Review: Grid-Connected Inverter with Its Filter and Providing Suggestions for Designing a Transformerless Inverter

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***Abstract*—The grid-connected inverter is the interconnect between a renewable energy source such as the wind and solar power and the grid. There are two types of the grid-connected inverter based on the transformer. These are called the transformerless inverter and isolated inverter. The former is a smaller size and weight; however, the one limitation of this inverter is a leakage current problem. The latter has the advantage of being applicable in isolated locations, but it suffers from high cost and significant weight. In general, the grid-connected inverter has required a filter to mitigate the harmonic components and produce a perfect sinusoidal waveform. But this filter should be properly selected, whether the L filter or LCL filter. This paper reviews the previous studies on the grid-connected inverter and highlights the limitations from the literature's point of view. Finally, suggestions and recommendations for designing the filter and an optimal control for the grid-connected inverter are presented with extensive and in-depth detail.**

***Index Terms*—grid-connected inverter, integration of energy storage systems, Maximum Power Point Tracking (MPPT)**

I. INTRODUCTION

In regions with warm weather and due to Heating, Ventilation and Air-Conditioning (HVAC) loads connected to the grid in the summer, the consumption of electricity increases, which leads to a peak demand in the summer that is higher than the winter demand. Therefore, solar energy with a grid-connected inverter can be deployed to reduce this peak demand and satisfy the utility network's requirements.

The prior research has focused on the impact of the grid impedance on the grid-connected inverter's stability [1], the integration of an energy storage system with a photovoltaic generator [2], the challenges of controlling the voltage of distributed energy resources [3], and the digital control of the grid-connected inverter by using a Field-Programmable Gate Array (FPGA) platform [4].

Although these publications were focused on dynamic voltage control [3], with easy and simple reconfiguration [4], some challenges present. These limitations are that the theoretical analysis and simulation are not taken into account. Also, the actual deviation of the delay time is slow, where it takes 0.5s to match the ideal curve, while the response time of the Maximum Power Point Tracking (MPPT) is very low in [3]. The study in [1] would have been more interesting if it had included the Total Harmonic Distortion (THD) of the output voltage and current. Moreover, the parasitic elements of the bridge were neglected in the analysis.

This paper reviews the grid-connected inverter and type of controllers, and will provide the key finding to design an optimum grid-connected inverter. It has been organized as follows: Section II reviews the grid-connected inverter with a filter. Section III presents a general review of different controls of grid-connected inverters that have been constructively and critically reviewed in order to improve the overall design. Section IV shows the methods for the reduction of ripple current on the battery side, which may reduce the battery life. Section V proposes a system that can be integrated with the grid to configure the grid-connected system or work alone to form a stand-alone system. Also, suggestions for the future of the grid-connected inverter are highlighted in the same section. Finally, the conclusions of this review are drawn.

II. GRID-CONNECTED INVERTER WITH LCL FILTER

In this section, previous studies on the grid-connected inverter so far are reviewed and the limitations presented.

Manuscript received August 1, 2016; revised December 9, 2016.

doi: 10.18178/ijoee.4.3.174-178

An interactive line of an uninterruptible power supply and its control system were proposed by Abusara *et al.* [5]. The dynamic response for varying the load is excellent, and the droop efficient was used to limit the produced power when it was higher than the demand and the batteries were full. One major drawback of the approach of Abusara *et al.* is that the ripple of battery current was not considered and this system was used for three-phase, high voltage level. Perhaps the most serious disadvantage of this method is that the two stages, which are the DC–DC converter and DC-AC inverter, were used, which increase the system's complexity. Nevertheless, the DC-link voltage controller that gave active power demand to control the charge and discharge of battery proved its effectiveness and gave a smooth transition. The key problem with Abusara *et al.*'s explanation is that the LCL filter is presented in a block diagram, in which the L filter was considered in the numerical model, which makes the analytical process unclear.

A passive filter for the grid-connected inverter was presented by Ahmed *et al.* [6]. Even though an analytical expression for the impact inductor ripple current was investigated, and how to reduce it, the capacitor value was not analyzed as per the inductor value. Perhaps the most serious disadvantage of the method that Ahmed *et al.* used is that the harmonic current was not analyzed by using Fast Fourier Transform (FFT) analysis and calculating the THD. Even though the current harmonic injected into the grid has been highlighted in the abstract, the results were only presented in Simulink and may be challenged in practice.

Modeling the LCL filter for the grid-connected inverter was the analysis conducted in [7]. There are some points that required consideration had the THD been presented, and the study would have been more interesting if it had included the evaluation of the model to validate the obtained results. The value of the inductor for the grid side should be less than the inductor value on the inverter side. However, in the literature, it has been mentioned by the authors in [7] that the grid-side inverter (L2) was determined as a fraction of (L1). Therefore, this rule should be considered. Another problem with this approach is that it fails to take the impedance of the grid into account.

A trial and error approach to designing the L and LCL filter for the grid-connected inverter was presented in [8]. Although the output current harmonic spectrum was analyzed, the THD of the output current was not taken into account to assess the performance and compare the LCL filter and L filter with IEEE-1547. A flow chart presents the process employed to find the filter inductance, switching frequency, filter capacitance and damping resistance. Nevertheless, this study would have been more useful if they had focused on the validation of the experimental works.

Modeling of the filter type for the grid-connected inverter was presented by Lettl *et al.* [9]. They presented an interesting block diagram of a Voltage Source Inverter (VSI) (as shown in Fig. 1. n ref. [9]).

It is clear that the controllers include the voltage on the output capacitor, the inductor current that is located on the inverter side, the capacitor current and the voltage controller on the DC side. All these controllers are very good. However, they are not explained in depth. Also, in the model, only one output current controller was used. Perhaps the most serious disadvantage of this method is that the THD of the output current is slightly higher than the IEEE-1547 requirements. Also, the damping resistor, which is utilized to reduce the resonance effect, may cause losses and lead to a reduction in the efficiency. Although the LCL filter was designed with a damping resistor in [10], there are some limitations such as the damping resistor creating losses and reducing the efficiency. The THD of the output current and voltage were estimated in a Simulink model. However, the experimental results only considered an FFT algorithm analysis, which makes it difficult to assess the performance of the proposed system. Also, there are some spike voltages during dead time internal commutation, even though An insulated-gate bipolar transistor (IGBT) module APTGFGOTA60PG, integrated gate driver 65D106EI and also FPGA (XILINX X C3500E) are explained. Moreover, this system was implemented for a three phase, where a single phase may be different.

III. Different Controls of the Grid-Connected Inverter

In this section, the various techniques for controlling the grid-connected inverters are reviewed based on the previous studies.

A. *Multi-Loops Control*

A capacitor-current-feedback controller was utilized in a PV inverter with the LCL filter in [11]. The current controller achieves a good quality and smooth response of the output current with a variation of the load. Besides, active damping reduces the resonance peak created by the LCL filter. Also, the selection of the LCL filter's parameters with switching frequency is very good, particularly the value of capacitor filter that was selected to be 10 µf. However, there are issues that were not taken into account:

- The fall current and tail current in an IGBT (CM100 PY-24NF) were not considered in the analysis or control system.
- There is no difference between the settling time when the PR controller or the PI controller were used.
- The design is complex, with three loops of control used.
- The THD was not measured, while the FFT analysis was presented. Therefore, it is difficult to interpret and evaluate the results.

B. *Hysteresis Controller*

Hysteresis control is often called a comparator, where it introduces as presented in two cases: rising voltages and falling voltages. The output current controller for single-phase voltage was controlled by the hysteresis controller by Bauer [12]. This technique is fast and simple, where the hysteresis controller can be realized as a simple bang-bang controller. Also, this system can operate in island mode and is possible as the grid-connected system. In island mode, a sinusoidal waveform must be generated, where the grid voltage is unavailable. It is worth considering that there are some weaknesses in Bauer's study, as follows:

- The ripple current is very high and may damage the source of voltage, which was not taken into account.
- The study would have been more relevant if the researchers had focused on the analysis of the THD of the output voltage and current.
- The selection of the LCL filter value may not be possible in practice, where the inverter side inductor value is 17.7 mH and the output current is 3 A. Thus, there is a significant cost, even though the switching frequency is very low (3000Hz).
- The damping resistor causes the losses in the inverter and reduces the efficiency.

C. *DQ Reference Frame with PR Controller*

Modelling of a single-phase PWM rectifier by using d-q transformation was presented by Saito and Matsui [13], which was used to control the active and reactive power in order to regulate a DC voltage. However, the DC capacitor is very large and requires a large space, while the lifetime of this capacitor is shorter than the capacitor on the AC side. For example, Fig. 1 shows two capacitors; each one is 820 μF and connected in parallel. The total capacitance is given by:

$$C_T=C_1+C_2 \quad (1)$$

Hence, the total capacitance is 1.64 mF, which is very large. Samerchur *et al.* presented a grid-connected inverter with L filter based on d-q transformation [14]. Although the results show a good dynamic response and high accuracy of the Simulink model, the THD of the output voltage is unacceptable, where the THD of the output current is slightly higher than the requirements of the IEEE-1992 Standard. Also, the DC capacitor is very large and thus requires space, while the lifetime is short.

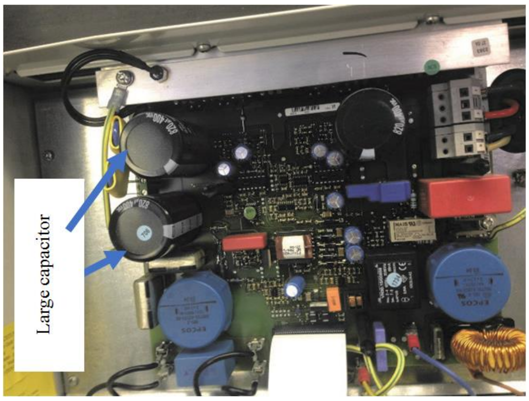

Figure 1. The large capacitor on DC side of the PV inverter.

D. *An Infinity Loop Controller and the IMC Controller*

An infinity loop controller of single-phase inverter was discussed by Lee *et al.* [15]. The transfer function (T(s)) and sensitivity (S(s)) must satisfy the following:

$$T(s)+S(s)=1 \quad (2)$$

The infinity controller depends on an Internal Control Model (IMC) referred to as H (∞) [15]. Although an H (∞) loop controller offers the advantages of ease in use and a reduction of the control circuit cost, the H (∞) controller is not suitable for assessing the performance and robustness.

Also, the gain controller is crucial in practice. Another problem with the approach of Lee *et al.* is that it fails to take the parasitic elements of the grid-connected inverter into account. The IMC is a development model that is identical to the real system and is included in the designed controller.

An IMC to improve the dynamic performance of a single-phase inverter was presented in [16]. Although the THD of the output voltage is acceptable and a simpler structure, the parasitic elements of the bridge were not included in the design control and assumed as ideal switches. Also, the Simulink results are presented without explanation of the designing control technique. In other words, it is difficult to track the control design procedures.

E. *Particle Swarm Optimization Controller*

Particle Swarm Optimization (PSO) is a population-based stochastic optimization technique that has been developed by observing the social behaviours of birds flocking or fish schooling [17]. PSO is easy to use and there are few parameters to adjust. However, PSO has a large range of particles to achieve a good result. The designed grid voltage control techniques for the distributed generation interface were presented in [18]. The tuning problem was solved by using PSO. PSO methodology can be described as a group of birds randomly searching for food in an area. This area has only one piece of food being searched for. All the birds know how far the food is in each iteration, but they do not know where the food is. The effective method is to follow the bird that is nearest to the food, as discussed by Khan [17]. Although Khan's approach is simple and provides accurate and robust tracking of the generation of the desired current trajectory, the control method is used for three phase and may not be possible for a single-phase inverter. The Khan's study would have been more interesting if it had included the parasitic elements of switching. Also, another problem with this approach is that it fails to take the THD of the output voltage into account.

IV. Reduction of Ripple Current in Storage Battery Side

Reducing the input current ripple in a fuel cell system with a load inverter was proposed to increase the fuel cell lifespan [19]. The active control technique was incorporated with a current control loop to reduce this ripple, even though the harmonic analysis of the output current was not analyzed. If it had been analyzed, it would have been interesting to evaluate the performance of the system. One major drawback of this approach is that the system has four stages, which causes a complexity.

Some issues should be considered when the storage battery is used [20]: the storage battery should maintain a discharged state during the day and be used during the night; if the lead-acid is left in a discharged state, its lifetime may reduce; and a ripple current in the AC link type may appear, which can possibly reduce the battery life.

Reducing the ripple current of a fuel cell by using a DC active filter with a center tap transformer for a single-phase inverter was suggested by Itoh and Hayashi [21]. Although the ripple current was reduced to 20% of the conventional circuit, the right values of the transformer and construction of a high-power rate were not taken into account.

Reducing the ripple current of a fuel cell with a power conditioning system was presented by Mazuander *et al.* [22]. Although the results show the ripple current reduces to 15% of the maximum input current ripple, the spike current on the high-frequency transformer on the primary side is very high. The main weakness with this theory is that the system is complex, where it consists of a zero-ripple boost converter, a soft-switched, multilevel high-frequency inverter and a single-phase Cyclo-converter. Thus, the cost will be high.

V. Proposed System

The grid-connected inverter or stand-alone inverter require an additional control load such as a capacitor current loop with the output voltage control, as presented by Al Gaddafi *et al.* [23]. The AC Mini-Grid system is proposed as an optimal solar PV system that can operate in the grid-connected system and stand-alone system. This system allows the integrating of different sources of energy such as wind power, solar energy, and supply network. This system consists of the storage battery with a bi-directional converter (Sunny Island 6.0H inverter) and network and system protection (NS protection), referred to as a protection box and as shown in Fig. 2.

Figure 2. AC Mini-Grid for solar PV system.

VI. Key Findings and Suggestions for Future

For designing the grid-connected inverter, the rated power should be determined first. This power should be calculated based on the PV panels. Based on the nominal power, the switching of the bridge can be selected while giving a marginal range for safety. Then, the current that will be injected into the grid is determined. According to the desired ripple current and ripple voltage, the LCL filter value is established. Furthermore, the ripple on the DC side of the inverter is reduced by a large capacitor on the DC side. However, this capacitor may face the problem of the size and large capacitance. Hence, a CLC filter can be used, although some commercial inverters such as the Sunny Boy 1700E inverter use multi-capacitors connected in parallel. After the PV inverter or grid-connected inverter has been developed, the waveform of the output voltage and current must be observed to evaluate the control design. To be precise in the design, the THD of the output voltage and current should be compared with the IEEE-519-1992 or IEEE-1547-2003 standards' requirements. If robust control and behaviors of the system are required under the disturbance of the system, thereafter the impact of the different load and variation of the voltage on the DC side can be evaluated. Finally, the grid-connected inverter should include the features of MPPT, island mode, fault ride through and also droop control feature.

Yinger and Kamiab [24] presented reviews for the future of a smart electric grid in Southern California, where the smart grid will provide increases in the transfer capacity, the possibility to integrate more renewable energy resources, and faster restoration when the grid is unavailable.

VII. Conclusion

This paper reviewed the grid-connected inverter with its filter. The type of controller for this inverter was discussed. The main limitations are (1) selecting an optimal filter value, (2) ignoring the parasitic elements, and (3) neglecting the THD of the output voltage and current and FFT analysis. The primary focus of the research has been focused on the presenting waveforms in the time domain. Thereby, those limitations are required to be considered in modelling or designing the grid-connected inverter. A filter value should be selected to be acceptable in practice and also should be available online to be realistic. An LCL filter value, for example, should be selected to be L1, which is located on the inverter side and is greater than the L2, which is located on the grid side. In addition, the damping resistor must be replaced with a virtual resistor, where the capacitor current controller is used. This damping resistor causes increased losses, and thereby lower efficiency. However, when the damping resistor is neglected the resonance is high, which leads to an unstable system. To overcome this problem, the capacitor current as the internal control loop is presented as a good solution. Furthermore, to reduce the LCL filter value, the LLCL filter as a new technique was revealed. Therefore, if the LCL filter is used with robust control, this is enough for designing a grid-connected inverter with an LCL filter. Also, the parasitic elements of the bridge and LCL filter are required to be taken into account, beside the ripple current on the battery side.

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