categories, namely, micro-inverters, string inverters, central inverters, and MW central inverter. Basically, the classification is according to the rated power of the inverters. Figure 2 summarizes the applications, products and corresponding power ratings. For residential and commercial applications, string inverters are generally adopted, since the power can be easily scaled up by paralleling the inverters. In overviews, the apparatus of solar energy conversion consists of PV panels to change solar energy to electrical energy, and PV inverter being an interface between the panels and the grids [11]-[13]. Figure 3 shows a system block diagram of a typical transformer-less single-phase (1-ph) or three-phase (3-ph) string inverter. It can be seen that in the block diagram, there are two power conversion stages in the system, namely pre-regulator and inverter. Inverter is a dc-ac converter to shape the output currents to sinusoidal to meet the international standards, such as IEC-1000-3-2 and IEEE-519, and maintain the dc link voltage level [11], [12]. Pre-regulator is a dc-dc converter which is used to perform Maximum Power Point Tracking (MPPT) functions by controlling the input voltage and current [14]. Both power stages also operate in high frequency switching by using semiconductors. Besides, magnetic components can be found in the system for energy storing or filtering. Since the semiconductors and magnetic elements are also lossy, it is a challenge to maintain high overall system efficiency.
2.1 Converter static efficiency

Leakage current is a critical factor in PV inverter design considerations [15]. In order to meet the leakage current standard [16], the simplest solution is to add galvanic isolation between the panels and grids by using high frequency or line frequency transformers [17]. However, the penalty is the lossy magnetic components. Therefore, some transformer-less topologies have been proposed to get rid of the problem so as to increase the system efficiency. Up to this moment, the published record of commercial PV inverter efficiency is 98.8% at the maximum efficiency [18]. It seems that the margin of improvement becomes narrow, but it can be foreseen that research of efficiency improvement will continue until the efficiency curve becomes flat in the whole operating power range in order to increase the European Efficiency and the CEC Efficiency [19].

2.2 Semiconductors

In a commercial PV String inverter, semiconductor loss is roughly one-third of the total system loss, another one-third is from magnetic devices, and the rest of the loss is from electronics and others [20]. Traditionally, Silicon-based (Si) diodes, MOSFETs and IGBTs are the main components for high frequency switching. Sometimes, low frequency semiconductor switches are used to invert the waveforms with line frequency [21]. However, the Si devices have their own shortages, such as reverse recovery current in high voltage diodes, and tail current in high voltage IGBTs, thus they cannot provide efficient switching in PV inverters. 3-level switching techniques were introduced in 80s to deal with the shortages of low breakdown voltage and high switching loss [22]. Fig. 4(a) is an example of 3-level topology, Neutral-Point-Clamped (NPC) inverter. It gives three voltage possibilities at the inverter output. It has been demonstrated that the topology is well applied in 3-ph PV inverters, since it gives high efficiency and relatively low cost. However, Silicon Carbine (SiC) semiconductor era is coming as well as the IGBT revaluation in 80s. It is well known that the benefits of SiC semiconductors are high breakdown voltage and high junction temperature but low conduction loss [23]. Besides the static characteristics, SiC semiconductors provide very efficient switching. More precisely, reverse recovery current of SiC diodes can almost be negleced. SiC active switches, e.g. MOSFETs, do not have turn-off tail current problems. To sum up the advantages of SiC devices, a SiC switching cell, which is the combination of a SiC diode and a SiC switch, can bring up the switching frequency and simplify the 3-level topology (Fig. 4(a)) back to 2-level (Fig. 4(b)). Thus, the efficiency can be up to 98.8% with right topology selection and system optimization [18].

2.3 Optimization

SiC semiconductors directly bring advantages of efficiency and circuit simplicity into PV inverters, the devices also influence the output inductor design. By operating a PV inverter at high switching frequency, generally, small size core and low cost materials, like ferrite, can be chosen and adopted. The operating frequency is generally determined by the following criteria, system cost, efficiency, size and reliability. Among the criteria, efficiency is always the highest priority in the PV inverter design considerations, since it is a big selling point to users who can sell the energy to electricity providers to receive payback. However, the fact is that higher efficiency must lead to higher system cost. It is difficult to find a balance in these two criteria. This trade-off will be a big challenge in the coming competitive PV inverter market to design a most suitable PV inverter. Besides the performance domains of efficiency, size and cost, reliability is slowly included into the performance index in the optimization process [24]. High voltage electrolytic capacitor (E-Cap) is always the critical components to limit the life time of PV inverters. Some methods have
been proposed, which use film capacitors or magnetic elements as energy storages instead of E-Caps [11], [25]. This multi-domain optimization makes the PV inverter perform better, but to determine the optimal point is a challenge for PV inverter R&D engineers.

2.4 MPPT dynamic efficiency

PV panel is not a pure voltage source or current source element. It requires either hardware impedance matching [26] or use of software to determine the operating point with maximum output power, it calls MPPT. From the algorithm point of view, the existing methods, such as perturbation and observation (P&O) and incremental conductance (IncCond), can track the MPP properly and the dynamic response is good enough to deal with the changes of temperature and irradiation [27]-[28]. However, the methods cannot be applied in the issues of partial shading, since multiple MPPs are in the output of strings. Figure 5 shows an example of partial shading issue. The P-V diagram shows the output characteristic of the string when the MPP of each panel is not the same. By using P&O in the situation, more probably local maximum point is tracked. Then, maximum power cannot be harvested from the panels. Solutions of the issues are being explored by researchers. Generally speaking, there are two directions. Direction 1: By using machine learning method [29], the method uses machine learning technique to determine the global MPP in a period of time. Direction 2: MPPT distributions [30]-[31], the method is to decentralize the MPPT function to a local tracker which is attached on each panel. Both methods can manage the issue effectively, but the machine learning method requires powerful computing units, and the method of MPPT distribution increases the hardware component-count and reduces the overall system efficiency. Thus, solving of partial shading issues will be a continuous task in the PV inverter design.

3 PV INVERTERS IN SMART GRIDS

It has already been mentioned that in introduction, PV inverter will be part of future smart grids. It is not only taking the traditional role to generate energy from solar panels, but it also will be integrated new features to support the grids to become more cost-effective. In this section, two additional features for future Smart Grids will be discussed.

3.1 Energy optimization

One of the key functions of the future Smart Grids is the energy generation which is decentralised. Each power inverter will not only support local power demands, but also supporting global energy consumers. This optimization is highly dependent on the infrastructure of the grids. Besides, the drawback of the PV energy has been mentioned, the amount of energy generation is not scheduled. It means that it can be over providing during the day time, but no energy generation during the night time. The local energy consumers have to get the energy externally. Some studies have been done to propose battery integrated PV inverters [32]-[33]. Figure 5 shows one of the proposed systems. In principle, it is a typical three-port PE system. The battery stores the over generated energy by the PV panels to avoid to produce power quality issues to the grid. The energy is released from the battery to the local consumers when the PV panels are out of generation. By means of this method, it will buffer the energy and stabilise the power flow between the local and global grids. However, this configuration is highly dependent on the technology development of batteries, which directly influences the capacity, the cost and the reliability of the PV inverters.

3.2 Power quality support

Recently, a new regulation has been published in Germany, PV inverters must have capability to adjust Power Factor (PF) to be 0.9 in inductive mode and capacitive mode [34]. It is used to balance reactive power (VAr) in the grids instead of using costly large capacitor banks in distribution substations. Accordingly, it further tightens up the selection of PV inverter topology due to this regulation. For example, a 1-ph inverter, Figure 7(a) shows a typical dc-ac inverter for PV applications, is formulated by a high frequency output current control buck converter and a line-frequency inverter. The buck converter crops the inductor current as a unipolar sinusoidal waveform. And the line-frequency inverter polarizes the current to be bipolar sinusoidal waveform and inject it into the grids [21]. For unity power factor, the switching actions of line-frequency inverter is at zero crossing of
the grid voltage, the converter works properly with the advantages of low switching losses, small output inductor core and low cost in overall. However, the converter gives very high THD at the output current when the line-current and line-voltage are not in-phase, i.e. PF does not equal to 1. For this case, either increases the cost and the loss of semiconductor components to adapt the regulation in the same topology, or uses other topology to manage the reactive power, e.g. Figure 7(b), a conventional full bridge inverter. Design of PV inverters becomes challenging, since the market and the regulation are very dynamic.

Another integrated feature in PV inverters will be active power filtering. The future smart grids would be polluted seriously by the harmonic currents which are generated by other PE loads. Active Power Filter (APF) is required to reduce the harmonics in the grids. Figure 8 shows the block diagram of PV inverter with APF (PV-APF) [35]. In principle, the structure of Figure 8 is almost the same as an APF, the difference is the PV panels attaching the dc voltage side of the APF. Conventionally, APFs inject reactive current and harmonic currents into the grid to ensure the input grid current is unity power factor and high THD. In Figure 8, the converter has energy support from the PV panels, it has ability to inject active power from the PV-APF. Thus, the PV-APF takes the role of APF and minimize the source by using the PV energy. The approach boosts the value of PV inverters and makes the future grids friendlier.

4 CONCLUSION

The paper has presented the state-of-the-art technologies of PV inverters and the features of PV inverter in the future Smart Grids. The input factors of

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