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Single-Stage Single-Phase Reconfigurable Solar Inverter System Using Fuzzy Logic Controller

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ABSTRACT:-

This project suggests a reconfigurable single phase inverter topology for a hybrid AC/DC solar powered home. This inverter possesses a single-phase single-stage topology and the main advantage of this converter is that it can perform dc/dc, dc/ac, and grid tie operation thus reducing loss, cost and size of the converter. This hybrid ac/dc home has both ac and dc appliances. This type of home helps to reduce the power loss by avoiding unnecessary double stages of power conversion. It improves the harmonic profile by isolating dc loads to dc supply side and rest to ac side. Simulation is done in MATLAB/Simulink environment. This type of solar powered home equipped with this novel inverter topology could become a basic building block for future energy efficient smart grid and micro grid.

Key Words:- Reconfigurable Solar Converter (RSC), Single-stage inverter, Hybrid AC/DC system, Fuzzy Logic Controller (FLC), Harmonic mitigation, Power quality improvement, MATLAB/Simulink simulation, Maximum Power Point Tracking (MPPT), Renewable energy integration, Smart grid

1. INTRODUCTION:-

1.1 Objective:-

The main contribution of this project is the implementation of a single-phase single-stage reconfigurable solar converter (RSC) designed for hybrid AC/DC solar-powered residential buildings equipped with energy storage systems. The RSC is capable of operating in various modes, including PV to grid (DC–AC), PV to battery or DC loads (DC–DC), battery to grid (DC–AC), combined battery/PV to grid, and grid to battery (AC–DC). This versatility allows for efficient power management and reduces the need for multiple converters. The system is tested in a home setup containing both AC and DC appliances, chosen based on their harmonic impact on the grid. Additional contributions of the project include the use of distinct electrical components and sensors, a standard inductor for DC–DC operation, and the inclusion of solar radiation variability in the system design. Circulating currents are minimized through optimized switching, and a custom control logic with unique sampling of input parameters further distinguishes this implementation from earlier works.

1.2 Description:-

The rapid growth of solar photovoltaics (PV) has led to increased use of rooftop systems due to cost reduction and supportive policies. However, the intermittent nature of PV and the rise of nonlinear household loads pose challenges like voltage instability and harmonic distortion. To address these, hybrid AC/DC home grids with energy storage and intelligent inverter systems are being explored. Literature suggests solutions such as virtual harmonic damping, PV-battery voltage control, and reconfigurable inverter topologies. Among these, single-phase single-stage reconfigurable inverters offer cost-effective, compact, and efficient power conversion for modern smart homes.

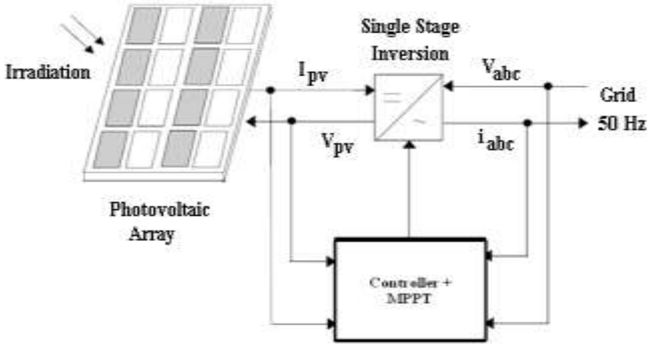


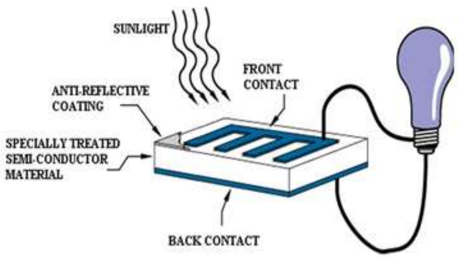
Figure-1: Single Stage Grid Connected PV Generation Block Scheme

1.3 Focus Of The Project:-

The focus of this project is to develop and implement a single-stage single-phase reconfigurable solar inverter system for hybrid AC/DC solar-powered residential buildings, aimed at enhancing energy efficiency, reliability, and power quality. The system integrates renewable energy sources with energy storage devices, allowing flexible operation in multiple modes such as PV to grid, PV to battery/DC loads, battery to grid, and grid to battery. Unlike traditional two-stage inverters that increase cost, size, and conversion losses, the proposed topology reduces these factors while maintaining performance. A Fuzzy Logic Controller (FLC) is used for intelligent decision-making and adaptive control, enabling better handling of nonlinear loads and variable solar conditions. The inverter supports both AC and DC household appliances, selected based on their harmonic contributions to the grid, effectively minimizing power quality issues like harmonics and voltage fluctuations. The system is modeled and simulated in MATLAB/Simulink, and results demonstrate its ability to efficiently manage power flow and improve overall system behavior. This project addresses the growing demand for compact, smart, and cost-effective solutions in modern energy systems and contributes toward the realization of smart homes and future-ready microgrids

2. PHOTOVOLTAIC TECHNOLOGY :-

Photovoltaic (PV) technology involves converting sunlight directly into electricity using semiconductors that exhibit the photovoltaic effect. This effect occurs when light generates voltage in a material. The basic unit of PV technology is the solar cell, typically made of silicon, a semiconductor whose conductivity is enhanced by doping with impurities like phosphorus (n-type). These impurities provide extra free electrons. The cell has ohmic contacts on both Figure-2: Conversion of light energy to electricity by using solar cell



n-type and p-type layers to connect to an external circuit. When sunlight hits the cell, photons energize the electrons, creating electron-hole pairs. An internal electric field drives these carriers in opposite directions, producing a direct current when the circuit is completed.

2.1 SOLAR CELL

The photovoltaic effect, discovered in 1839, is the principle behind solar cell technology. Modern photovoltaic modules consist of multiple solar cells connected in series or parallel to achieve the required voltage and current. Series connections increase voltage, while parallel connections increase current. Proper matching of cells is essential to ensure maximum power output and system efficiency.

2.2 THE PHOTOVOLTAIC ARRAY

A photovoltaic (PV) array is a collection of interconnected solar modules that convert sunlight into electricity. These arrays can range from small residential systems to large-scale installations, often divided into sub-arrays for efficiency. The mounting structure secures the modules, ensuring stability and optimal orientation to maximize energy capture. Proper tilt and azimuth angles are crucial; typically, modules are tilted at an angle equal to the local latitude and oriented towards the equator for optimal performance. PV systems can be stand-alone, grid-connected, or hybrid, each serving different energy needs and configurations

2.3 MAXIMUM POWER POINT TRACKING:

Maximum Power Point Tracking (MPPT) is an electronic technique used in photovoltaic (PV) systems to optimize energy extraction by adjusting the electrical operating point of solar panels. This method continuously seeks the voltage (VMPP) or current (IMPP) at which the panels deliver maximum power, compensating for variations in sunlight and temperature. MPPT differs from mechanical tracking systems, as it electronically regulates the panels' operating conditions without physically moving them.

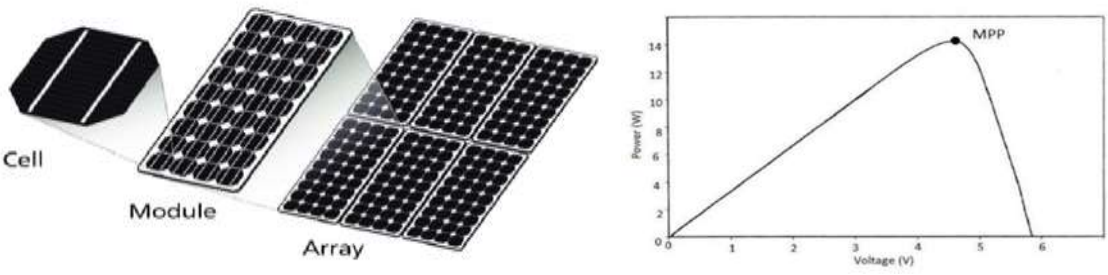


Figure-3: P-V Characteristics of PV Cell

3. PHOTOVOLTAIC INVERTER:-

A solar inverter is essential in photovoltaic (PV) systems, converting DC output from solar panels into AC power suitable for household use and grid integration. Unlike mechanical trackers, inverters electronically optimize power output without moving parts. They are part of the power conditioning unit

(PCU), which interfaces the PV system with the grid and, if applicable, battery storage. Notably, inverters are inherently safer than traditional synchronous generators, as they produce significantly lower fault currents—typically between 1.2 to 1.5 times their rated current—reducing potential hazards during electrical faults.

3.1 INVERTER CLASSIFICATION

Solar inverters are categorized into three main types:

Stand-alone inverters: Operate independently, drawing DC power from batteries charged by solar panels or other sources. They don't connect to the utility grid and thus don't require anti-islanding protection.

Grid-tie inverters: Synchronize with the utility grid's AC waveform and shut down during power outages to prevent backfeeding, ensuring safety.

Battery backup inverters: Manage battery charging and can supply power to specific loads during grid outages. They include anti-islanding protection to prevent unintentional power feeding into the grid.

Anti-islanding protection is a safety feature in grid-connected inverters. It detects grid outages and promptly stops the inverter from supplying power, preventing potential hazards to utility workers and equipment.

3.2 DETECTION METHODS

Slanding occurs when a solar inverter continues to power a location despite a grid outage, which can be dangerous for utility workers. Detection methods include passive (monitoring voltage/frequency deviations), active (injecting signals and observing response), and utility-based notifications. Maximum Power Point Tracking (MPPT)

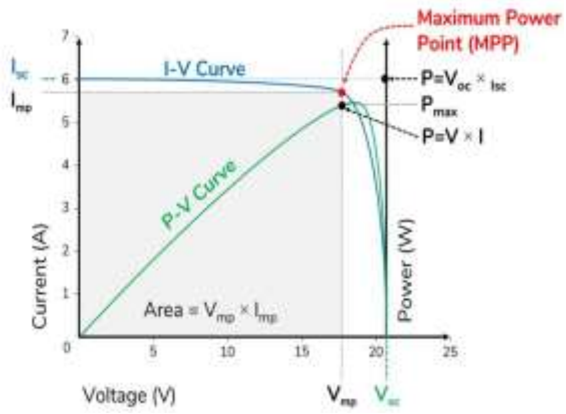


Figure-4: Curve for a solar cell, showing the maximum power point

ensures the PV system operates at peak efficiency by adjusting the electrical load to extract maximum power. Modern MPPTs optimize each panel individually, improving performance under conditions like shading or mismatch. In grid-tied systems, MPPTs consistently operate at peak power unless the grid fails and batteries are full.

3.3 GRID TIED INVERTERS

Stand-alone inverters operate off-grid, converting DC from solar panels and batteries into AC, often incorporating charge controllers to manage battery charging. Grid-tied inverters synchronize with utility power, automatically shutting down during grid outages for safety. Battery backup inverters can supply AC power during outages and require anti-islanding protection to prevent feeding power back into the grid during such times.

3.4 POWER QUALITY PROBLEMS WITH PV INVERTERS:

Grid-connected photovoltaic (PV) inverters can introduce power quality issues, notably harmonic distortion, which may exceed national standards like EN50160—even when individual inverters comply with IEC 61000-3. Factors such as resonance between the grid and inverters, and harmonic current emissions, contribute to this challenge. To mitigate these effects, inverters are designed with high-frequency switching, low output capacitance, and advanced current control loops. Additionally, incorporating inductive components and optimizing output impedance can help reduce harmonic emissions and improve overall power quality.

4. HARMONICS :-

Harmonics are voltage or current waveforms in electrical systems whose frequencies are integer multiples of the fundamental frequency (50 or 60 Hz). They arise from non-linear loads like rectifiers and certain electronic devices, leading to distorted waveforms and potential power quality issues. Understanding and managing harmonics is crucial for maintaining efficient and reliable electrical systems.

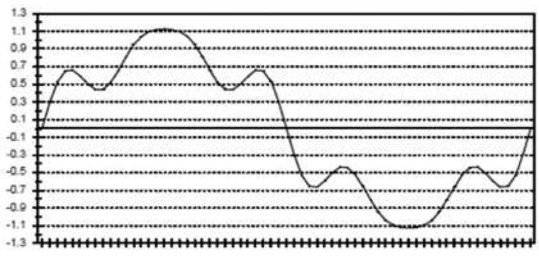


Figure-5: Fundamental with two harmonics

4.1 Sources of Harmonic Distortion in Electrical Systems

Harmonics in electrical systems arise when non-linear loads, such as rectifiers and inverters, draw current in abrupt pulses, distorting the ideal sinusoidal waveform. This distortion can lead to various power quality issues, including increased heating in transformers and motors, malfunctioning of protective devices, and interference with communication lines. Managing harmonics involves understanding their sources and implementing mitigation techniques to maintain system efficiency and protect equipment..

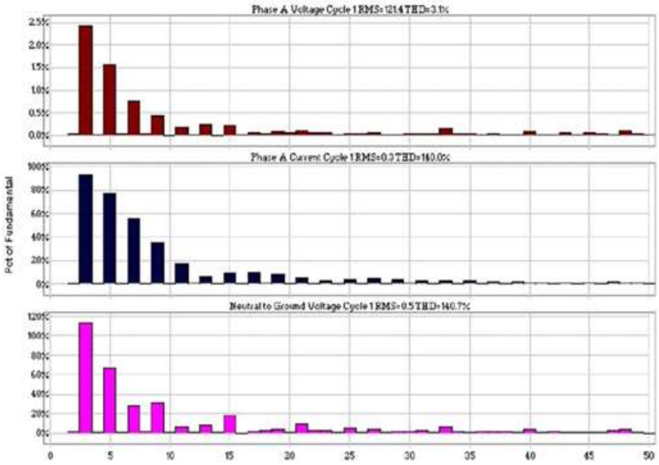


Figure-6: Harmonic Spectrum of Current Waveform

4.2 Locating the Sources of Harmonic Distortion

Monitoring voltage and current waveforms at the Point of Common Coupling (PCC) is essential for identifying and managing harmonics in electrical systems. Harmonic voltages depend on the harmonic currents drawn by non-linear loads and the source impedance, as described by Ohm's Law (Voltage = Current × Impedance). A low source impedance ("stiff" system) results in lower harmonic voltages, while a high source impedance can lead to higher harmonic voltages. The IEEE 519 standard recommends assessing harmonic limits at the PCC to ensure both utility and customer equipment operate within acceptable distortion levels. Effective monitoring at the PCC aids in pinpointing the sources of harmonic distortion and implementing appropriate mitigation strategies.

4.3 Harmonic Monitoring Techniques and Signature Analysis

Harmonic monitoring is essential for assessing power quality, especially in facilities with non-linear loads like computers, printers, and industrial equipment. Handheld harmonic meters are useful for spot checks, but their readings can fluctuate due to varying load conditions. For comprehensive analysis, continuous monitoring with advanced power quality analyzers is recommended. These devices can capture harmonic data over extended periods, helping to identify sources and assess the impact of harmonics on the electrical system. Understanding the harmonic spectrum is crucial; for instance, the equation $h = (n * p) \pm 1$ can predict harmonic numbers based on the number of pulses in a circuit.

4.4 Getting rid of Harmonics:

To effectively mitigate harmonic issues in electrical systems, it's crucial to implement corrective measures carefully to avoid exacerbating the problem. Resonance between harmonic filters, power factor correction capacitors, and system impedance can inadvertently amplify harmonics. Strategies such as isolating harmonic-producing devices on separate circuits, employing harmonic filters, and balancing loads can help reduce harmonic effects. Ensuring neutral conductors are adequately sized, in line with NEC-1996 standards, is essential, especially in setups with high impedance, like modular office partitions. Additionally, de-rating transformers and motors according to IEEE, ANSI, and NEMA guidelines can prevent overheating. While using higher pulse converters, like 24-pulse rectifiers, can eliminate lower-order harmonics, they may introduce higher-order harmonics, necessitating a balanced approach in system design.

5. PROPOSED TOPOLOGY :

The proposed single-stage, single-phase Reconfigurable Solar Converter (RSC) is capable of operating in multiple modes to efficiently manage power flow between solar PV, battery, and the grid. It supports four key modes: PV-to-grid, PV-battery-to-grid, PV-to-battery charging, and battery-to-grid, enhancing system flexibility and reducing conversion losses. A PQ controller regulates active and reactive power, while a Fuzzy Logic-based MPPT ensures maximum power extraction from the PV source. PI controllers manage voltage and current regulation, and Space Vector PWM ensures precise inverter switching. The RSC design enables seamless operation for both AC and DC loads, making it ideal for hybrid solar-powered systems.

Mode 1: PV to Grid

In this mode, the photovoltaic (PV) system is directly connected to the grid to supply power under normal solar conditions. An MPPT (Maximum Power Point Tracking) controller is used to continuously extract the maximum possible power from the solar panels by adjusting the operating voltage. The inverter controller is responsible for synchronizing the PV output with the grid voltage and frequency, allowing smooth active power transfer to the grid.

This mode is highly efficient and utilized during periods of strong sunlight, ensuring optimal renewable energy usage and reducing dependency on conventional power sources.

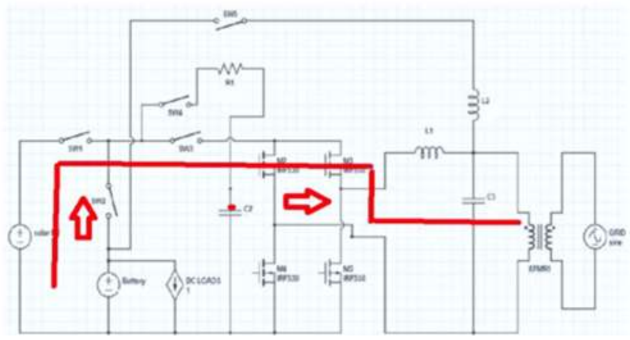


Figure-7: PV to Grid

Mode 2: PV and Battery to Grid

This mode is activated when the solar irradiance is insufficient—such as during cloudy weather or in the evening—causing a drop in PV power generation. In such conditions, the battery bank supplements the PV system to maintain uninterrupted power supply to the grid. However, as the battery operates at a fixed voltage, the MPPT controller cannot be applied effectively. Therefore, the battery and PV voltages must be closely matched. Despite this limitation, this mode ensures a continuous and stable output to the grid by leveraging stored energy along with real-time solar generation.

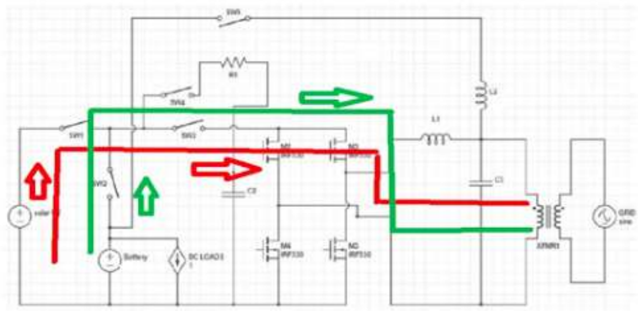


Figure-8: PV and Battery to Grid

Mode 3: **PV to Battery (DC/DC Operation)**

When there is surplus solar energy and the load demand is low, this mode charges the battery bank using a DC/DC conversion mechanism. A chopper circuit, often assisted with an optional inductor to reduce current ripple, is used for efficient charging. The MPPT controller determines the ideal current from the PV array, which is then processed through a PI controller to generate a voltage reference. This is compared with the battery voltage, and the resulting error is used to derive the duty cycle for PWM control. This ensures controlled and efficient charging, preparing the battery for later use during non-generating periods.

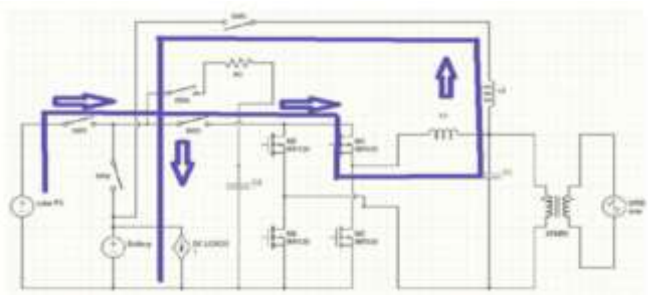


Figure-9: PV to Battery Charging (DC/DC Operation)

Mode 4: Battery to Grid or Load

This mode is used when there is no solar generation—such as at night or during prolonged overcast conditions. The battery bank discharges stored energy to supply either the grid or domestic AC/DC loads. The inverter converts the DC output from the battery into synchronized AC power, maintaining stability and supporting grid voltage. This mode plays a crucial role in improving power quality and offering ancillary services like load balancing or peak shaving. It ensures energy availability and supports continuous operation even in the absence of solar input

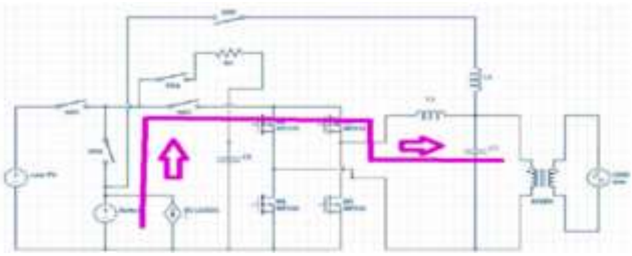


Figure-10: Battery to Grid or Load

6. CONTROLLERS & MODULATION TECHNIQUES:-

A controller compares a controlled variable with a desired value and acts to correct any deviation. Controllers play a crucial role in improving system performance by enhancing steady-state accuracy, reducing steady-state errors and offsets, improving stability, minimizing overshoot, suppressing noise, and speeding up slow system responses. The basic types of controllers include Proportional (P), Integral (I), and Derivative (D), with combinations like PI and PD commonly used in practical applications.

6.1 Proportional and Integral Controller (PI Controller)

The PI controller combines the strengths of proportional and integral actions, delivering both improved steady-state accuracy and acceptable transient response. The proportional term responds to the current error, while the integral term eliminates residual steady-state errors. This combination is widely used in industry for systems where a moderate speed of response is acceptable. However, the absence of a derivative term means it cannot predict error trends, which may limit performance in rapidly changing systems. PI controllers are ideal where large noise disturbances exist or where the system is relatively slow and stable.

6.2 Effects of Changing Controller Parameters

The behavior of a control system is heavily influenced by the tuning of controller parameters. Increasing the proportional gain (Kp) reduces steady-state error but may increase overshoot. The integral gain (Ki) helps eliminate the steady-state error but can worsen system stability and increase settling time. Adding derivative gain (Kd) improves stability and reduces overshoot without affecting steady-state error. Proper tuning balances rise time, overshoot, and stability based on application requirements.

6.3 Fuzzy Logic Controller (FLC)

The Fuzzy Logic Controller (FLC) is a powerful, non - linear control approach inspired by human reasoning, capable of handling imprecise inputs and uncertain environments. Unlike classical controllers which rely on exact mathematical models, FLC uses linguistic rules and membership functions to map input variables (such as error and change of error) to control actions. It consists of four stages: fuzzification, rule evaluation, inference, and defuzzification. In fuzzification, crisp numerical inputs are converted into fuzzy sets using membership functions. The rule base, typically expressed using IF-THEN statements, forms the core logic of the controller. The inference engine evaluates these rules based on current input values, and defuzzification converts the fuzzy output into a precise control signal.

In this project, FLC enhances performance by adapting to dynamic system conditions without requiring an accurate mathematical model. It offers smoother control, improved harmonic mitigation, and better transient response compared to traditional controllers. The fuzzy rule base includes terms like NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), etc., which represent the qualitative state of error and error rate. These linguistic values help the controller to make intelligent decisions in real-time. The use of triangular membership functions makes the implementation computationally efficient while maintaining a good level of precision. Overall, FLC is highly effective in applications where system non-linearity and external disturbances are significant, such as in renewable energy integration and smart inverter systems.

6.4 Membership Functions

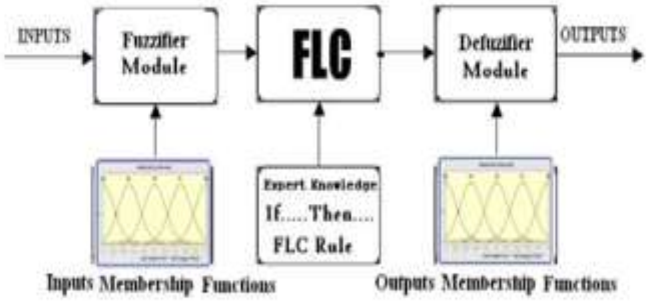


Figure-11: Block Diagram of Fuzzy Logic

Membership functions (MFs) quantify how much an input belongs to a fuzzy set, mapping each input value to a degree between 0 and 1. They allow FLCs to interpret vague inputs such as "low voltage" or "high error." Triangular MFs, used in this project, are defined by three parameters and offer a simple yet effective representation of fuzzy concepts. Each input (error and change of error) and output variable has its own set of MFs, and the system's performance depends greatly on their proper definition and distribution.

6.5 Modulation Techniques

Modulation techniques in inverter systems are essential for shaping the output voltage into a desired waveform, typically a sinusoidal form, from discrete voltage levels. These techniques control the timing and sequence of switching events, directly influencing efficiency, harmonic content, and voltage control. The goal is to ensure smooth voltage output with minimal distortion and losses. PWM (Pulse Width Modulation) is widely used due to its simplicity and effectiveness in power control applications.

6.6 Carrier-Based Three-Level PWM

This method compares a sinusoidal reference signal with two triangular carrier signals to generate gate pulses for inverter switches. Depending on the reference voltage's position relative to the carriers, the output switches between discrete voltage levels. This technique is widely adopted in three-level inverters for its simplicity and effective harmonic control. It is ideal for applications requiring moderate precision with minimal control complexity.

6.7 Space Vector Pulse Width Modulation

SVPWM is an advanced PWM technique that represents output voltages as vectors in a two-dimensional plane using the d-q (direct-quadrature) transformation. By selecting appropriate voltage vectors and determining their durations within a switching period, SVPWM synthesizes the desired output waveform. It offers superior DC bus utilization, reduced THD, and smoother motor operation in AC drives and inverter applications. The method calculates optimal switching times (T1, T2, T0) for each sector to achieve precise control over voltage and frequency.

6.8 SVM PWM Technique

The Space Vector Modulation (SVM) technique defines the space vector (u*) as a combination of phase voltages and distributes switching times among adjacent vectors. Using mathematical transformations, it maps the desired voltage vector within one of six sectors of a hexagon representing inverter states. The switching times are optimized to produce sinusoidal phase voltages with minimal harmonics. This results in high-quality output suitable for grid-connected and motor control applications.

9. MATLAB-SIMULINK ENVIRONMENT:-

This Simulink model represents a grid-connected solar inverter system. It includes a PV panel (highlighted in orange), an MPPT controller to extract maximum power, and a boost converter to increase the voltage. The boosted DC voltage is smoothed using a DC link capacitor and then fed into a multi-switch inverter, which converts it to AC. An LCL filter cleans the AC output before it connects to the grid and load. The system uses a Phase-Locked Loop (PLL) for grid synchronization and control blocks (like PI or fuzzy logic controllers) to manage voltage, current, and switching. The model also includes voltage and current measurements for monitoring performance. It's likely built using Simscape Electrical and Simulink control blocks.

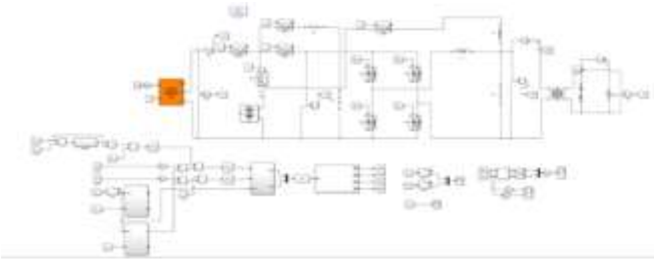


Figure-11: Simulink of the Grid Connected PV system

The given model uses several key parameters to ensure efficient and stable operation. These include PV voltage (Vpv) and current (Ipv) for power generation, DC link voltage (Vdc) for maintaining a steady DC level, and grid voltage (Va) and current (Ia) for synchronization and power delivery. Control parameters such as duty cycle for the boost converter, modulation index for the inverter, and gains for PI or fuzzy controllers are also used to regulate power flow. Inductance (L1, L2), capacitance (C), and switching frequencies are carefully selected to reduce harmonics and ensure smooth grid integration.

Table-1

Parameters	**Values**
Solar irradiance G ref	1000 W/m^2
Cell temperature T ref	25 ^0C
I mp	7.25A
V mp	28V
P mp	212.24W
I sc	7.27A
V oc	35.9V

Figure-12 Control Block Diagram of Single-Stage Grid-Connected PV Inverter with MPPT and dq Control Strategy

Figure 12 shows the control architecture of a grid-connected single-stage photovoltaic (PV) inverter system. The system uses a Maximum Power Point Tracking (MPPT) algorithm to extract the maximum power from the PV array based on the instantaneous voltage (Vpv) and current (Ipv). A PI controller regulates the DC-link voltage (Vdc), ensuring steady operation.The active and reactive power control is implemented through separate PI controllers in the dq frame, using reference values for active power (Pref) and reactive power (Qref). These are compared against the actual d and q-axis currents to generate appropriate control signals.

The outputs from the PI controllers are transformed back to the αβ frame and further processed by the modulation index calculator f(u). The final modulation signals (M2, M3, M4, M5) are fed to the inverter switches.

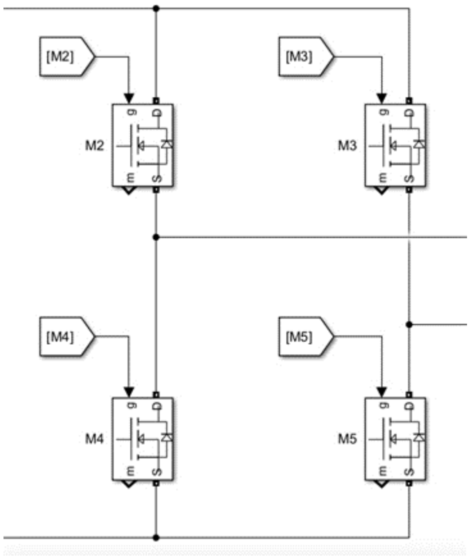


Figure-9 Simulink diagram of inverter

10. RESULTS AND SIMULATION:

The system uses several key parameters to ensure efficient and stable operation. These include PV voltage (Vpv) and current (Ipv) for power generation, DC link voltage (Vdc) for maintaining a steady DC level, and grid voltage (Va) and current (Ia) for synchronization and power delivery. Control parameters such as duty cycle for the boost converter, modulation index for the inverter, and gains for PI or fuzzy controllers are also used to regulate power flow. Inductance (L1, L2), capacitance (C), and switching frequencies are carefully selected to reduce harmonics and ensure smooth grid integration.

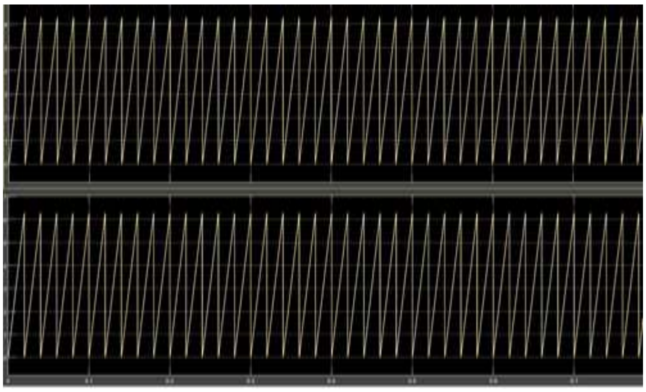


Figure-9 Grid voltage and Inverter voltage Waveforms

The graph displays high-frequency triangular carrier signals used for SPWM. These carriers are compared with reference sine waves to generate switching signals for the inverter, enabling efficient and smooth control of output voltage and waveform shaping in the solar inverter system.

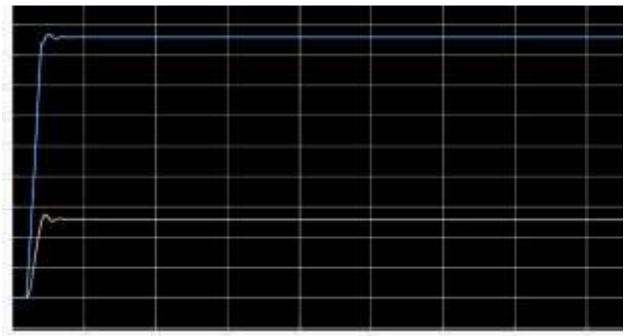


Figure-9 Active and reactive power generation.

The blue curve represents the DC-link voltage, which rapidly rises and stabilizes around 430V — this is essential for inverter operation as it feeds the modulation and switching stage. The yellow curve shows the AC output voltage amplitude, settling around 130V after some initial oscillations (transients). This indicates that the inverter successfully regulates the output after startup, using SPWM controlled by fuzzy logic.

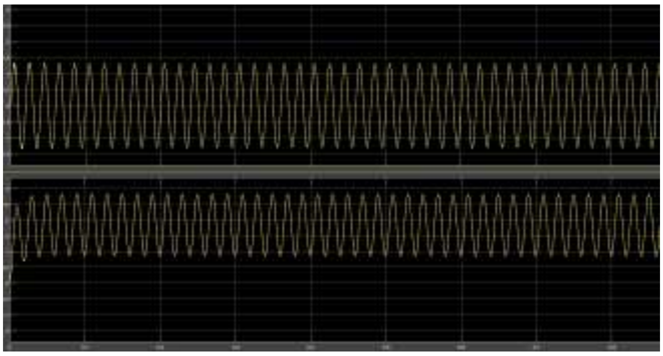


Figure-9 Inverter voltage and Inverter current

The waveform illustrates the output voltage and current of the inverter connected to the grid. The signals are nearly sinusoidal and are synchronized in frequency, confirming proper operation of the inverter stage.The top waveform represents the inverter output voltage, which fluctuates symmetrically around zero, showing a peak-to-peak value close to ±1.5 V (per unit), indicating successful AC conversion.

The bottom waveform shows the inverter output current, which is also sinusoidal and in phase with the voltage waveform, suggesting that the inverter operates at unity power factor.This synchronized operation between voltage and current waveforms signifies effective PWM control and grid synchronization through the PLL (Phase-Locked Loop), ensuring stable power injection into the grid.

11. FUTURE SCOPE:-

Power electronic devices can enhance PV system stability under varying shadow conditions. Cost analysis with carbon credits can determine economic feasibility. Key loss factors like shading, PCS losses, mismatch, and temperature rise must be reviewed for accurate performance evaluation.DC-DC boosters and choppers with filters improve voltage and reduce ripples, especially in direct DC applications. Intelligent controllers like microprocessors and PLCs help maintain maximum power point for better efficiency.Solar PV is a clean, local, and sustainable energy solution. With India’s high solar irradiance, it holds great potential for widespread use.

12.CONCLUSION:-

This project suggested a more suitable converter topology for a solar powered hybrid ac/dc home. The main idea of this topology is to utilize single conversion of ac power to dc and vice versa, which improves the efficiency, reduces volume, and enhances the reliability. The hardware implementation validates that the suggested converter topologies would be helpful to reduce significant amount of harmonics in the residential feeders of the future smart grid. Though, here only solar PV is considered as source of power, this topology could be equally applicable to wind, fuel cells, etc.

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