Microgrid Power Electronic Converters: State of the Art and Future Challenges

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***Abstract*- This paper presents a review of the state of the art of power electric converters used in microgrids. The paper focuses primarily on grid connected converters. Different topologies and control and modulation strategies for these specific converters are critically reviewed. Moreover, future challenges in respect of these converters are identified along with their potential solutions.**

***Index Terms*—Distributed Generator (DG), Grid connected converters.**

I. INTRODUCTION

Fossil fuels are running out and current centralised power generation plants are inefficient with a significant amount of energy lost as heat to the environment, in addition to producing harmful emissions and greenhouse gases. Furthermore, current power systems, especially in developing countries, suffer from several limitations such as high cost of expansion and efficiency improvement limits within existing grid infrastructure. Renewable energy sources can help address these issues, but it can be a challenge to get stable power from these sources as they are variable in nature.

Distributed generators (DG), including renewable sources, within microgrids can help overcome power system limitations, improve efficiency, reduce emissions and manage the variability of renewable sources. A microgrid, a relatively new concept, is a zone within the main grid where a cluster of electrical loads and small micro generation systems such as solar cell, fuel cell, wind turbine and small combined heat and power (CHP) systems exist together under an embedded management and control system with the option of storage devices. Other benefits of generating power close to electrical loads include the use of waste heat locally, saving the cost of upgrading the grid to supply more power from central plants, reducing transmission losses and creating opportunities for increasing competition in the sector which can stimulate innovation and reduce consumer prices [1, 2].

Power electronic converters are used in microgrids to control the flow of power and convert it into suitable DC or AC form as required. Different types of converter are needed to perform the many functions within a microgrid, but it is not the aim of this paper to review all of these possible types of converter, many of which are covered in textbooks and other publications [3]. The paper will primarily focus on converters used to connect DG systems including micro CHP and renewable energy sources to an AC grid or to local loads, as illustrated in Fig 1. They convert DC (photovoltaic, batteries, fuel cells) or variable frequency AC (wind and marine

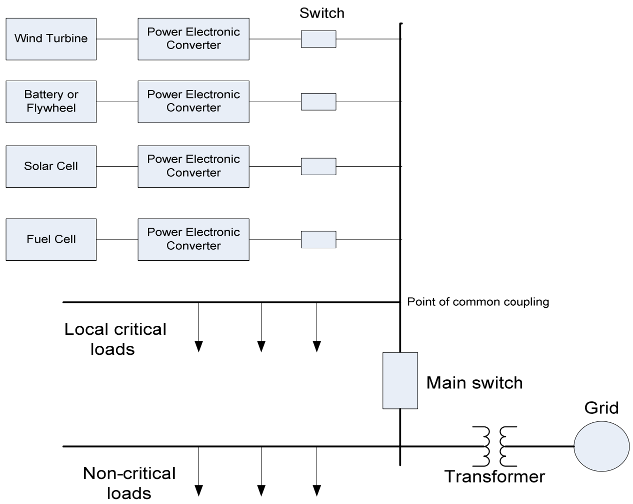


Fig. 1. A Schematic Diagram of a Microgrid

turbine) into 50/60 Hz AC power that is injected into the grid and/or used to supply local loads. Of these , they have been extensively used for photovoltaic [4], fuel cell [5] and wind based generation systems [6]. Converters are also used to connect to batteries and flywheel energy storage systems or connect high-speed micro turbine generators to the grid.

II. MODES OF OPERATION OF MICROGRID CONVERTERS

Normally, converters are used to connect DG systems in parallel with the grid or other sources, but it may be useful for the converters to continue functioning in stand-alone mode, when the other sources become unavailable to supply critical loads. Converters connected to batteries or other storage devices will also need to be bidirectional to charge and discharge these devices.

A. *Grid Connection Mode:*

In this mode of operation, the converter connects the power source in parallel with other sources to supply local loads and possibly feed power into the main grid. Parallel connection of embedded generators is governed by national standards [7-9]. The standards require that the embedded generator should not regulate or oppose the voltage at the common point of coupling, and that the current fed into the grid should be of high quality with upper limits on current total harmonic distortion THD levels. There is also a limit on the maximum DC component of the current injected into the grid.

The power injected into the grid can be controlled by either direct control of the current fed into the grid [10], or by controlling the power angle [11]. In the latter case, the voltage is controlled to be sinusoidal. Using power angle control however, without directly controlling the output current, may not be effective at reducing the output current THD when the grid voltage is highly distorted, but this will be an issue in the case of electric machine generators, which effectively use power angle control. This raises the question of whether it is reasonable to specify current THD limits, regardless of the quality of the utility voltage.

In practice, the converter output current or voltage needs to be synchronized with the grid, which is achieved by using a phase locked loop or grid voltage zero crossing detection [12]. The standards also require that embedded generators, including power electronic converters, should incorporate an anti-islanding feature, so that they are disconnected from the point of common coupling when the grid power is lost. There are many anti-islanding techniques; the most common of these is the rate of change of frequency (RoCoF) technique [13].

B. *Stand-Alone Mode*

It may be desirable for the converter to continue to supply a critical local load when the main grid is disconnected, e.g. by the anti-islanding protection system. In this stand-alone mode the converter needs to maintain constant voltage and frequency regardless of load imbalance or the quality of the current, which can be highly distorted if the load is non-linear.

A situation may arise in a microgrid, disconnected from the main grid, where two or more power electronic converters switch to stand-alone mode to supply a critical load. In this case, these converters need to share the load equally. The equal sharing of load by parallel connected converter operating in stand-alone mode requires additional control. There are several methods for parallel connection, which can be broadly classified into two categories: 1) Frequency and voltage droop method [14], 2) Master-slave method, whereby one of the converters acts as a master setting the frequency and voltage, and communicating to the other converters their share of the power [15].

C. *Battery Charging Mode*

In a microgrid, due to the large time constants of some microsources, storage batteries should be present to handle disturbances and fast load changes [16]. In other words, energy storage is needed to accommodate the variations of available power generation and demand. The power electronic converter could be used as a battery charger thus improving the reliability of the microgrid.

III. Converters Topologies

Most of the current commercially available power electronic converters used for grid connection are based on the voltage-source 2-level PWM inverter as illustrated in Fig. 2 [10, 17]. An LCL filter is commonly used, although L filters have been also used [18, 19]. An LCL filter is smaller in size compared to a simple L filter, but it requires a more complex control system to manage the filter resonance. Additionally, the impedance of L_2C in Fig.2 tends to be relatively low, and provides an easy path for current harmonics to flow from the grid, which can cause the THD to go beyond permitted limits in cases where the grid voltage THD is relatively high. Ideally, this drawback could be overcome by increasing the feedback controller gain in a current controlled grid connected converter. But this can prove to be difficult to achieve in practice while maintaining good stability [20].

Other filter topologies have also been proposed. For example, Guoqiao et al. [21], proposed an LCCL filter arrangement, feeding back the current measured between the two capacitors. By selecting the values of the capacitors to match the inductor values, the closed loop transfer function of the system becomes non-resonant.

The size and cost of the filter can be very significant. Filter size can be reduced by either increasing the switching frequency of the converter or reducing the converter voltage step changes. However the switching frequency, which is limited by losses in the power electronic devices, tends to reduce as the power ratings of the devices and the converters increase. This means that high power 2-level converters could have disproportionally large filters.

Alterative converter topologies, which can help reduce the size of the filter, have been the subject of recent research. Multi-level converters have been proposed including neutral point clamped shown in Fig. 3a [22] and cascaded converter shown in Fig. 3b [23]. Multi-level converters have the advantage of reducing the voltage step changes, and hence size and the cost of the main filter inductor for given current ripple, at the expense of increased complexity and cost of the power electronics and control components [24]. Additionally, since the switching frequency of commercial power electronic devices tends to reduce and their rated voltage tends to increase as their current ratings increase; practical multi-level converters devices may be underrated. For example, a practical high power multi-level converter may use a relatively low switching frequency device with a voltage rating greater than necessary to meet the current rating requirement.

An alternative to the multi-level converter is to use an interleaved converter topology as illustrated in Fig 4. A grid connected converter based on this topology has already been designed, built and tested by the authors, and further publications on this will follow. Interleaving is a form of paralleling technique where the switching instants are phase shifted over a switching period. By introducing an equal phase shift between parallel power stages, the output filter capacitor ripple is reduced due to the ripple cancellation effect [25, 26]. Additionally, by using smaller low current devices, it is possible to switch at a higher frequency, and therefore the inductors and the overall filters requirement would be smaller. The number of channels in an interleaved converter is a compromise between complexity and filter size.

Other possible converter topologies, which are worth investigating for this application, include current source converters [27] (Fig. 5a), and matrix converters [28] (Fig. 5b). The matrix converter is particularly appealing when the power source is AC, e.g. high frequency turbine generator or variable frequency wind turbine generator. Using a matrix converter, the cost of the AC/DC conversion stage and the requirement for a DC link capacitor or inductor could be saved. Combinations of the above converters may be also possible, e.g. an interleaved multi-level converter or an interleaved matrix converter, perhaps with soft switching.

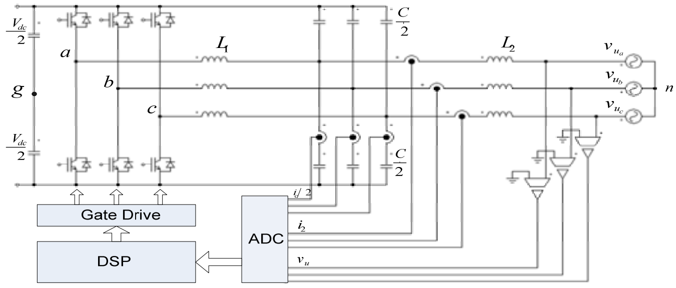
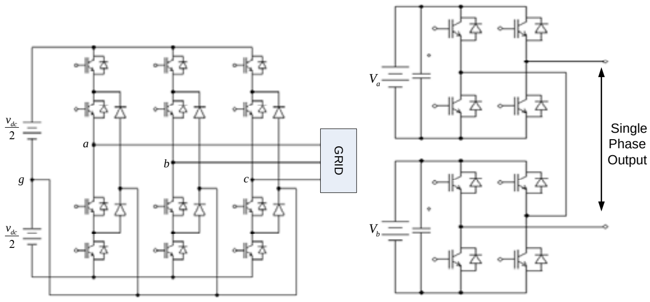


Fig. 2. Two Level Grid Connected Inverter with LCL Filter



(a) (b)

Fig. 3. Multi-level Voltage Source Inverter a) NPC and b) cascaded

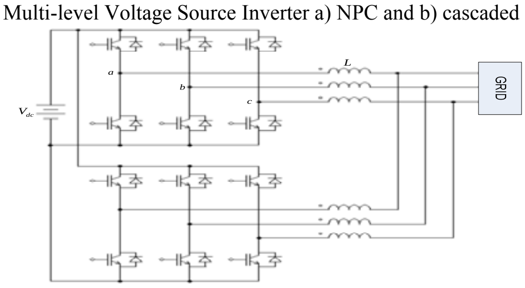
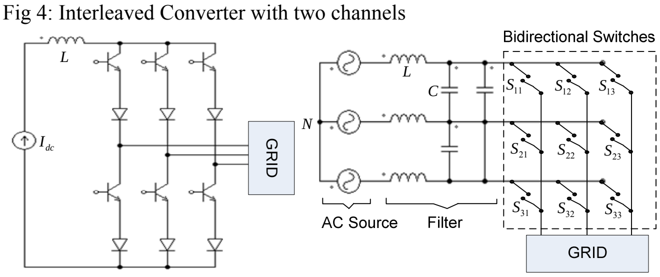


Fig 4: Interleaved Converter with two channels



(a) (b)

Fig 5 a) Three- Phase Current Source Converter, b) Matrix Converter

IV. MODULATION STRATEGIES

There are a variety of modulation techniques that can be used in power electronic converters in general, including pulse width modulation (PWM), hysteresis modulation and pulse density modulation (PDM).

Hysteresis modulation is perhaps the simplest to implement in practice, but it has many shortcomings: (i) variable switching frequency in the fundamental cycle and hence spread harmonic spectrum (ii) increased current error if the middle point of dc-link and system neutral are not connected, (iii) due to the non-linear characteristic of this modulation technique, the controller cannot actively control the oscillations of the output filter and hence passive damping becomes essential (iv) poor quality of output current means it has to be used with other techniques such as repetitive feedback to improve the output current quality [17]. Due to these shortcomings, it is not preferred for microgrid inverters where high quality output current and good transient response are essential requirements.

Not surprisingly, most grid connected converters use pulse width modulation (PWM), either carrier based on using space vector modulation (SVM) which has the advantage of ease of implementation using a microprocessor. Third harmonic injection is often used to reduce the required DC link voltage headroom, thus allowing a lower switching frequency to be used. Space vector modulation strategies have also been developed to minimize switching losses or eliminate certain harmonics. In multi-level and interleaved converters, the number of SVM states increases significantly, with many redundant states, which create further opportunities for device switching strategies to reduce or redistribute the losses within the converter and eliminate certain harmonics [29, 30].

Pulse density modulation (PDM) is another possible modulation technique. It is not commonly used in conventional converters, but it has been used in high-frequency (150 kHz) converters used for induction heating [31]. The potential for this modulation strategy is yet to be explored in the context of converters for grid connection applications.

V. CONTROL AND SYSTEM ISSUES

The control system of a grid connected converter needs to cater for the different possible operating modes that were discussed earlier in section II. In the grid connected mode, either a maximum power tracking system or the user will specify the power and power factor to be injected into the grid. The control system needs then to translate that into a reference demand current, if the output current into the grid is to be controlled. Alternatively, the controller needs to determine the output converter voltage and power angle, if power flow into the grid is based on power angle control. The reference signals need to be synchronized with the grid, as mentioned earlier.

It is common to use the d-q transformation (see Fig .6) to translate the measured AC signals of voltage and current to DC, which simplifies controller design and implementation using a microprocessor based controller [32]. But, such an approach assumes that the measured signals are pure sinusoids and that the grid is balanced, which in practice is often not the case. A slight imbalance as well as harmonic distortions are often present, which act as disturbances that cause a deterioration of the output current THD.

The alternative is to have a separate controller for each phase, with direct control of the sinusoidal output current. But direct feedback of the output grid current of an LCL filter on its own can be inherently unstable, and it is necessary to have another feedback loop of the capacitor current (see Figs 1 and

7) or the current in the main inductor L_1 [10, 17, 33]. One of the challenging aspects of this controller structure is that it is not possible to have a high outer loop gain using a simple compensation or PID controller. Resonant controllers [34] and virtual inductance [35] could be used to help increase the outer loop gain, and, hence, improve disturbance rejection. Other types of controllers, including optimal control strategies[36], state-feedback approach [20], and sliding mode controllers [37] have also been proposed.

An alternative is to use feedforward schemes to compensate for grid voltage harmonics [17] or inverter dead time [38] at the expense of extra complexity and cost. Repetitive or cyclic feedback has also been proposed: the output current is compared with the demanded current on a cycle by cycle basis, and accordingly, the effective reference current demanded from the inverter is modified to compensate for the disturbances. However, repetitive feedback was found in practice to lack robustness and to be sensitive to parameter uncertainty [39].

Guoqiao et al. [19] proposed splitting the capacitor into two capacitors in parallel, and adding a minor feedback loop of the current measured after the first capacitor. By carefully selecting the capacitor values, the transfer function of the system can be reduced to first order, which helps to mitigate the resonance problem and enables the outer loop gain to be increased, thus improving disturbance rejection. In practice, it may be difficult to find capacitors with the right values and the uncertainty in the filter values will make the condition for resonance elimination difficult to achieve.

For simplicity and guaranteed stability, many authors [40-42] choose to control the inverter current before the filter rather than the grid current. Such systems can, however, suffer from problems resulting from filter resonance, such as underdamped transient response oscillations, large overshoot and oscillations induced by utility harmonics near the resonance frequency, in addition to poor utility voltage harmonic disturbance rejection. Blasko and Kaura [43] proposed a lead-lag compensating loop in the filter capacitor voltage to actively damp filter resonance. Resistors connected in series with capacitors or inductors are also sometimes used, although this is not an efficient option.

Computational time delay, when a digital controller is used can be significant and could affect system stability. To maintain system stability, a time delay compensation scheme may need to be implemented [15], but with faster DSPs and microcontrollers, this is becoming less of an issue. Care also needs to be taken when generating the reference sinusoidal signal using a look-up table in a microprocessor as using an insufficient number of samples may cause sub-harmonic distortions [44].

The controller also needs to incorporate an anti-islanding protection feature, and needs to seamlessly switch from grid connected mode to stand-alone mode to supply critical loads, in parallel with other converters. This could mean switching from a current control strategy to a voltage control strategy, which can be challenging to implement. An alternative is to adopt a voltage and power angle (i.e. frequency) control strategy for all modes of operation which will make transition between different modes seamless. As mentioned earlier, however, this control method does not directly control the current injected into the grid and meeting the THD standards may be challenging if the grid voltage THD is relatively high.

Often, metering of power is incorporated as a function in commercial controllers, which can be remotely interrogated via Ethernet, CAN bus or wireless connection.

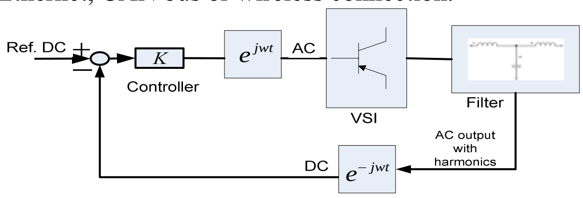


Fig 6: The basic idea of the d-q transformation approach

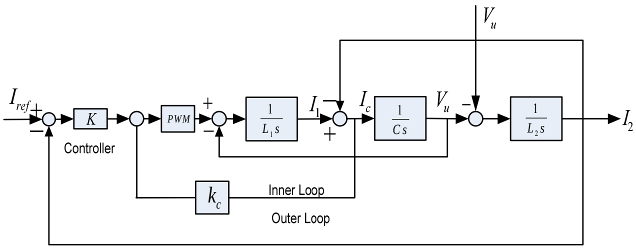


Fig 7: Two Feedback Loop Structure

VI. Future Challenges and Solutions

Cost and size of the converter, particularly the filter components, remain an issue. This, in principle, may be addressed by increasing the frequency and using either muti-level or interleaved topologies as discussed earlier. But further research is needed to establish the optimum tradeoff between power electronic devices and filter components.

It may also be beneficial to take an overall system approach when designing the converter, rather than considering the design of the converter in isolation. For example, a cascaded multilevel converter requires multiple isolated DC links which requires a multi-tap transformer, or complex schemes using flying capacitors. An alternative could be to design the electric machine (of say a wind generator) to have multiple sets of 3 phase coils isolated from each other to connect to independent rectifiers to generate the isolated DC links for the multilevel converter. In a photovoltaic system, the solar cells may be connected to form isolated DC sources.

The proliferation of inverter interfaced DG units is already raising issues related to coordination of protection relays both in grid connected and stand alone modes. This is currently an active area of research [45].

The standards governing these converters are still evolving and practical implementation is continuously giving rise to new issues that need to be thought about and regulated.

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