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IMPLEMENTATION OF A THREE-PHASE GRID-CONNECTED SOLAR SYSTEM IN MATLAB

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Abstract
This study explores the implementation of a three-phase grid-connected solar photovoltaic (PV) system using MATLAB/Simulink. The system incorporates critical components such as Maximum Power Point Tracking (MPPT) algorithms, DC-DC converters, and inverters to maximize energy extraction and enable efficient power conversion. A detailed analysis of grid synchronization techniques, including Phase Locked Loop (PLL) and Pulse Width Modulation (PWM) control strategies, highlights their role in maintaining system stability and grid compliance. The simulation framework allows for performance evaluation under varying operating conditions, addressing key aspects such as energy efficiency, harmonic distortion, and power quality. By leveraging MATLAB/Simulink, the study demonstrates how system behavior can be optimized to adhere to regulatory standards while minimizing energy losses. This research underscores the importance of simulation tools in the design and optimization of grid-connected solar systems, providing valuable insights into control strategies and system integration. The findings serve as a foundational reference for researchers and engineers aiming to enhance the performance and reliability of solar PV systems in modern energy networks.
Keywords: Grid-connected solar system, three-phase inverter, solar PV system, MATLAB/Simulink.

I INTRODUCTION
Solar-grid integration is a network allowing substantial penetration of Photovoltaic (PV) power into the national utility grid. This is an important technology as the integration of standardized PV systems into grids optimizes the building energy balance, improves the economics of the PV system, reduces operational costs, and provides added value to the consumer and the utility. Solar-grid integration is now a common practice in many countries of the world; as there is a growing demand for use of alternative clean energy as against fossil fuel. The increasing demand for renewable energy has highlighted the critical role of solar photovoltaic (PV) systems in modern power grids. A grid-connected solar PV system facilitates the integration of clean and sustainable solar energy into the electrical grid, ensuring energy efficiency and reducing dependence on fossil fuels. The implementation of a three-phase grid-connected solar system is particularly important for industrial and large-scale applications, as it ensures balanced power distribution and improved system reliability. This system typically involves a solar PV array, a Maximum Power Point Tracking (MPPT) controller, a DC-DC boost converter, an inverter, and a grid synchronization mechanism. MATLAB/Simulink serves as an ideal platform for modeling, simulating, and analyzing these components, offering robust tools to study the dynamic performance of the system under varying solar irradiance and load conditions. The primary objectives include efficient power conversion, seamless grid synchronization, and adherence to power quality standards. This project aims to design and simulate a three-phase grid-connected solar PV system, providing insights into its operational characteristics and potential for real-world deployment.
Additionally, the implementation of a three-phase grid-connected solar system provides opportunities for exploring advanced control strategies and optimization techniques. For instance, adaptive control methods can be integrated to handle dynamic environmental conditions more effectively, ensuring

maximum power extraction and minimal energy losses. Furthermore, the use of smart grid technologies can enhance system performance by enabling real-time communication and coordination between the solar system and the grid, thereby improving energy management and distribution efficiency. In the context of renewable energy research, the three-phase grid-connected solar system serves as a testbed for evaluating the impact of grid integration on stability and power quality. Challenges such as voltage fluctuations, frequency deviations, and harmonic distortions can be addressed through the implementation of advanced filtering techniques and grid-support functionalities like reactive power compensation and fault ride-through capabilities.

1.1 Solar Energy Systems

Solar energy systems harness sunlight to generate electricity or heat, playing a crucial role in the global transition to renewable energy sources. These systems offer an environmentally friendly alternative to fossil fuels, reducing greenhouse gas emissions and dependence on non-renewable resources. Among various solar energy technologies, photovoltaic (PV) systems, concentrating solar power (CSP), and solar thermal systems are prominent, with PV systems being widely used for their simplicity and efficiency. Photovoltaic systems convert sunlight directly into electricity using semiconductor materials. These systems consist of solar panels, an inverter, and other components such as charge controllers and batteries. Solar panels, composed of multiple solar cells, generate direct current (DC) electricity when exposed to sunlight. The inverter then converts this DC power into alternating current (AC) power, which can be used by household appliances or fed into the electrical grid. The efficiency of PV panels typically ranges from 15% to 20%, with high-performance panels achieving slightly higher values.

CSP systems use mirrors or lenses to concentrate sunlight onto a small area, generating high temperatures to produce steam that drives a turbine connected to an electricity generator. These systems are suitable for large-scale power plants and require direct sunlight to operate efficiently. CSP technologies include parabolic troughs, solar towers, and dish Stirling engines. CSP systems can achieve thermal efficiencies of up to 30% and are complemented by thermal storage systems that enable power generation even when the sun is not shining. Solar thermal systems capture sunlight to produce heat, which can be used for various applications such as domestic hot water, space heating, and industrial processes. These systems typically use flat-plate collectors or evacuated tube collectors to absorb and transfer solar heat to a fluid. Solar thermal systems are known for their high efficiency in converting solar energy into heat, with typical efficiency values ranging from 40% to 60%. Three-phase grid-connected solar systems are designed to supply electricity to the electrical grid. They consist of three-phase inverters that convert the DC power from solar panels into three-phase AC power, which is compatible with the grid. These systems are favored for their ability to handle higher power outputs and maintain stable voltage levels, making them suitable for both residential and commercial applications. By feeding excess electricity back into the grid, these systems contribute to a more sustainable and resilient energy infrastructure.

2. Solar-Grid system

Solar-Grid integration is the technology that allows large scale solar power produced from PV or CSP system to penetrate the already existing power grid. This technology requires careful considerations and attentions including in areas of solar component manufacturing, installations and operation. The levels of solar energy penetration must be interconnected effectively onto the transmission grid; such interconnection requires an in-depth understanding of the effects on the grid at various points.

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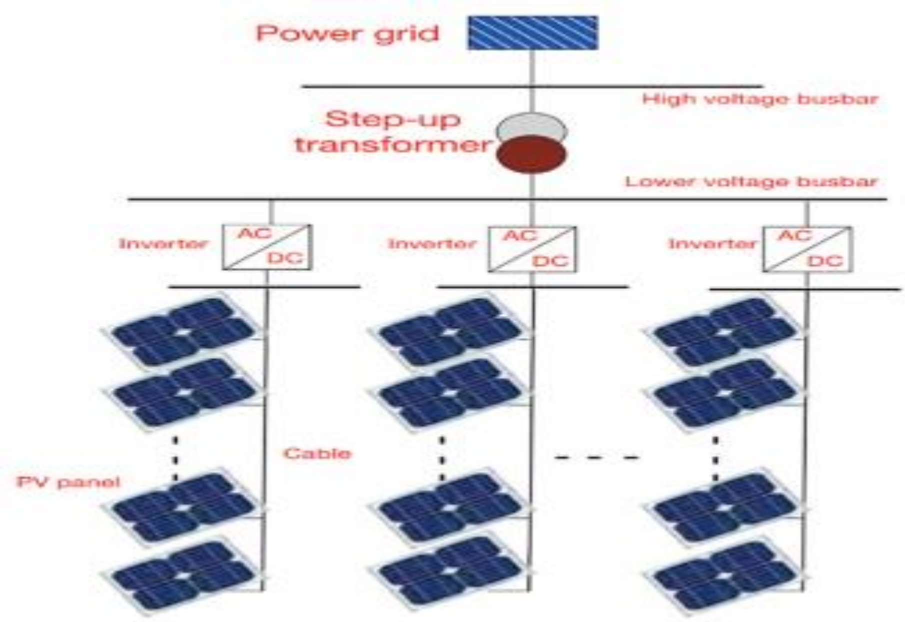

Fig. 1 Diagram of a PV power station

Photovoltaic plant which uses PV modules to feed into the grid essentially consists of different components, but basically the inverter is the most important component for integration. Other components include PV generator (solar modules), Generator junction box (GJB), Meters, Grid connection, and DC and AC cabling as shown in Fig. 1. Inverters play a crucial role in any solar energy system and are often considered to be the brains of a project. An inverter's basic function is to ''invert" the direct current (DC) output into alternating current (AC) which is the standard used by all commercial appliances. Inverters are required to supply constant voltage and frequency, despite varying load conditions, and need to supply or absorb reactive power in the case of reactive loads. Apart from inverting, inverters do reconcile the systems with each other and to feed the solar power into the grid with the highest possible efficiency. A PV installation's yield is, therefore, just as heavily dependent on the reliability and efficiency of the inverter as on the orientation, interconnection and quality of the PV modules.

3. Grid Connected PVSystem

Grid-connected PV systems can vary greatly in size, but all consist of solar modules, inverters (which convert the DC output of the solar modules into AC electricity), and other components such as wiring and module mounting structures.

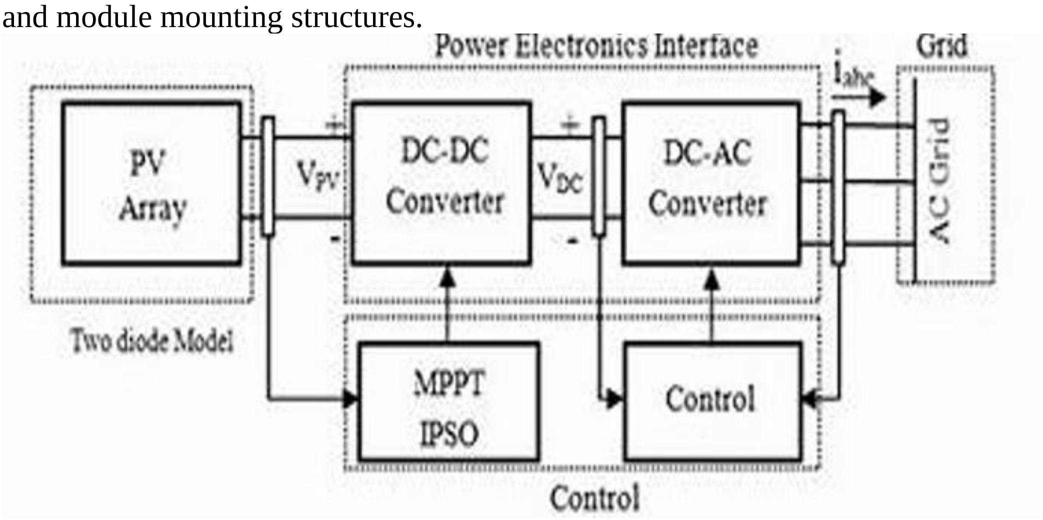

Fig 2 Block Diagram of a Typical PV-Utility Grid Connected

Some of the first grid-connected systems consisted of several hundred kilowatts of PV modules layed out in a large centralized array, which fed power into the local high voltage electricity network in much the same way as a large thermal generator. In recent years, small rooftop mounted systems have become increasingly popular, as improved technology has enabled the advantages of such systems to be exploited. It is now becoming increasingly common for homeowners to install a small PV system on their roof to supply some or all of their electricity needs. For a small grid-connected rooftop PV system, the power produced by the array during the day can be used to supply local loads, with the excess energy fed into the local grid for use by other customers. At night, the local loads are simply supplied by the grid. If the PV system is large enough, it can supply more energy into the grid than is used by local loads. Instead of receiving a bill every month, the customer would then receive a cheque from their utility for generating this electricity.

Anjali et.al (2017), presents a literature review of the recent technological developments and trends in the Grid Connected Photovoltaic Systems (GCPVS). In countries with high penetration of Distributed Generation (DG) resources, GCPVS have been shown to cause unwanted stress on the electrical grid. A review of the existing and future standards that addresses the technical challenges associated with the growing number of GCPVS is presented. Maximum Power Point Tracking (MPPT), Solar Tracking (ST) and the use of transform-less inverters can all lead to high efficiency gains of Photovoltaic (PV) systems while ensuring minimal interference with the grid. Inverters that support ancillary services like reactive power control, frequency regulation and energy storage are critical for mitigating the challenges caused by the growing adoption of GCPVS. **Manasseh Obi et.al (2016)** review the recent developments and trends pertaining to Grid-Connected Photovoltaic Systems (GCPVS). In countries with high penetration of Distributed Generation (DG) resources, GCPVS have been shown to cause inadvertent stress on the electrical grid. A review of the existing and future standards that addresses the technical challenges associated with the growing number of GCPVS is presented. Maximum Power Point Tracking (MPPT), Solar Tracking (ST) and the use of transform less inverters can all lead to high efficiency gains of Photovoltaic (PV) systems while ensuring minimal interference with the grid. Inverters that support ancillary services like reactive power control, frequency regulation and energy storage are critical for mitigating the challenges caused by the growing adoption of GCPVS. **J Sreedevi et.al (2016),** Photovoltaic (PV) energy has a fast growing annual rate and is quickly becoming an important part of the energy balance in most regions and power systems. This paper aims to study the effects of connecting a PV system to the grid through simulation of the system in RSCSD software in real time on the Real Time Digital Simulator (RTDS). Effect of variation of power factor of loads, variation of PV penetration, introduction of harmonics into the system by the PV inverter and anti-islanding effect of the PV system are studied. Finally, the Performance Ratio (PR) of a typical grid connected PV system is evaluated to determine the reliability and grid connectivity of the PV system. **Bo Yang, Wuhua Li et.al (2010),** A grid-connected photovoltaic (PV) power system with high voltage gain is proposed, featuring a ZVT-interleaved boost converter with winding-coupled inductors and active-clamp circuits as the first power-processing stage to boost low PV array voltage to a high DC-bus voltage. The system uses a full-bridge inverter with bidirectional power flow for stabilizing the DC-bus voltage and shaping the output current. Compensation units are included in the control loops to achieve low total harmonic distortion (THD) and fast dynamic response. A simple maximum power point tracking (MPPT) method based on power balance is employed to reduce complexity and cost while maintaining high performance. A 2-kW prototype was developed and tested, validating the theoretical analysis and system effectiveness.

4. Challenges, benefits and environmental impact of solar-grid integration

J. Katz et.al (2019) In most electric utility systems, power flows in one direction - from centralized generators to substations, and then to consumers. With solar power generation, power can flow in both directions. However, most electric distribution systems were not designed to accommodate two-way flow of power. For distribution feeder circuits that are long and serve rural or developing areas, even small amounts of PV may impact system parameters if the load and PV generation are not closely matched. When PV generation exceeds local energy demand, energy will move through the distribution feeder and possibly through the local substation, increasing the potential for damage to the utility grid and for impacts to other utility customers served by the same distribution circuit

For large-scale PV projects or farms, most of which are located far away from urban centers, they often require transmission lines to carry the electricity long distance to where it will actually be used. This requires more investment in building the transmission lines and often results in ‘‘line losses” as some of the energy during transportation are converted into heat and lost. Some notable challenges associated with Solar-Grid integration include problems of voltage stability, frequency stability, and overall power quality. According to Belcher et al.(2017), a distributed system is considered large-scale when loading on the system is greater than 10 MW. Systems under this limit do not qualify for power integration and usually have many power quality issues. However, large-scale systems also experience power quality problems. Power generation plants that use the conventional method to spin a turbine benefit from having complete control over generation, Photovoltaic generation does not have the luxury of producing power on demand Power quality issues range from voltage and frequency to other areas such as harmonics. The harmonics problem comes mainly from power inverters used in converting renewably generated DC voltage into AC. Harmonics are created by certain loads who introduce frequencies that are multiples of 50 or 60 Hz and can cause equipment to not operate as intended. **E. Mulenga et.al (2015),** The inherent non-dispatchable characteristics of PV systems (i.e. generation of electrical energy that cannot be turned on or off in order to meet societies fluctuating electricity needs) allow voltage generation fluctuations that have not previously been present in the grid. In order to combat these voltage issues, storage solutions along with other instantaneous power producing solutions are on the forefront of current PV research and development. Alongside the intermittency of PV generation itself, there are also grid-connected voltage quality issues that must be considered. Power plants must be able to ride-through various voltage levels sags in order to operate with-out outages. This requires that PV plants should be adaptable to voltage sags just as conventional power plants. PV is also the only solar power generation technique that does not result in inertial power generation which proves to be a challenging problem with large-scale grid integration. The lack of inertia injected into the grid is the result of the lack of a rotating machine in PV integration

5. Overview of the global energy scenario and the need for sustainable energy sources.

This scenario shows an increase in total primary energy demand of 47% from 2020 to 2050. Consumption of all energy sources increases from today with renewables growing significantly faster than all other sources. The right-hand panel shows the percentage share of energy consumption by source for 2020 and 2050.

Cherp et al. (2018) suggests a system approach to global energy analysis in which a mixture of different methods is used. More recently, global energy scenarios have focused on social considerations in addition to technological and economic dimensions Dahl (2015) reviewed energy drivers in terms of social and economic approach. She has mentioned that the world economic and income growth of different countries are the main economic drivers and the population growth rate and life expectancy are considered to be the most important social factors playing significant roles in reshaping the future global energy system. Ansari and Holz (2019) identified four major drivers including population growth and urbanization, energy cost reduction, fossil fuel availability, and economic integration using the STEMPLE framework. Technological progress as one of the major global trends has led to the fossil energy dominance in the global energy market up to 2040 Blazev 2016. According to Florini and Sovacool (2009), the inappropriate governance, government intervention in the pricing system, and lack of investment are important factors adversely influencing the future of international energy markets. S. Ghasemian (2020) maintained that the technological advancement, population growth and gross domestic product growth will be the main energy drivers in China and India. Huang (2014) has considered structural, demographic, technological and temperature changes as the main drivers of the global energy demand. Gielen et al. (2019) introduced the energy efficiency and renewable energy technologies as the major drivers of energy transition to 2050.

6. Evolution of solar PV technology and grid-connected systems

Grid-connected PV systems are typically designed in a range of capacities from a few hundred watts from a single module, to tens of megawatts from a large ground mounted system. Nick Jenkins et.al (2018), presents the electricity companies with a range of connection requirements depending on where they connect to the electricity network and at which voltage level. While the main components of a grid-connected PV system may differ in detail between system sizes the overall concepts are the same. **H. Haeberlin et.al (2001),** conducted extensive tests on small grid-connected PV inverters since 1989. In 1994, a new test center with a 60 kWp PV generator enabled testing of medium-sized inverters up to 30 kW. Between 1998 and 2000, solar generator simulators up to 25 kW were developed, allowing faster and more automated inverter tests. This paper provides an overview of grid-connected PV inverter concepts, test results from over 28 inverters, and insights into advancements in inverter performance and reliability. Despite significant improvements, challenges remain, including RF suppression and MPPT efficiency testing. HTA Burgdorf continues to enhance inverter testing capabilities, contributing to the evolution of PV inverter technology and supporting manufacturers in improving product quality. **Michael Emmanuel et.al (2017),** The evolving smart grid emphasizes plug-and-play connections of spatially distributed microgrids integrating renewable and non-renewable energy sources. A shift towards renewable distributed generation, particularly photovoltaic (PV) systems, is driven by global incentives, climate concerns, and energy market deregulation. However, PV systems face challenges such as mismatches between power output and load profiles, leading to voltage violations, energy losses, and reverse power during low load conditions. To address this, dispatchable PV units with load-following capabilities are crucial for grid modernization, enabling controllable output when combined with storage systems. This article reviews deployment scenarios of dispatchable PV units, utility-interactive inverter technologies, and the evolution of control, monitoring, and communication systems for integrating dispatchable distributed energy resources into modern electric power systems.

Table 1. Required Fundamentals for Grid Integration of Renewable Energies.

Area of Interest	Target Goals
Standards	Must abide and comply with ANSI, UL, NEC, and OSHA standards for operational safety.
Implementation planning and future forecasting	Must be able to perform for approximately 25–30 years. Modern energy management systems to incorporate variability of renewable resources. Computational intelligent forecasting tools. Integrate storage demands. Predict long-term needs. Avoid component exhaustion in severe disturbances.
Performance of the components	Over a 25-30 year projected lifetime performance the device should be able to: - Have less than 5% internal loss while in a fully charged state. - Have an efficiency of over 90%. - Be able to perform over 50,000 cycles of charging and discharging with no less than 90% capacity retention. - Must be supplied as a reactive dynamic resource and provide power on demand regardless of the time of year.
Financial/Cost of overall project	Must have flexible costs in regards to performance and duration. Should cost less than 4¢/kWh after the system is fully installed. Must provide cost-effective and adaptable benefits for the system integration of the PV plant, inverters, storage devices, transformers, busbars, interconnectors, and other devices which will ensure optimal operational states.
Communication to and from components on the smart grid	Must allow monitoring and communication to and from the components within the smart grid. Safe to maintain and prevent against external attacks. Must be able to be controlled and provide feedback to the supply utility agency. Communication protocols must be compatible with current power electronic devices in the system for data sharing in a homogeneously operating system. Must be able to respond to electrical market price trends and changes in energy demand. Must be able to predict, simulate, and optimize the optimal methods to provide best power quality within the smart grid.

7. THREE-PHASE GRID-CONNECTED INVERTERS

Three-phase inverters are widely used in industrial applications such as motor drives, standby power supplies and uninterruptible power supplies. However, in three-phase grid connected inverter, the output of the inverter is connected to the grid. The inverter includes six IGBT switches connected in the form of a bridge configuration. The three-phase grid connected inverter topology is shown in Fig. It contains of a dc voltage source (Vdc), six power switches (SI-S6), a (L) filter, two capacitors (C) and utility grid (Vgrid). In inverter based DG, the output voltage from inverter must be higher than the Vgrid, in order to assure power flow to the grid.

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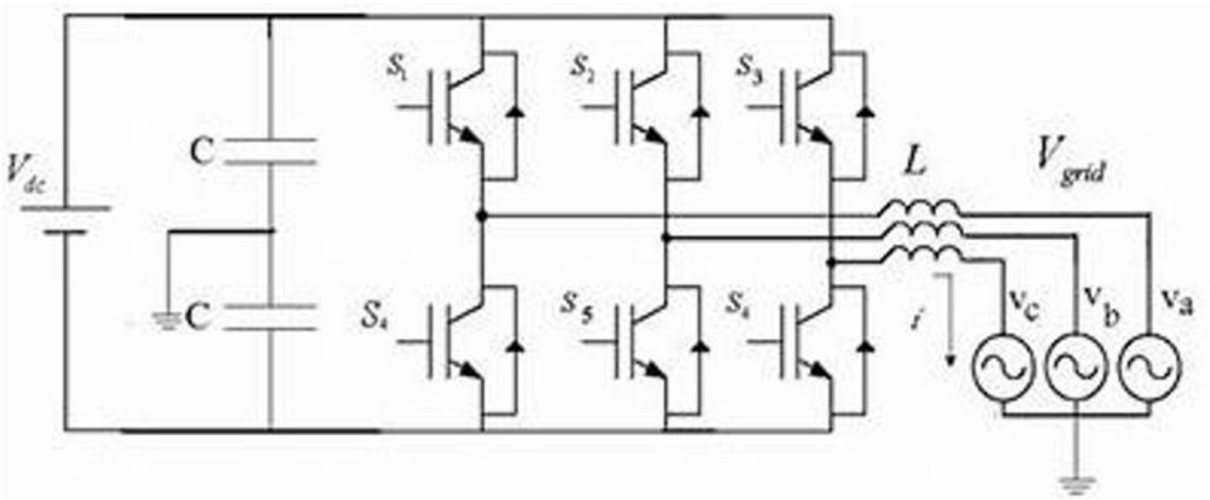

Fig. 3: Three phase grid connected inverter

Figure 3 shows an electronic circuit structure to connect a photovoltaic to a three-phase grid. The major circuit consists of main blocks such as photovoltaic cells, turbochargers, DC lines, 3-phase inverters, filters and grids. The control circuit includes maximum power point detection, space vector modulation for inverters and grid synchronization.

1. Photovoltaic Generator

PVG Photovoltaic generators are considered as current source with an equivalent electrical diagram as shown in Fig. 3. The relationship between the current, voltage, and power (Ipv, Vpv and Ppv) parameters of a photovoltaic (PV) depends on the intensity of the solar radiation and its temperature.

2. DC/DC Converter

The DC/DC converter is a voltage boost that includes L1 inductance, IGBT transistors and Diode D. They are responsible for increasing the voltage and performing the maximum power point detection algorithm of the photovoltaic (MPPT). DC/DC has 2 energy accumulation factors and therefore, has 2 control variables. They are the photoelectric voltage U_{pv} and the photoelectric current I_{pv}

3. DC Line

In general, the DC line voltage varies depending on the environmental conditions, means that depending on the temperature and the density of solar radiation.

4. Three-phase grid connected inverter

The three-phase grid connection has 6 IGBT switches connected in form of bridge diagram as shown in Fig. The output of the inverter has a filter inductance to filter the harmonics to reduce current distortion. The inverter needs to operate as a power controller between the DC link and the grid.

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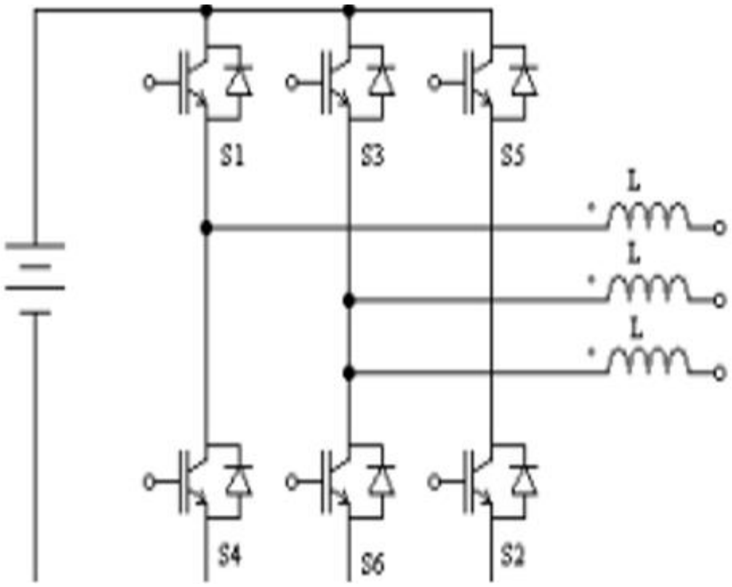

Fig 4. The three-phase inverter

5. Grid According to Thevenin, it can be represented the three-phase grid by voltage source that has 220V voltage, 50Hz of frequency in series with the Z = R + jx, in which the Z impedance includes the impedance of filter output of the inverter (Fig. 5).

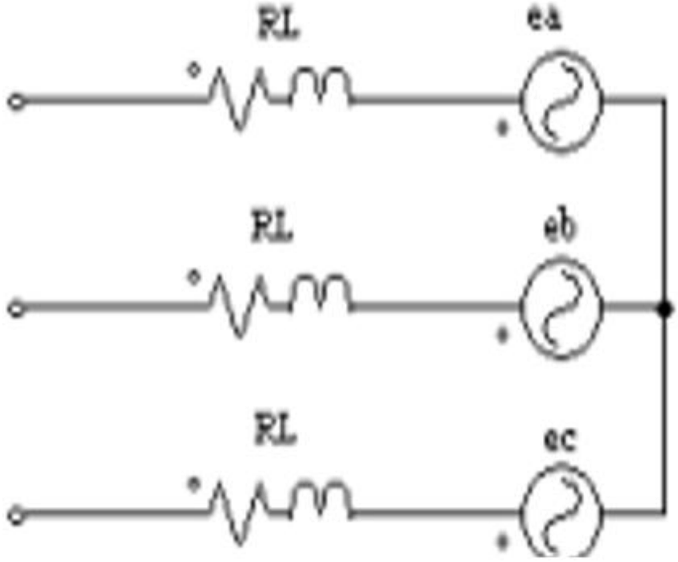

Fig.5.The Thevenin diagram of three-phase grid

8. Advancements in MPPT techniques, inverter designs, and grid interfacing methods.

Yogita Sahu et.al (2017), review the most commonly used MPPT methods has been done for grid connected systems. Also, the paper provides a survey of different modelling parameters required for grid connected systems, such as photovoltaic cell, dc to dc converter, etc. In this paper various design strategies for grid connected PV systems with MPPT has been surveyed & a design for new grid connected PV systems with MPPT is proposed. **Omorogiuwa Eseosa et.al (2020),** Technical advancements in solar photovoltaic (PV) systems have grown significantly in recent years, making them technologically viable but still economically challenging due to affordability issues. To address this, the development of maximum power point tracking (MPPT) techniques has become critical for optimizing efficiency and effective utilization of solar energy. This study reviews various MPPT methods, including their design, characteristics, operational principles, PV array planning, and the necessity of such systems. Techniques covered include offline methods like open circuit voltage, short circuit current, and look-up tables, hybrid approaches such as Perturb and Observe (P&O) and incremental conductance, as well as temperature-based, artificial intelligence (AI)-controlled, and fuzzy logic control techniques. The significance of irradiance and fill factor in MPPT technology is also discussed.

CONCLUSION

This review highlights the critical aspects of implementing a three-phase grid-connected solar photovoltaic (PV) system using MATLAB/Simulink. The study emphasizes the importance of simulation tools in understanding and optimizing the performance of solar PV systems for efficient integration into power grids. Key components such as MPPT algorithms, DC-DC converters, inverters, and synchronization techniques have been discussed, showcasing their roles in enhancing energy extraction, power quality, and grid compliance. While simulation provides a cost-effective and scalable platform for testing various configurations and control strategies, challenges such as accurate modeling of real-world conditions and minimizing harmonic distortion remain areas for further research. This review serves as a valuable resource for researchers and engineers working on solar PV system design and optimization, offering insights into current practices and future directions.

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