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Improving Functional Efficiency of Solar Photovoltaic for Grid connected systems with the help of MPPT charge controller

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Abstract

In recent years, global energy demand has surged due to the expansion of manufacturing industries, transportation systems, and the IT sector. However, the majority of electricity generation continues to rely on non-renewable sources such as coal, natural gas, oil, and uranium, leading to slow replenishment rates and exacerbating short-term energy shortages. This review paper is centered on the integration of photovoltaic (PV) systems into the electric power grid. Its primary objective is to optimize the management of power supplied to the grid from solar panels, enhancing the configuration and control of inverters to improve efficiency and align with networking requirements for seamless interaction between the grid and PV systems. The paper also addresses communication power management, encompassing both active and reactive power control. Proposed algorithms aim to simplify and strengthen grid-connected inverter power systems, leveraging digital power strategies. Furthermore, the study analyzes and enhances the performance constraints of Voltage Source Converters (VSCs) utilized for supplying active and reactive power to the grid. This involves streamlining the connection of solar panels, ensuring efficient operation of inverters, boosting current injection into the grid, and reducing harmonic levels to improve overall performance
Keyword: Photovoltaic system, inverter, Current, VSC, Capacitor.

1. Introduction

The increasing demand surpasses available supply, leading to significant fluctuations in global oil prices. Conversely, this energy consumption pattern exerts a considerable environmental footprint. Notably, the combustion of oil and coal generates substantial daily greenhouse gas emissions, contributing to climate change and heightened pollution levels [1]. These analyses prompt the exploration of innovative solutions to tackle energy deficits and mitigate environmental harm. Consequently, there is a growing emphasis on developing clean, non-polluting energy sources based on renewables, as sought after by energy producers and governments. Yet, the key to reducing reliance on fossil fuels lies in generating electrical energy from renewable sources, which are naturally and indefinitely replenished over time. Solar energy meets these criteria perfectly, as it is plentiful on Earth with virtually unlimited regenerative potential. It can be utilized directly for thermal purposes [2] or transformed into electrical energy using the photovoltaic effect. Despite its recognition for numerous years, the widespread adoption of solar energy continues to be constrained, largely due to the high cost associated with solar pannels.

Globally, the market for photovoltaic systems has experienced significant expansion, maintaining an impressive growth rate of approximately 30 to 40% annually for over a decade [3]. As per the Association of the European Photovoltaic Industry (EPIA), it is anticipated that by 2020, photovoltaic energy will fulfill 12% of Europe's electricity requirements, thanks to the swift progress of this technology. For instance, in 2009, solar panels in Spain catered to more than 1.5% of the nation's electricity demands, marking a transition from insignificance to significance. Projections suggest that solar power will become more cost-effective than traditional electricity by 2012. This notable growth is exemplified not only by technological advancements and reduced costs in photovoltaic panels but also by substantial research and development efforts in the power electronics sector, particularly driven by photovoltaic installations integrated into the power grid [4, 5].

Indeed, the efficacy and dependability of electrical inverters utilized in photovoltaic systems can vary significantly from year to year, impacting the financial viability of an electricity setup. Investors often face diminished returns on actual installations due to numerous technical challenges, indicative of suboptimal energy conversion and transfer from the panels, which exhibit erratic behavior. This renders the systems excessively costly and deficient in reliability. Moreover, their lifespan of three to five years falls short of meeting the demand for a durable and dependable power source compared to the extended lifespan of PV panels, typically guaranteed for over 25 years in commercial settings. Conversely, the proliferation of photovoltaic installations linked to the grid and inverters serving as interfaces to renewable energy systems has necessitated the formulation of new, more stringent guidelines and regulations pertaining to the quality of energy fed into the grid. Among these specifications is the requirement for inverters to solely inject active power into the grid with a high-power factor in accordance with prevailing standards.

Currently, the significant increase in grid-connected photovoltaic installations and the development of new standards have led to the rise of investors capable of supplying reactive power to the grid. To alleviate the concerns of numerous prospective consumers and adhere to the specifications of the new European standards concerning the expected performance of these systems upon conversion into operational installations, it is imperative to conduct research aimed at resolving technical challenges associated with power electronics. This involves enhancing the power quality and efficiency of inverters through advancements in topology and control. Among the persistent issues encountered in the operation of photovoltaic conversion plants is the challenge of effectively coupling the photovoltaic generator with various types of continuous and alternative loads or grid connections. The technological hurdles inherent in this coupling mechanism often result from poorly designed systems, leading to suboptimal production and transmission of power from the photovoltaic generator (GFV), thereby deviating from its maximum potential. While power generation is assured, it often occurs with significant production losses, rendering it more costly than anticipated. The primary objective is to optimize the operation of the GFV to achieve its maximum power output. A wealth of literature in this dynamic field presents algorithms for trackers designed to aid in locating the maximum power point (MPPT) when the grid-connected photovoltaic system is linked to a load via a static converter. Evaluating the exact performance of full power point trackers often proves to be difficult, leading to numerous research efforts focused on defining criteria for comparative assessment.

1.1 Photovoltaic Solar Energy

Renewable resources are abundant, sustainable, autonomous, and additionally serve to enhance integration. Photovoltaic solar energy emerges as a highly promising alternative, representing one of the innovative forms of "green" energy. Its rapid expansion is buoyed by the growing environmental consciousness among governments and various organizations, leading to increased support and subsidies to foster its adoption. Previously, photovoltaic solar energy primarily powered select applications such as satellites or remote locations lacking access to conventional energy sources. Indeed, the growing awareness of environmental issues has spurred a significant shift towards renewable energy sources such as solar and wind power. These sources offer a sustainable alternative to fossil fuels, which contribute to air and water pollution as well as climate change. Moreover, advancements in technology have made solar and wind energy more efficient and cost-effective, further bolstering their appeal as primary energy solutions. As society continues to prioritize environmental preservation, the adoption of renewable energy is likely to play a crucial role in shaping a cleaner and more sustainable future.

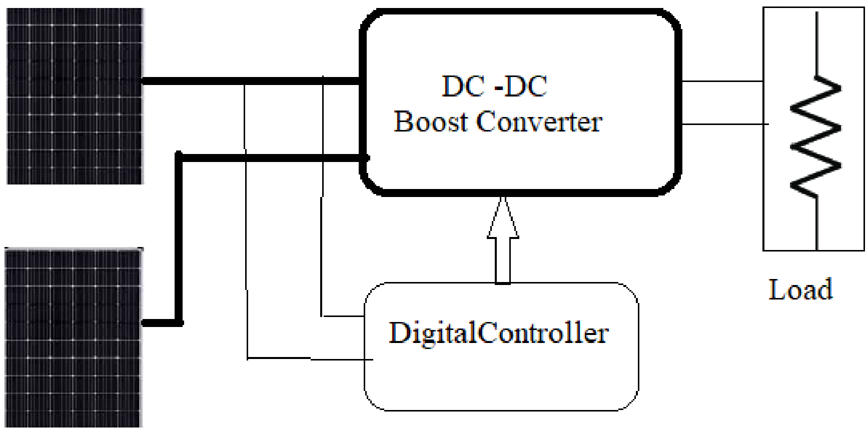

Figure 1: *PV Generation Systems Block Diagram*

Despite the cost limitations associated with utilizing renewable energy as a primary source, there is an increasing acknowledgment of the role solar energy can play in mitigating pollution, particularly in stabilizing carbon dioxide levels and preserving the environment. This form of energy presents a viable solution for electricity generation across various applications in developing nations, where a significant portion of the population lacks access to electricity. Photovoltaic solar energy holds immense potential for dispersed and diversified usage. Given its modular nature, it can be deployed in both rural and urban settings, in densely populated areas as well as remote locations, spanning from small-scale to large-scale installations. Essentially, there are two main applications for photovoltaic solar energy: standalone systems and grid-connected systems. Standalone systems offer a wide range of application possibilities, including powering isolated homes, rural electrification centers, telecommunications infrastructure, water pumping stations, cathode protection systems, signaling equipment, entertainment devices like stereos, lighting systems, computers, portable phones, cameras, calculators, and more. While standalone systems are highly regarded for their contribution to solidarity, especially in underserved areas, we believe that grid-connected photovoltaic solar energy could make a significant difference, particularly in regions where electrification levels are nearing saturation. The increasing adoption of solar photovoltaic energy is facilitated by grid integration. Currently, various countries in Europe, Japan, the USA, and others are providing economic incentives for renewable energy as part of their efforts to combat climate change. These incentives include funding for photovoltaic grid connections and compensation for the electricity generated and sold back to the grid.

1.2 Motivation

These discoveries have inspired diverse research endeavors aimed at creating sustainable photovoltaic sources, enhancing cell efficacy, and cutting expenses. Presently, there's a consistent decrease in the silicon necessary to generate a Wp, with a reduction rate of approximately 5% annually, leading to substantial cost reductions. This continual enhancement, coupled with the wide array of cell varieties or materials capable of generating the photovoltaic effect, reflects the extent and caliber of innovation within the sector.

2. Literature Review

Absolutely, the efficiency of a photovoltaic (PV) system is heavily dependent on the performance of its inverter. Inverters play a crucial role in converting the DC power generated by solar panels into usable AC power for consumption or grid connection.

From a technical standpoint, the topology of the inverter, which includes its design and configuration, can significantly impact its efficiency and overall performance. Additionally, the inverter's ability to perform optimal power point tracking (MPPT) is essential for maximizing the power output from the solar panels, especially under varying environmental conditions like shading or changes in sunlight intensity.

Furthermore, inverters must meet certain specifications to ensure superior performance and grid compatibility. This includes efficient grid regulation to maintain stability and reliability within the network, as well as minimizing harmonic distortion to prevent interference with other electrical devices and systems connected to the grid.

Overall, selecting the right inverter with optimal specifications is critical for maximizing the energy yield and reliability of a network-linked PV system, ultimately contributing to its high capacity factor and effective integration into the grid.

The initial segment of this section delineates various inverter topologies interfaced with the network. Subsequently, the second segment elucidates the predominant control methodologies employed in grid-connected inverters:

a) Current linear control
b) Current hysteresis control
c) Predictive current control

The concluding part examines the control architectures utilized in contemporary grid-connected inverters, alongside the remedies proffered in diverse literature for both three-phase and single-phase inverters.

Reference [6] introduced maximum power point trackers (MPPT), which are electronic devices designed to optimize the operation of photovoltaic modules by aligning them with the point at which maximum power output is achievable given prevailing irradiance and temperature conditions. MPPT monitoring systems typically regulate panel variables (voltage and current), although control of output electrical variables from the inverter (voltage and current) is also feasible, as these are linked to panel variables through a variable termed the duty cycle (D). Armed with this data, the system establishes the generator's operating point, continuously aiming to approximate it to the maximum power point (MPP) to enhance overall system efficiency.

In the study conducted by Author [7] concerning grid-connected photovoltaic systems, the design topology of the inverter consistently confines itself to supplying solely active power to the grid, omitting the injection of reactive power. The inverter's configuration prioritizes synchronizing current with the mains voltage and achieving unity power factor. There is a lack of analysis regarding the inverter's capability to furnish reactive power to the electrical grid, and the implementation of control mechanisms invariably entails complexity. Consequently, this study proposes an inverter design capable of delivering both active and reactive power in accordance with the requirements of the electrical network, employing a robust and straightforward digital control scheme.

In grid-connected inverters [8], the output voltage reflects the grid signal for grid-switched inverters, or it requires synchronization with the grid signal for auto-switched inverters. Ideally, the injected current in these devices should display sinusoidal characteristics. Static inverters employ semiconductor power devices that operate in either OFF or ON states. The output alternating signal may initially appear square, but power filters can transform it into a sinusoidal waveform. However, conventional harmonic filtering methods necessitate bulky capacitors and coils, which can compromise device efficiency. Hence, the objective when designing an inverter is to achieve output signals with minimal harmonic distortion.

The author [9] presents an examination of the development of inverters presently employed in grid-connected photovoltaic systems. The majority of low-power inverters utilize high-frequency switching control. Consequently, the resulting output waves exhibit sinusoidal characteristics, A high power factor, along with minimal harmonic distortion, ensures that the inverter consistently delivers active power to the grid while avoiding the injection of reactive power. Effective management of the real and reactive power output of photovoltaic systems is crucial for maintaining the integrity of the power distribution network.

Within PWM (pulse width modulation) [10], voltage regulation occurs through adjusting the widths of multiple pulses. In a single-phase inverter, control signals entail comparing a sinusoidal reference signal (Vref) with amplitude Vref and frequency fref, to a triangular signal (Vtri) with amplitude Vtri and constant frequency ftri. This comparison outcome triggers the inverter's driving circuit. The output voltage frequency remains steady, dictated by the frequency of both the output voltage and the triangular signal, which in turn determines the pulse count per half cycle.

Adjusting the output voltage, ranging from 0 volts to its maximum, is achieved by modifying the amplitude of the reference sinusoidal signal. This modification controls the variation in pulse width, spanning from its minimum to maximum, contingent upon the relationship between the frequencies of the triangular signal and the reference signal. In scenarios involving grid-connected inverters (VSI), it becomes crucial to precisely adjust the output voltage level. Voltage regulation relies on the reference signal, orchestrating the inverter's function and determining the triggering pulses for its controlled switches. The reference signal originates from feedback loops within the system, tasked with compensating for fluctuations in load or supply voltage.

The arrangement [12] of the power circuit, coupled with the photovoltaic module's current source linked to its input and the AC connection to the electrical grid, can be achieved through various configurations, commonly referred to as bridge configurations. These configurations include single-phase setups suitable for low-power applications and three-phase setups ideal for medium to high-power scenarios. In a single-phase bridge setup, two sets of semiconductors are connected to the poles of the photovoltaic array. The midpoint between these switch branches is directly connected to the electrical grid in grid-connected installations.

3. Methodology

In the scenario of an off-grid photovoltaic system, voltage control is essential. However, in grid-connected inverters, both voltage and current control methods are applicable. Among these, the prevalent choice for photovoltaic applications is the self-switched current-controlled inverter. This option facilitates achieving a high power factor [13] through a straightforward control circuit while effectively mitigating current transients induced by distortions or noise, such as voltage fluctuations in the power system. Conversely, auto-switched inverters can synchronize their output alternating voltage with the grid's voltage, enabling them to inject varying levels of current into the grid. Voltage regulation is executed via PWM pulse width modulation, wherein pulse width adjustments trigger circuit breakers to maintain output voltage stability. At elevated frequencies, these inverters can synchronize the current signal with the mains voltage signal, thereby rectifying the power factor [14]. A Voltage Source Inverter (VSI) can transition to current control mode by integrating a current regulation loop, while a Current Source Inverter (CSI) can function in voltage control mode through the inclusion of a voltage regulation loop.

In VSI inverter modulation techniques, two distinct control methods can be identified:

Scalar control of VSI inverters:

This approach involves adjusting the value of an electrical parameter to match a reference signal, thereby dictating the switching signals for the switches.

Vector control of VSI inverters

Here, the focus is on modifying both the amplitude and phase of a reference signal, referred to as the reference vector. This reference vector then determines the switching signals for the controlled switches, enabling the attainment of the desired output signal.

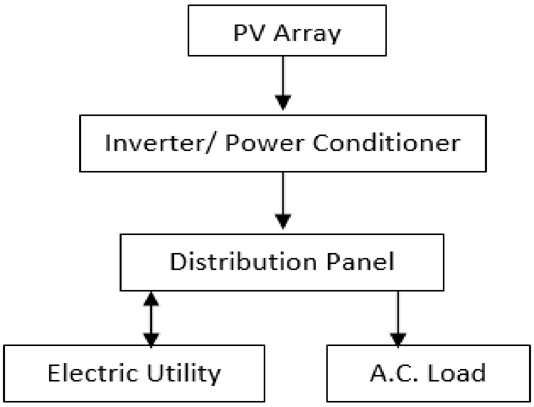

Figure 2: *Block Diagram of Grid Connected PV System*

Below, a comprehensive explanation is provided regarding the structure and functioning of a VSC converter, elucidating its role as a VSI inverter.

3.*1 Proposed Methodology*

To begin, a generator is essential for producing photovoltaic solar electricity, comprising interconnected solar panels. Subsequently, to convert the direct current generated by a photovoltaic solar generator [15] into alternating current ("AC") with identical specifications to the conventional grid (230V AC with a frequency of 50Hz), an inverter is required. Photovoltaic inverters designed for grid connection [16] differ from those used in standard electronics, as they are specifically designed to operate directly connected to the photovoltaic generator. Positioned between the photovoltaic generator and the grid connection point [17], these inverters facilitate the transformation of solar energy into electrical energy, subsequently injecting it into the grid, thereby offering economic benefits and addressing environmental concerns [18].

To enhance the efficiency of the PV system, inverters need to track the peak power point. Moreover, they should operate at peak efficiency, producing electricity with specific quality parameters (such as minimal harmonic distortion, high power factor, and reduced electromagnetic interference), while adhering to safety regulations for individuals, equipment, and the electrical grid. Indeed, the photovoltaic system (comprising photovoltaic modules) exhibits a nonlinear curve characteristic.

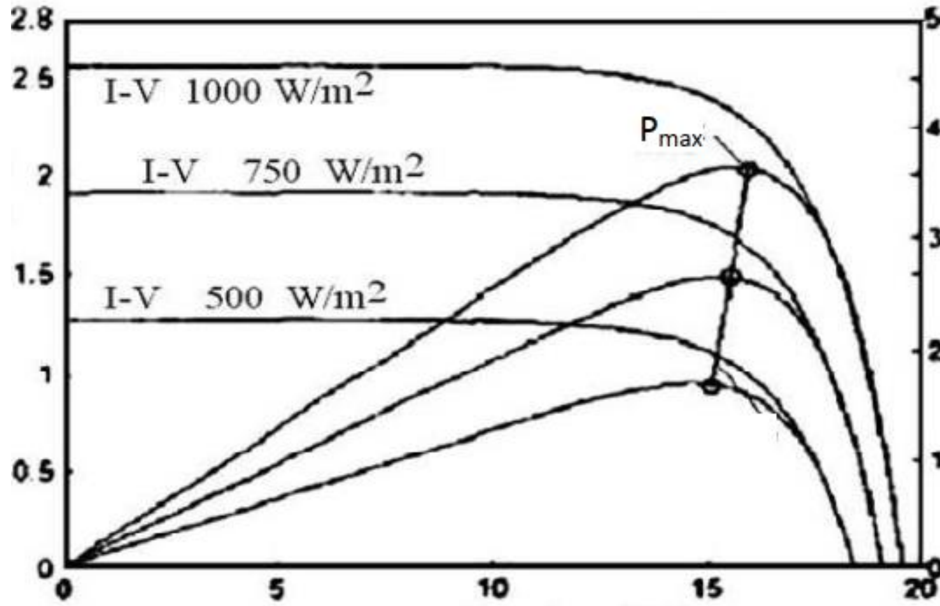

Figure 3: *Photovoltaic Module Graph*

4. Result and Analysis

To assess the effectiveness of the control strategy proposed in the study for the single-phase inverter connected to the grid using either a filter or an LCL filter, we utilized power factor and harmonic distortion measurements [19]. Figure 4 illustrates the relationship between the switching frequency (fc) and the inductance value of the output filter (L), resulting in a power factor MP = 0.996. Figure : 4 illustrates the variation of the filter inductance L concerning the switching frequency (frequency modulation index).

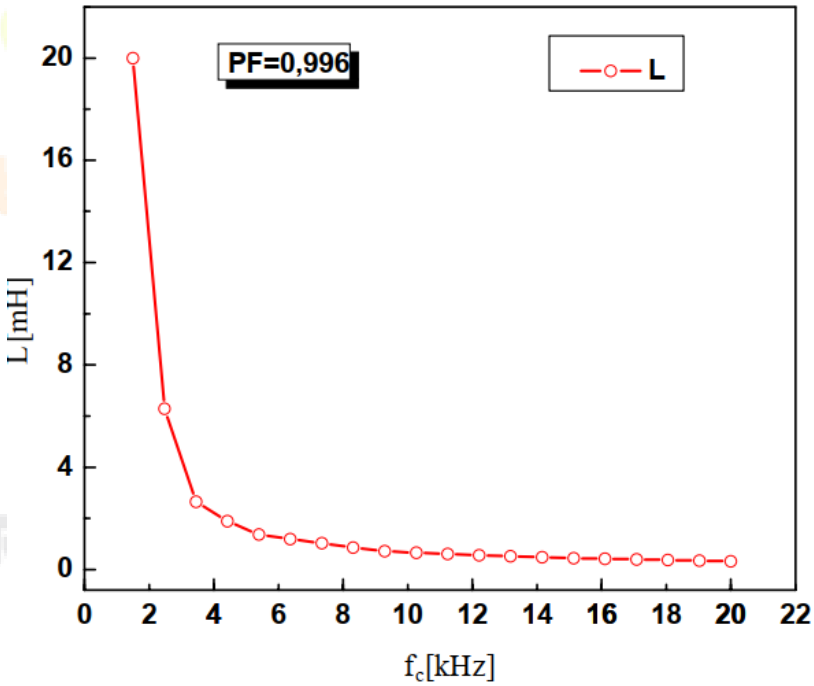

Figure 4: *Variation of Filter Inductance L with Switching Frequency fc*

Using this approach enables the attainment of inductance levels around 0.327 mH at a switching frequency of 20 kHz and 8 mH at a frequency [20] of 2.2 kHz. Table 1 presents several switching frequency f_c values corresponding to different inductance values L.

Table 1: Comparison of Switching Frequency and Filter Inductance for Power Factor (FP) of 0.996

Fc	L
1,5 **kHz**	20x10^{-3} **Hz**
2.2 **kHz**	8 x10^{-3} **Hz**
3.0 **kHz**	3 x10^{-3} **Hz**
5.0 **kHz**	1.43 x10^{-3} **Hz**
9.0 **kHz**	0.74 x10^{-3} **Hz**
10.0 **kHz**	0.67 x10^{-3} **Hz**
15.0 **kHz**	0.56 x10^{-3} **Hz**
20.0 **kHz**	0.45 x10^{-3} **Hz**

5. Conclusion

The primary purpose of the research is to enhance the operational efficiency of the photovoltaic system integrated with the grid through digital monitoring of a single-phase inverter. We aim to utilize the phase shift of the inverter output voltage in conjunction with grid-connected power regulation. Our investigation delves into the relationship between the inverter output phase shift, grid voltage, and the limitations encountered in supplying active and reactive power to the grid. We propose a novel technique for monitoring the inverter output current amplitude, power factor, and subsequently, the active and reactive voltage delivery. This method relies on modulation patterns and the phase variation of the inverter's power output voltage.

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