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Fuzzy Logic Inverter Controller in Photovoltaic Applications: Issues and Recommendations

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ABSTRACT Fossil fuels and other conventional energy sources used to generate electricity are finite. Therefore, alternative energy sources should be pursued to meet present and future energy demands. The photovoltaic (PV) is a promising renewable energy source, especially for the remote areas. The PV is a DC power source that needs to be converted into usable AC power using an inverter. However, its nonlinearity and output fluctuation pose challenges in the design of PV based inverter. In this paper, a PV inverter controller system with the fundamentals of a fuzzy logic controller (FLC) and its applications and execution are reviewed. The different fuzzy controllers, inverter control algorithms, and switching techniques are studied. The findings indicate that the fuzzy logic controls have been gaining attention in the area of power control engineering, especially in inverter controller design for PV applications and generation. The FLC has a flexible and intelligent design, expedient user interface, easy computation and learning system, and combinations of different control algorithms. The FLC is also verifiable for completeness, redundancy, and consistency. However, finding the boundaries of membership functions and other rules of FLC requires manual tuning, long computation time, and considerable effort. This paper comprehensively reviews the FLC-based inverter control system to minimize PV output fluctuations, which cause inverter issues related to output harmonics, power factor, switching schemes, losses, and system implementation. The inverter system and its control strategy for future PV applications and generation require further research and development. Consequently, this review focuses on many factors and challenges and provides recommendations for designing capable and efficient inverter control systems for converting PV power to usable AC power. All the highlighted insights of this review will hopefully lead to increased efforts toward the development of the advanced inverter control systems for PV applications for AC loads and the utility grid.

INDEX TERMS Power converter, fuzzy logic, fuzzy logic controller, inverter, photovoltaic system.

NOMENCLATURE

ANFIS Adaptive Neuro-Fuzzy Inference System
ANN Artificial Neural Network
AVR Automatic Voltage Regulator
BJT Bipolar Junction Transistor
CCM Continuous Current Mode
COG Center-of-Gravity
CSI Current Source Inverter

DG Distributed Generation
DSP Digital Signal Processor
FLC Fuzzy Logic Controller
FNN Fuzzy Neural Network
FPGA Field-Programmable Logic Array
GTO Gate Turn-Off Thyristor
IGBT Insulated-Gate Bipolar Transistor
IT2FLC Interval T2FLC
I-V Current vs. Voltage
LC Inductor-Capacitor

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LOH	Lowest-Order Harmonics
MF	Membership Function
MIMO	Multi-Input Multi-Output
ML	Multilevel
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MPPT	Maximum Power Point Tracker
NB	Negative Big
NM	Negative Medium
NS	Negative Small
P&O	Perturbation and Observation
PAS	Power-Assisted Steering
PB	Positive Big
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PLL	Phase-Locked Loop
PM	Positive Medium
PS	Positive Small
PV	Photovoltaic
PWM	Pulse-Width Modulation
SHE	Selective Harmonic Elimination
SOPWM	Synchronous Optimal Pulse-Width Modulation
SPWM	Sinusoidal Pulse-Width Modulation
SVM	Space-Vector Modulation
SVPWM	Space-Vector Pulse-Width Modulation
T1FLS	Type-1 Fuzzy Logic System
T2FLC	Type-2 Fuzzy Logic Control
T2FLS	Type-2 Fuzzy Logic System
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply
VSI	Voltage Source Inverter
ZERO	Zero

I. INTRODUCTION

The growth of human population has resulted in significant increase in energy demand. Fossil fuels are a conventional energy source used to generate electricity. This resource poses harm to the environment directly or indirectly due to carbon gases emissions [1]. Thus, alternative energy sources should be harnessed to address present and future energy demands. Following the current consumption trend, less than 50 years' worth of petroleum reserves remain [2]. Fossil-based energy generation indirectly degrades air quality in the environment. Fossil energy sources include petroleum, natural gas, and coal [3]. Consumption of fossil-based energy by fuel-based machines and engines, such as automobiles and generators, releases harmful carbon dioxide to the atmosphere, leading to air pollution and global warming. The preservation of the green, clean, and pollution-free environment for future generations can be realized through the utilization and implementation of pollution-free renewable energy sources, such as solar photovoltaics (PV). Extensive research on renewable energy technology has led to the development and utilization of green energy sources, such as PV, biomass, geothermal energy, hydropower, and wind.

Depending on their feasibility, advantages, and disadvantages, these energy sources can be harnessed for alternative energy to meet the rising energy demand.

PV is a promising renewable energy source that has been applied in various sectors, such as construction, transportation, and residential, especially in remote or rural areas, over the past few decades [1]. As a cost-effective and pollution-free energy source [4], PV can produce energy that can be delivered to the utility grid in a grid-connected system with proper equipment and method. Unlike fossil fuels, PV is abundantly available and can be maintenance-free. However, PV produces DC power that has to be converted into AC power using an inverter before it can be used, particularly in AC-related applications [5]. The evaluation of PV technology depends on the development of materials and structures with the consideration of maximum power at minimum cost. Silicon crystalline structure such as mono-crystalline, poly-crystalline, and emitter wrap through is used to build PV modules in first generation technology [6]. Mono-crystalline PV occupies 80% of world market, however it has 24.7% efficiency. Poly-crystalline PV has been attracted in large scale production due to reduction of manufacturing cost and defects in metal contamination and crystal structure, however it has less efficiency (15%) as compared to mono crystalline based PV. Emitter wrap-through cells provide full surface area for absorbing solar radiation that improves efficiency with a rise of 15–20% without material changes [6]. However, this technology faces high resistance problem and poor fill density [7]. In the next generation of PV technology, thin film technology is used with deposition of thin layer of certain materials in glass or SS substrates that makes PV modules flexible. Hence, it reduces the manufacturing cost. However, due to its thin structure the efficiency is comparatively low. Efficiency can be increased by depositing different alloy materials. Thin film PV modules have 15-20% market share for its versatility [6]. These are available with the technologies of amorphous Si multiple-junction structured cell, thin poly-crystalline Si on a low cost substrate, copper indium diselenide/cadmium sulphide hetero-junction cell, and cadmium telluride/cadmium sulphide hetero-junction cell [6].

In amorphous Si the bigger bandgap in a junction absorbs visible portion that infrared portion of solar radiation. This technology uses several variations of glass or flexible SS, tandem junction, double and triple junctions of different characteristics to improve the efficiency and define degradation hitches [8]. Cadmium telluride or cadmium sulphide/cadmium telluride is a promising PV material for thin film technology with high absorption coefficient. However, the toxicity of cadmium has an environmental issue. Conversely, this introduces first PV recycling and reduces the manufacturing cost [6], [9]. Copper indium diselenide or copper indium gallium diselenide has high optical absorption coefficient and electrical characteristics for device tuning. This technology attracts researchers and developers in its deposition processes to make it more cost effective to compete the world market with Si based PV modules. [10].

Compound semiconductor is being used for PV technologies that have wide band absorption of solar radiation. Moreover, it shows the robustness in cost reduction and efficiency around 41% by introducing dual and triple junction devices, and widely used in space satellites and large scale solar plants [6]. However, this technology has some negative issues such as heat, UV light, and interaction of solvents within the encapsulation of the cell. Other solar cells such as organic solar cells and polymer solar cells are made from thin films of organic semiconductors pentacene, polyphenylene vinylene, copper phthalocyanine and carbon fullerenes that is attracted for its mechanical flexibility and disposability. For the use plastic materials, this technology is cheap. "The year 2007 has been a turning point for PV thin film technology at least for US-based PV manufacturing with US thin film shipments reaching a market share of about 65%" [11]. However, for superior efficiency and cheap production nanotechnology shows a great prospect in PV development. With a control on the energy bandgap the nanotechnology lessens deficiencies of other PV technologies [6]. As reported in [12], nanomaterials have the most promising sector in solar energy conversion in the device formation of carbon nanotubes, quantum dots (QDs), and "hot carrier" solar cells [13]–[15]. These have higher efficiency of solar energy conversion, however, the research and development is conducting materials composition, recycling, cost effective production toward sustainable energy generation.

The inverter, which is an electronic device that converts DC power to AC power at a desired output voltage or current and frequency, plays an important role in ensuring the operability of the abovementioned products and applications in the field of renewable energy, such as PV. In these applications, the inverter should produce a clean output sine waveform at a precise voltage over controlled frequency ranges and within certain load variations. Certain features have to be considered when designing PV inverters. The PV inverter system design should be simple (not complex or bulky), stable, reliable, efficient, and low-cost. The inverter design should allow for flexible control, ease of maintenance and testing, low waveform total harmonic distortion (THD), and unity power factor [16]. In addition, inverter systems should be small and light [17]. The nonlinearity and output fluctuation of PV pose challenges to PV inverter design [18]. The inverter control system should minimize the impact of output fluctuation on the stability and power quality of the inverter. For a PV with a low output voltage, a DC-to-DC boost converter is incorporated into the power conversion system [19].

The progress of PV system applications is associated mainly with the power electronic interface, such as inverters and controllers. Inverter and controller technologies are upgraded continuously to enhance the efficiency of PV systems because inverter errors and failures are the primary sources of failure of PV systems [20]. Power conversion in a PV system depends on inverter controllers and control algorithms [21]. Accordingly, quality inverter

controllers are required to generate power efficiently in PV systems. Controllers, such as sinusoidal pulse-width modulation (SPWM) and space-vector pulse-width modulation (SVPWM), have been utilized in PV inverter applications to obtain regulated inverter output. The SVPWM technique is more difficult to implement than the SPWM technique, which is applied in multilevel inverters [22]. APV inverter system uses analog or digital control circuits, microcontrollers or microcomputers, FPGAs, or digital signal processors (DSPs) [23]. Research and development continues to improve the control algorithm of PV inverters for sustainable renewable energy applications.

PV inverters can be employed as stand-alone power systems to provide AC power for residential appliances, such as fluorescent lamps, fans, and refrigerators [24]. Inverters with high-quality power output can be the main components in automatic voltage regulator (AVR), uninterruptible power supply (UPS), and power-assisted steering (PAS) systems [25]. These inverters can also be used individually or as part of the distributed generation (DG) system in the power system, which interfaces and feeds alternative energy power to the grid system [26], [27]. Therefore, the power electronic-based conversion system (inverter) should deliver the proper amount of energy to provide an effective and efficient connection for the grid [28].

The main issues concerning PV inverters include the DC-output nature of PV devices, intermittent fluctuations, output voltage regulation, harmonic content, and conversion efficiency [21]. The intermittent voltage, power, and DC nature of the PV output produce unstable inverter output unexpected by sophisticated loads. Therefore, these issues need to be considered in designing PV inverters [29]. Many methods have been introduced to lessen and control PV deficiency with enhanced inverter control systems that regulate output voltage and power of PV inverters. On the contrary, self-power dissipation affects overall inverter efficiency, which is a significant issue in system design even with the proper switching frequency [30]. Designing the filter to generate quality output waveform in the inverter is easy with a high switching frequency, which produces a high level of harmonic components that cause power loss and efficiency reduction. Therefore, the switching frequency should be appropriately selected to produce quality inverter output and prevent power loss.

A suitable inverter controller has to be selected for the inverter design to optimize the inverter parameters effectively. Both the quality of the inverters and the flexibility of the inverter control system design are important in providing the inverter designer a platform for further product research and design development, which commercially available inverters lack. This feature enables the control systems to be assessed for upgrades to inverter parameters, such as voltage, current harmonic content, and power factor. Various types of inverter controller platforms have been presented in the literature, including the microcomputer [23], DSP [31], and FPGA [32]. The utilization of controllers,

such as microcontrollers [33], microprocessors [34], and analog and digital circuit controllers [35], has also been reported. Most studied controllers require users to have software programming knowledge to develop inverter control algorithms, which is time consuming. The design platform should allow for a simple and short design and development process for inverter control system algorithms.

A novel improved design method for PV system inverter controllers needs to be developed to acquire results with low harmonic content, unity power factor, simple hardware implementation, low-loss switching scheme, easy system implementation, and short product design period. With high-quality output, the inverter can be connected and feed PV power to the utility grid. This review can lead to more research opportunities on further PV system improvement.

II. OVERVIEW OF PV INVERTER CONTROLLER SYSTEMS

Today, power electronic converters are widely used in various applications as single-phase and three-phase inverters [36]. They may operate as stand-alone units that connect and link DC power to AC loads, such as AC motors [36]. They can also be used as UPS [37], AVR [38], and many other systems. Normally, three-phase inverters are preferred for medium- to high-level applications [37]. In a utility grid-connected system, inverters are used as interface devices to feed DC power to the grid [39]. In this regard, components such as relays or switches are required to enable the system to connect to the grid [40]. An inverter's design is simple with fixed input voltage and loads. However, fluctuating PV output and varying load disturbances affect the performance of the inverter [41], [42]. Thus, inverter control systems should be designed and developed to minimize the effect of these disturbances on the performance of inverters and their control systems for PV applications. Fig. 1 shows the general block diagram of a PV conversion system, which consists of a system controller, PV panel, filter, and power converters [43], [44]. The integration of these elements enables the proper utilization of solar energy in the energy conversion system. The system is a feedback control system that runs the output (voltage) of the process. The controller and power converters ensure a stable voltage supply for the load.

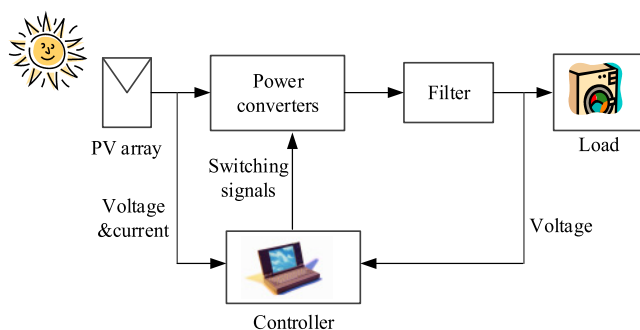


FIGURE 1. Generalized block diagram of a PV energy conversion system.

A. PHOTOVOLTAIC SYSTEM

Different power sources, such as PV, wind generators, fuel cells, and batteries, can be utilized for the energy conversion system and integrated with the inverter using different methods. However, connecting the different power sources to the inverter may require additional stages or devices. For example, a wind turbine generator, which produces AC power, requires an additional AC-to-DC converter (e.g., a rectifier) to connect to an inverter [45]. Unlike a wind turbine, a PV panel produces DC power and therefore can be connected directly to the inverter, thereby reducing the overall cost of the PV system [46]. A PV cell is a semiconductor with a p-n junction diode that converts light directly into electricity [47]. When the common junctions of the p-n diode are struck by sunlight, which contains photons, the energy is absorbed by the electron system of the material. Electron-hole pairs, as charge carriers, are created with a potential barrier at the junction that generates a voltage that allows current to flow through the external circuit. This process, called the photovoltaic effect [48], is illustrated in Fig. 2.

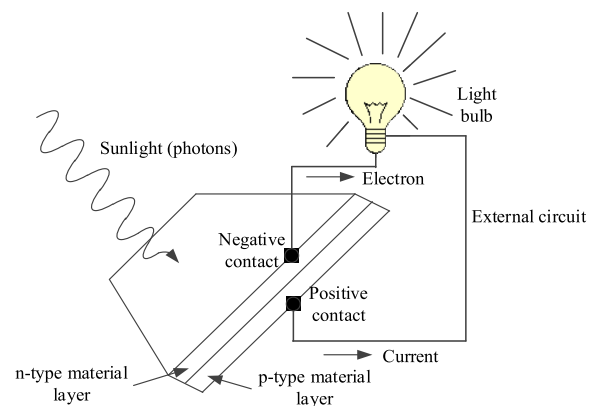


FIGURE 2. Photovoltaic effect of a PV cell.

Cell arrangements, such as series, parallel, and series-parallel, form a PV module that acquires the specified power capacity [49]. Similarly, an array or panel is constructed by a series-parallel combination of modules to obtain higher power capacity [50]. The output voltage generated in the PV cell depends on the photocurrent and level of the real-time solar irradiation. [51]. Equation (1) presents the output current of the solar cell I_c [52].

$$I_c = I_{ph} - I_o = I_{ph} - I_{sat} \left[e^{\frac{q}{AKT_c}(V+IR_s)} - 1 \right] \quad (1)$$

where I_{ph} is the photocurrent, I_o is the diode current, I_{sat} is the p-n junction reverse saturation current, q is the electron charge, A is the ideality factor, K is the Boltzman constant, T_c is the cell temperature in Kelvin, and R_s is the stack internal resistance.

The required PV voltage V_{PV} , and current I_{PV} are generated by considering the series-parallel combination of modules N_s and N_p . The voltage and current of PV arrays are expressed

by Equations (2) and (3).

$$V_{PV} = N_s (V_{ref} - \beta (T - T_{ref}) - R_s (T - T_{ref})) \quad (2)$$

$$I_{PV} = N_p \left(I_{ref} + \alpha \left(\frac{G}{1000} \right) (T - T_{ref}) + I_{sc} \left(\frac{G}{1000} - 1 \right) \right) \quad (3)$$

where α and β are the current and voltage temperature coefficients, T is the actual temperature, T_{ref} is the reference stack temperature, V_{ref} and I_{ref} are the PV reference voltages and current, I_{sc} is the short circuit current, and G is the irradiance on the PV surface.

Equation (4) represents the PV's output power, which is the product of the output current and the output voltage of the PV array [4,50].

$$P_{PV} = I_{PV} \times V_{PV} \quad (4)$$

Some of the disadvantages of PV are its high initial installation cost and low-efficiency energy conversion [53]–[55]. In a PV system, which utilizes power converters, such as inverters and DC-to-DC converters, the control system plays a vital role in enhancing system performance and efficiency [56].

B. POWER CONVERTERS

A DC-to-DC converter converts one DC power level to another that has the advantage of regulating its output voltage even with variations in the DC input voltage [57]. This converter is suitable for use in a PV system with unstable and fluctuating PV output. In a PV system that utilizes both DC and AC converters, DC output voltage stability is enhanced using the DC-link capacitor of the inverter, thus minimizing the effect of PV fluctuation on the inverter AC output [57]. Depending on the size or capacity of the PV output voltage, these converters may be utilized along with DC voltage regulation and stabilization capabilities to provide proper voltage level for the inverter input stage [54]. As the first stage in a PV system, a DC converter receives input power from the PV panel, and then amplifies and feeds the said power to the inverter. The boost converter steps up the DC input voltage to the voltage level required by the inverter. Utilizing this converter is cheaper and more preferable than investing in additional PV panels. Increasing the quantity of PV panels tends to increase the overall PV system cost [39], [53]. A boost converter is not necessary when the DC output voltage from the PV panel meets the inverter DC input voltage requirement [58]. Considering the fluctuating nature of the PV array, a boost converter is integrated with the inverter to produce stable power for the loads [59]. Fig. 3 shows a basic DC-to-DC boost converter with constant DC voltage source. However, utilization of this converter increases system cost and slightly decreases system efficiency due to the losses that occur in the switching devices. The relationship among the converter input voltage V_{dc} , output voltage V_{out} , and the duty ratio D of the IGBT are expressed by [60, eq. (5)].

$$V_{out} = \frac{1}{1 - D} V_{dc} \quad (5)$$

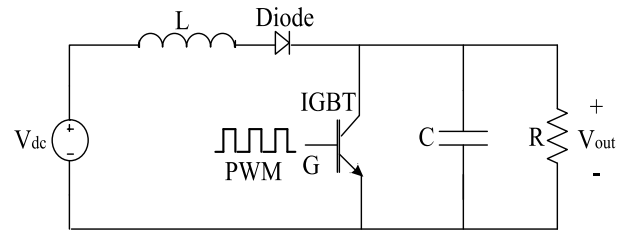


FIGURE 3. DC-to-DC boost converter with constant DC voltage source.

Equation (5) shows that the DC converter output depends on its input voltage and IGBT duty ratio. Increasing the duty ratio increases the output voltage. Nonetheless, this DC-to-DC boost converter only increases the output voltage higher than that of the input. The ratio is modulated and forms a PWM switching signal. This signal is generated by the boost converter controller and fed to the gate of the IGBT, as shown in Fig. 3. Increasing the duty ratio increases the converter output voltage. As for example, the available DC input voltage is 450 V and the DC output voltage requirement is 750 V, the boost factor would be 1.67 and the appropriate constant IGBT duty ratio would be 0.4. Thus, the fixed duty ratio can maintain a higher constant DC input voltage for the inverter. Parameter values, such as the inductor, capacitor, and switching frequency, should be selected properly when designing an inverter to allow the converter to operate in continuous current mode (CCM). This mode ensures that the inductor current flows continuously (i.e., the minimum inductor current is higher than zero) and has low output current ripple [61]. Therefore, with selected load resistance R and switching frequency f , the minimum value of the required inductor L_{min} is described by Equation (6) [60], [62].

$$L_{min} = \frac{D(1 - D)^2 R}{2f} \quad (6)$$

The selection value of the capacitor C , which determines the peak-to-peak voltage ripple, is based on [60, eq. (7)].

$$\frac{\Delta V_o}{V_o} = \frac{D}{RCf} \quad (7)$$

Hence, solving for C , the value of the required capacitance is described by Equation (8):

$$C = \frac{D V_o}{Rf \Delta V_o} \quad (8)$$

where ΔV_o is the change of the output voltage or peak-to-peak voltage ripple of the capacitor voltage.

Considering the variations in PV panel output power in different sun irradiances, the boost converter includes an MPPT feature with a controller that ensures that the PV array always operates at maximum power [63], [64]. The MPPT is essential especially in a stand-alone system with a battery back-up system and a grid-connected PV system that allows for maximum power extracted to be stored in batteries and exported to the grid system [65], [66]. The load determines the required amount of energy for extraction, provided that an

adequate supply of energy is available [65], [66]. However, the MPPT is not recommended for a stand-alone PV system without a battery back-up system because the former will cause a sustained energy imbalance [65]. A PV DC-to-DC boost converter with MPPT is illustrated in Fig. 4.

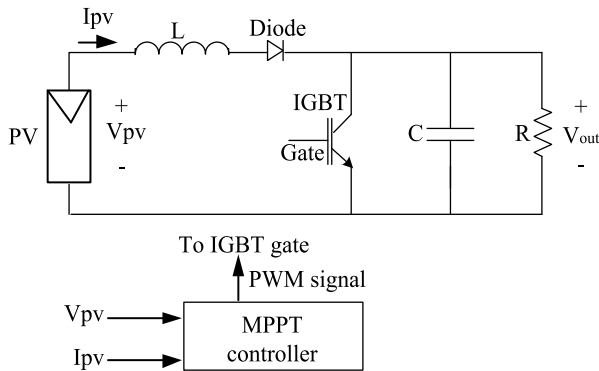


FIGURE 4. DC-to-DC boost converter with MPPT controller.

Hill climbing, P&O, and incremental conductance methods are some of the MPPT methods that have been reported in the literature [67]. The most common and popular method is the P&O [68], where the PV panel parameter (voltage or current) is increased or decreased to find the highest power available in the PV panel. As illustrated in Fig. 4, the MPPT controller accepts PV voltage and current as inputs to generate the PWM switching signal for the gate of the IGBT. In the MPPT algorithm, the sensed PV voltage and current determine the available PV output power. Fig. 5 illustrates the position of the maximum power point on the I-V curve for a certain solar irradiance of 1000 watt/m² at 25 °C. The variations in solar irradiation and ambient temperature produce several maximum output power levels. Thus, the MPPT controller should extract and determine the maximum power available in the PV panel at different solar irradiances [69]. PV output current and voltage change with the IGBT duty ratio, thereby varying the PV output power. By continuously varying the duty ratio, the maximum power point can be

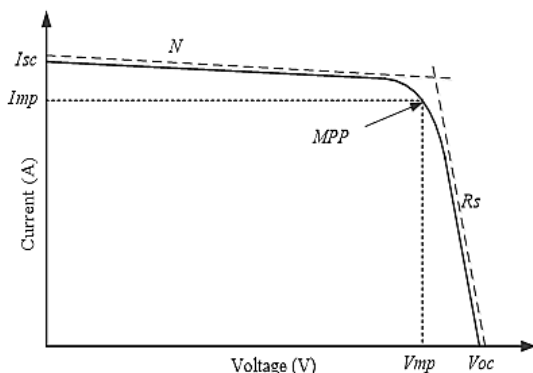


FIGURE 5. Solar panel of I-V curve showing the maximum power point location.

located on the PV I-V curve, thereby enabling the PV to operate at its maximum power point at different solar irradiances.

An inverter performs a DC-to-AC power conversion [36] and mainly produces a sinusoidal AC output with controllable magnitude and frequency [60]. Inverters can be categorized based on their DC input source. Inverters with DC current input sources are called current source inverters (CSIs) and are used for high-power AC motor drive applications. Inverters with DC voltage input sources are called voltage source inverters (VSIs); a three-phase VSI is considered for PV application. As shown in Fig. 6, the three-phase inverter consists of a DC input voltage source V_{dc} , DC-link capacitor C , and power stage with three legs, namely, leg 1, leg 2, and leg 3. The DC input voltage source is a constant voltage source connected to the DC-link capacitor C . The required level of the DC input voltage depends on the specifications of the inverter. In a power system for a three-phase inverter, the DC input voltage level must be higher than the peak voltage of the inverter’s line-to-line AC output voltage. In a fluctuating DC power source, such as a PV panel, the specifications of the capacitor are essential in maintaining the stability of the DC-link voltage during power device switching [70]. The DC-link capacitance should be large enough to reduce the DC-link voltage ripple, resulting in good inverter output power quality [71]. Based on the energy flow of the system, the suitable capacitance for the three-phase system can be expressed as [72, eq. (9)].

$$C_{dc} = \frac{P_{Load,max}}{2V_{dc} \times \Delta V_{dc} \times 2\pi \times f}, \tag{9}$$

where $P_{Load,max}$ is the maximum load rating, ΔV_{dc} is the input voltage variation, and f is the output voltage frequency.

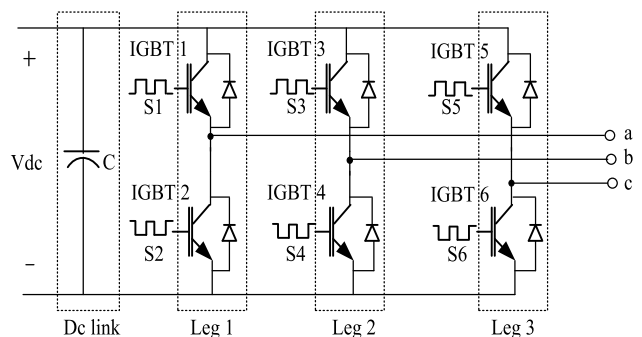


FIGURE 6. Schematic diagram of a three-phase PV inverter.

Switching devices play an important role in DC-to-AC conversion. Each leg consists of two IGBTs that have anti-parallel diodes and are never turned on at the same time [36]. The type of switching devices to be used depends on the power capacity and switching speed of the system. Generally, a MOSFET is utilized in systems with low power capacity and high switching speed; meanwhile, IGBTs are designed for systems with high power capacity and moderate switching speed [60]. The legs constitute the phase of the inverter

output. Leg 1, leg 2, and leg 3 are regarded as output phase a, phase b, and phase c of the inverter, respectively. The gates of the IGBTs receive the PWM switching pulses from the controller. The control algorithm developed in the control system generates these PWM switching signals so that the desired output voltage pattern and quality, i.e., sinusoidal waveform, is produced at the IGBTs collector terminals, a, b, and c [73]. The control strategies for the PV inverter controller are explained in the following sections.

III. INVERTER CONTROL STRATEGIES

An inverter control system aims to maintain the AC output voltage at a desired level and frequency and achieve minimum THD [73]. This role is played by the controller using a suitable control strategy that maintained the voltage at a specific reference input or set point. With a proper control strategy design, the harmonic content of the output voltage may be reduced [74]. The duty cycle of the power devices is one of the control parameters in power converters. The duty cycle is controlled to enable the inverter output voltage to track the reference voltage signal [73]. Tracking accuracy usually depends on the capability of the controller in the control system. Fig.7 depicts the general concept of the closed-loop control system of an inverter.

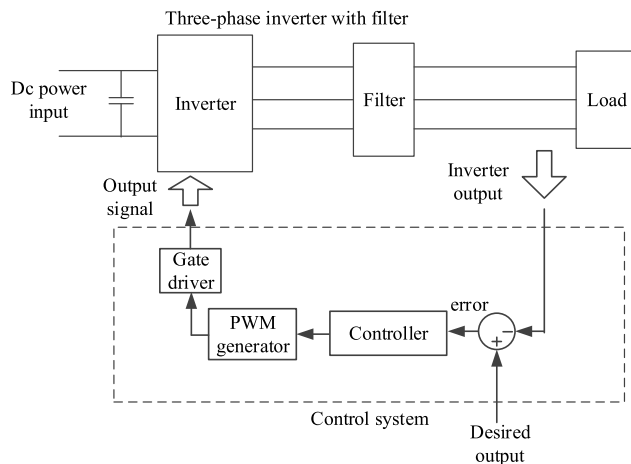


FIGURE 7. General concept of an inverter closed-loop control system.

Based on the concept of the control system, the combination of the inverter and the filter is the main component to be controlled. Thus, the output of the filter, which is the variable, needs to be controlled so that it resembles and tracks the desired output. In controlling the output, the inverter output waveform is fed to the control system input by a sensor. Depending on the control system input requirement, different types of sensors (e.g., voltage sensors and current sensors) are utilized. The control algorithm is designed based on the property (e.g., voltage level) of the input signal to the control system so that the plant output meets the desired output. The comparison of the input parameter with the desired output parameter in the algorithm generates an error signal [75]. The error is the difference between the reference signal

$v_{ref}(t)$ and the inverter output voltage $v_{inv}(t)$, as expressed by [76, eq. (10)]. A control signal is then generated based on the error signal level to determine the specific control signals fed to the actuator, which, in this case, comprises the switching devices, e.g., the MOSFET and IGBT. After the control signal is generated, it regulates the required voltage (DC input) to make the latter suitable for the plant according to the control strategy. This is accomplished through the control of the turn-on duration of the switching devices.

$$e(t) = v_{ref}(t) - v_{inv}(t) \quad (10)$$

Plant dynamics need to be modified to meet the system performance specifications [77]. Unfortunately, in the real-world environment, most plants are fixed and unalterable. System performance can be improved by inserting a controller or a compensator. The compensator manages to overcome the drawback of a fixed plant in the control system. The commonly used controllers are proportional–integral (PI) and proportional–integral–derivative (PID) controllers. The PI controller algorithm in the time domain is described by [76, eq. (11)].

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau, \quad (11)$$

where $u(t)$ is the output of the PI controller and K_p and K_i are the gains of the proportional and integral terms.

The values of the gains determine the behavior of the system, which in turn, performs satisfactorily. The system keeps the output voltage as close as possible to the reference voltage and reduces steady-state errors, thereby regulating the output voltage. Hence, the output voltage of the inverter may be controlled and stabilized.

System performance is achievable through the execution of the proper control strategy integrated with the PWM switching technique. To get a sinusoidal AC output waveform, an SPWM switching technique is employed in the inverter control algorithm. Moreover, controlling the inverter switching scheme can significantly reduce the harmonic content of the output voltage, especially the lowest-order harmonics (LOH) [36], [37]. PWM techniques to inverter control produce the output power with low loss, high efficiency, low distortion, short computation time, and minimal harmonics [78]. PWM switching techniques are sinusoidal PWM (SPWM), hysteresis band PWM (HBPWM), and random pulse width modulation (RPWM). These switching techniques are applied to have various systems with satisfactory performance. However, in some cases, high computational time, harmonic distortion and switching loss cause problems in PV inverter control. The space vector pulse width modulation (SVPWM) switching technique has robustness in minimizing switching loss and harmonic output signals from the inverter controller [79]. Besides, as an advanced computation intensive PWM method, the SVPWM technique is applied for inverter control applications to minimize harmonic distortion. Many researchers have used the SVPWM with the V/f control

TABLE 1. Comparison of AI control methods.

No.	Control Method	Operation	Advantage	Disadvantage	Ref.
1.	ANN	SVPWM based inverter control with PI	Efficient; optimal dynamic control	Complex online computation; lack of accuracy	[86-88]
2.	FLC	Simple PWM inverter control with PI	Simple and efficient, no mathematical model required; adjusted online control for both linear and non-linear systems	Complex control; trial & error process	[89]
3.	Adaptive Fuzzy	PWM/SVPWM inverter control	Efficient; simpler than ANFIS	Complex control; poor performance during disturbance	[90]
4.	ANFIS	SPWM/SVPWM inverter control with PI/PID	Efficient; good performance in sudden input change; THD minimum	Huge data required; complex computational burden; needs long time for data training and learning	[91-98]
5.	Optimization based	GA, PSO, BSA, LSA etc. based FLC/ANN control	Robustness and precise control	Time consuming and complex control; much iteration required	[99,100]

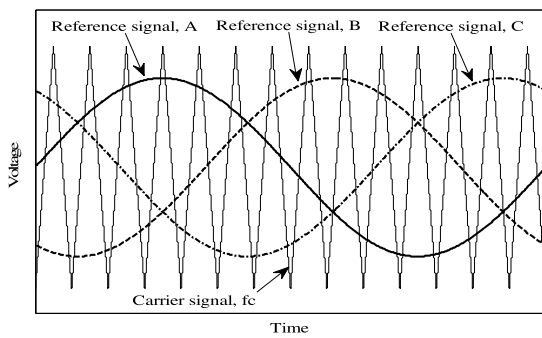


FIGURE 8. PWM signal generation mechanism.

strategy based on the ANN controller in the TIM [80]. The SVPWM is applied in IFOC control for a TIM and is executed with an FLC to control the PV grid inverter system [81]. V/f control is used the SVPWM technique for three-level VSIs is used in the V/f control for high-power variable speed drive [82]. The SVPWM is also employed with the FLC to adjust the position loop for the vector control of the IM drive [83]. The DTC is used with the SVPWM technique to improve and minimize the torque ripple for an induction machine [84]. The PMSM drives use the SVPWM to control torque and flux in the vector control [85]. The ANN with the SVPWM based on sensorless control estimates the rotor speed in the vector control of the TIM drive [86]. However, the SVPWM requires a complex online computation, which leads to difficulty in real-time implementation. Therefore, the conventional SVPWM requires additional memory that limits the selection of switching frequency, thereby reducing its accuracy [87]. Some researchers have solved this problem and have improved the power quality problem by utilizing the GA-based SVPWM, ANN-based SVPWM for two-level inverter, ANN-based SVPWM for three-level inverter, and the ANFIS-based SVPWM used for two-level inverters [87], [88]. Table 1 shows the comparison of AI control methods of PV inverter system.

For generation of simple PWM switching signal, as shown in Fig.8 voltage comparison among reference signals A, B, and C and the carrier signal f_c , is based on the following

criteria. Whenever the reference signal voltage is higher than that of the carrier signal, a “high” pulse signal is generated, which turns on the upper IGBT of the corresponding leg. Otherwise, a “low” pulse signal is produced, which turns the IGBT off. The comparison of each reference signal produces individual PWM switching signals for the IGBT of each leg. The complementary of this signal should be fed to the IGBT in the lower side of the corresponding leg. As a result, the DC input voltage appears at the output phases of a, b, and c.

Fig.9 illustrates the general relationship among the average value of the generated inverter output voltage V_{an} , reference signal waveform $v_{reference}$, carrier signal waveform $v_{carrier}$, and DC input voltage V_{dc} [60]. A bipolar voltage switching technique may be applied on the inverter to simplify the analysis.

The average DC output of the inverter can be regulated by controlling the duty ratio of the IGBT. Only one switching cycle is considered to simplify the analysis because the entire process requires constant switching. The reference signal resembles a constant signal with the amplitude of the carrier signal waveform in the case of the sinusoidal reference signal waveform with high switching frequency. Thus, inverter output can be generalized in terms of the three parameters, namely, reference signal waveform $v_{reference}$, carrier signal waveform $v_{carrier}$, and DC input voltage V_{dc} . The average value of the line-to-line voltage V_{ab} is represented by Equation (12).

$$V_{ab} = V_{an} - V_{bn} = V_{dc}(D_{IGBT1} - D_{IGBT3}) = \frac{v_{reference}}{v_{carrier,peak}} V_{dc}, \tag{12}$$

$$V_{ab} = m_a V_{dc}, \tag{13}$$

where D_{IGBT1} is the duty ratio and m_a is the modulation index.

Equation (13) shows that the output voltage V_{ab} depends on modulation index m_a and DC input voltage V_{dc} . This equation is also valid for the unipolar switching scheme [60]. The modulation index or amplitude modulation ratio is the ratio of the peak amplitude of the reference waveform to the carrier

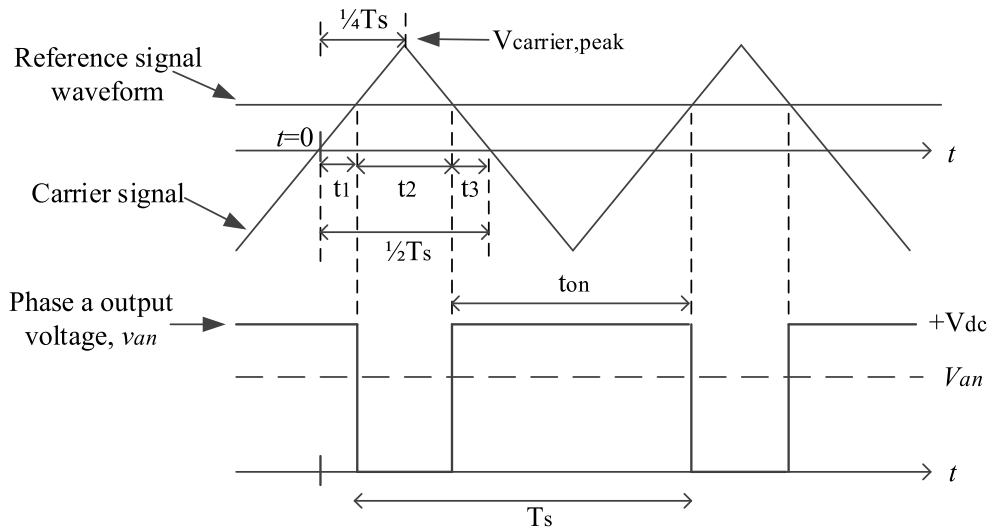


FIGURE 9. Illustration of inverter output voltage generation.

waveform [101]. The value of the modulation index should be maintained below 1 to avoid over-modulation, which results in an output waveform with a high output voltage value and a considerable amount of harmonics. Similar to the periodic function, the line voltage waveform acquires a time period T and a fundamental frequency f in a steady state. In addition to a dominant component at the fundamental frequency, the line voltage waveform contains unwanted harmonic components of the fundamental frequency [60]. The three-phase inverter line voltage is considered a non-sinusoidal periodic function waveform.

Considerable research has been conducted on inverter control issues, internal power losses, system nonlinearity, power fluctuation, environmental variation, low PV efficiency, harmonic distortion, DC-bus voltage fluctuation, electromagnetic interface, and unity power factor maintenance [102]. Therefore, developing an efficient inverter controller to enhance the overall performance of a PV system is challenging [103]–[107]. A number of PID and PI controllers has been implemented in PV inverter systems [100]. However, the conventional PID, PI, and other controllers have demerits in terms of large-scale output filtering, grid frequency, and intelligence application. The utilization of adaptive control in PV inverter systems drive researchers and developers to practice intelligence application in controllers, such as neural network, fuzzy logic, and neuro-fuzzy [89]. A supervisory control employing an adaptive neuro-fuzzy interface system (ANFIS) can be developed for three-phase grid-connected PV inverter systems to address the demand for grid power. Nevertheless, the ANFIS has certain network training problems in a large number of data sets [91]. Meanwhile, intelligent controllers may be in demand in PV inverter systems because they reduce the mathematical model analysis problem and the complexity of handling the nonlinearity of the system.

The fuzzy logic controller (FLC) is the simplest among all intelligent controllers for inverter control application. The FLC is much better than conventional controllers in terms of response and settling time, sensitivity to parameter and load changes, and robustness [108]. An inverter without a transformer can conveniently improve its size and weight issues [109]. The complexities in implementing the PV system are related to the inverter type and switching topology used in the condition of the system environment. Different types such as two or three level inverters can be implemented easily in terms of their inverter topology and control algorithm. On the contrary, multilevel inverters require a complex control algorithm in generating switching signal and system coordination, which provide extra computational hassle to the processing unit [26]. The inverter system also becomes costly because of the increase in semiconductor switches [110]. In [89] FLC based inverter control is proposed for PV systems through simulation and experimental performances having 2.5% voltage THD and 3.5% current THD. An experimental analysis for grid connected VSI is shown with optimum LCL filter design using complex PWM control having 2% THD of inverter current [111]. Using predictive power control algorithm a grid integration PV qZSI system is developed in [112]. The system is designed with a complex SVPWM switching having 3.2% current THD. The experiment is going on the reduction of THD of PV inverter, however, the control algorithm and design approach is becoming more complex and memory use as the optimization algorithm is being incorporated [99]. It might be recommended for developing a robust inverter controller the compromise between the improved algorithm and system complexities is necessary.

The performance of inverter systems is summarized in Table 2, which includes the parameters of THD in the output voltage and current, power factor value, switching

TABLE 2. Summary of the inverter system performance comparison.

Inverter parameter	Ref. [26]	Ref. [105]	Ref. [113]	Ref. [31]	Ref. [104]	Ref. [114]	Ref. [103]	Ref. [89]	Ref. [111]	Ref. [112]
Voltage THD (%)	1.5	N/A	N/A	6.8	N/A	N/A	N/A	2.5	N/A	N/A
Current THD (%)	N/A	8.87	6.8	N/A	4.0	19.8	8.4	3.5	2.0	3.2
Power factor	N/A	0.994	N/A	Unity	N/A	Unity	0.96	Unity	Unity	Unity
Topology	3-Ø 3-L	3-Ø 3-L	3-Ø 3-L	1-Ø 5-L	3-Ø 3-L	3-Ø 3-L	1-Ø 5-L	3-Ø 3-L	3-Ø 3-L	3-Ø 3-L
Switching Tech.	PWM	SPWM	PWM	SPWM	SVPWM	SPWM	SPWM	PWM	PWM	SVPWM
Hardware	Complex	Moderate	Simple	Complex	Moderate	Complex	Moderate	Simple	Complex	Complex
System	Program- ming	Program- ming	Program- ming	Program- ming	Simulink	Program- ming	Program- ming	Simuli- nk	Program- ming	Program- ming
Transformer	Yes	No	No	No	No	No	No	No	No	No

technique use, and designing platform. The design and implementation of the inverter system face difficulties in terms of its design, switching topologies, and design environment. The multilevel inverters should be implemented simply for efficient inverter design and control. The design of these inverter types appears to be more feasible because it simplifies the overall system algorithm, weight, and size. However, inverters with five levels and more require complex switching control and algorithm, which then produce computational difficulties. The increased number of switches also causes the inverter system to become bulky and costly.

IV. CONCEPT OF FLC SYSTEM

An inverter is an essential device for interfacing a DC power source, such as PV to an AC load. With the integration of the essential components of the system such as the control algorithm, which are embedded into the controller or system processor, the inverter can perform an effective energy conversion. With the appropriate and proper design of a control system algorithm, successful power conversion, and effective filtering, the inverter manages to convert the DC input voltage to AC sinusoidal waveform to power up the AC loads. The inverter controller plays an important role in ensuring a successful and effective energy conversion. Hence, the selection of a suitable and effective controller is the key to the excellent performance of the power converter. Fuzzy logic is a theory of fuzzy sets that calibrates ambiguity. A fuzzy set is defined without crisp boundaries Current research on the FLC implementation in the application of a DC to AC converter (inverter) to convert the PV power for AC loads has received considerable attention [115].

A. FUZZY SET AND MEMBERSHIP FUNCTIONS (MFS)

In the FLC system, the controller mimics how the human brain thinks by interpreting the incoming information as imprecise terms [116]. Several examples of the imprecise terms are warm, hot, and cool, which describe the states of the degrees of truth [117]. Fuzzy set A in the universal set U (also called universe of discourse) is a set of ordered pairs of a generic element u (generally not numerical quantities) and

its membership degree, $\mu_A(u)$, as shown in [118, eq. (14)]. The universe of discourse temperature level. These terms are described in terms of sets called fuzzy sets. A specific control action is generated and does not have binary membership characteristics [119]. Scenario is the basic concept of fuzzy logic application in a control system. Through these fuzzy sets, which are associated with the corresponding MFs and integrate with the fuzzy rules. This Fuzzy logic is determined by the thought refers to the range of possible values regarded for fuzzy set members [120].

$$A = \{ (u, \mu_A(u)) : u \in U \} \tag{14}$$

Fuzzy set theory is ideated in such manner that an element belongs to a fuzzy set with a certain degree of membership (associated with an MF), which has a real number in interval [0, 1]. MF provides the degree of membership of any element of the universe of discourse within the set. The types and quantity of MF employed contribute to controller performance, memory space occupation, and execution speed [121]. They map the elements of the universe on to numerical values in the interval [0, 1] [119]. In particular, the MF converts the degree of fuzziness into the normalized interval [0,1] [120], [122]. Unlike an ordinary set, where each element either belongs or does not belong to the set, partial membership in a fuzzy set is possible [119]. The example of the MF, $\mu_A(u)$, of set A is expressed in Equation (15).

The fuzzy set and its MF are illustrated in Fig. 10.

$$\mu_A(u) = \begin{cases} 0, & \text{for } u < 4 \\ \frac{u - 4}{10}, & \text{for } 4 \leq u < 14 \\ -\frac{u - 24}{10}, & \text{for } 14 \leq u \leq 24 \\ 0, & \text{for } u > 24 \end{cases} \tag{15}$$

For example, number 10 in Fig. 10 is the element of fuzzy set A with a membership degree of $\mu_A(10) = 6/10$, which is equal to 0.6. The closer this value is to 1, the more the u (or element) is considered to belong to set A [119]. The fuzzy set and its MF are determined and formed based on expert



FIGURE 10. Illustration of a fuzzy set.

knowledge [117]. Among the commonly utilized MF forms are trapezoidal, Gaussian, and bell shaped [120].

B. LINGUISTIC VARIABLE AND RULES

A linguistic variable is a fuzzy variable that is not a number and is represented in the form of a word or sentence. It is applied in the formation of fuzzy rules of a fuzzy rule base, which can be found in the fuzzy controller [117], [120]. Generally, the variables are named according to the systems input and output. The rule is a conditional statement in the form of IF-THEN, and make the algorithm and fuzzy controller intelligent based on the human-like decision [120], [123]. For example, an air-conditioning control system has the rule “IF temperature is high and humidity is low THEN speed is fast”, where the words “temperature,” “humidity,” and “speed” are the linguistic variables, and “high,” “low,” and “fast” are the linguistic values. These values are determined by fuzzy sets in the universe of discourses, namely, “temperature,” “humidity,” and “speed” [118]. In this rule, the “IF . . .” part is called the antecedent (causes), whereas the “THEN . . .” part is called the consequent. Examples of the linguistic variables are defined as follows:

- temperature = {very high, high, medium, low, very low}
- humidity = {very high, high, medium, low, very low}
- speed = {very fast, fast, medium, slow, and very slow}

Given that each variable (e.g., temperature or humidity) contains five linguistic values, 25 possible rules are considered.

V. FLC ARCHITECTURE

Fuzzy logic is suitable for the control system because of the non-linear nature of a power converter, such as an inverter [18]. The general architecture for the FLC used in a control system is shown in [89, Fig. 11]. This FLC acts as the controller, which controls the plant (process) to attain the plant requirements and specifications. Fig. 11 shows the basic type-1 FLC architecture with three main components: (i) fuzzifier unit, (ii) knowledge based rules and inference engine, and (iii) defuzzifier unit. The other elements associated with the FLC control system are the reference (desired) signal, and the input and output signals from the plant or process to be controlled.

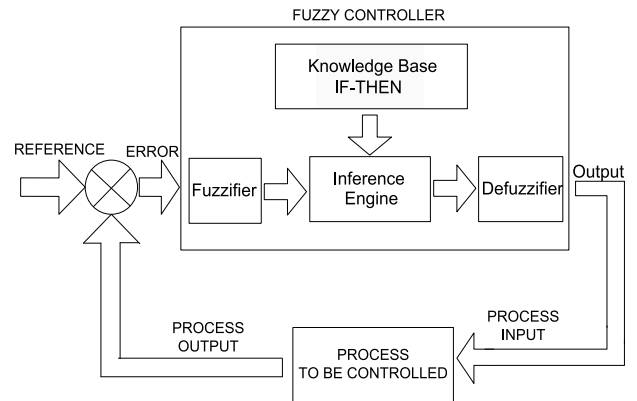


FIGURE 11. Basic type-1 FLC architecture.

The output of the fuzzy system can be obtained with the defined fuzzy sets of the input and output variables, as well as the fuzzy rules. The fuzzy expert system aggregates all fuzzy output sets into a single output fuzzy set and then produces a single crisp solution for the output variable [117]. This condition is accomplished through the inference process, which consists of fuzzification, rule evaluation, aggregations of the rule outputs, and defuzzifications [121].

A. FUZZY INTERFERENCE

The inference process produces a fuzzy output set according to the IF-THEN rule logic. In particular, it maps the input to an output by utilizing the theory of fuzzy sets [120]. The fuzzy expert system combines all fuzzy output sets into a fuzzy set and generates crisp results for the output variable [117]. The system defuzzifies the resulting fuzzy set into a single number. The Mamdani method is a more popular method applied for the inference process compared with Sugeno style [120].

B. FUZZIFICATION

Before input data can be processed by the fuzzy system, the degree to which the physical values (crisps) of each input belong in the appropriate fuzzy sets should be determined [117]. Thus, they are transformed into a degree of membership by the MF [124]. For example, the input is fuzzified over all MFs, which yields a membership degree (value) (e.g., $\mu_A(u) = 0.5$) applied to the antecedents of the fuzzy rules.

C. DEFUZZIFICATION

Defuzzification, which is the final step in the inference process, extracts the crisp output value from a fuzzy output set [120]. This process takes the aggregate output fuzzy set and produces a single-number output. The centroid technique is one of the most popular methods of defuzzification. This method identifies a point that represents the center-of-gravity (COG) of the fuzzy set at a certain interval of $k = 1$ to n [117].

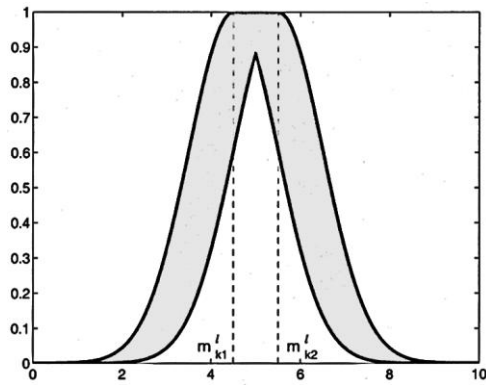


FIGURE 12. Type-2 membership function with the shaded region as footprint of uncertainty [126].

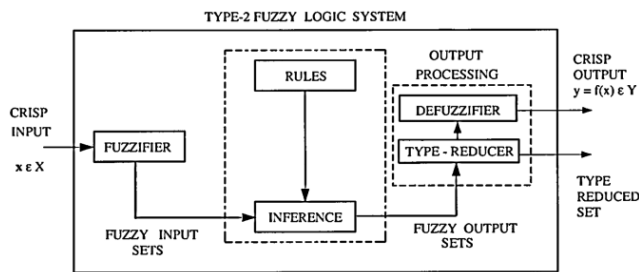


FIGURE 13. Type-2 fuzzy logic system overview [126].

D. TYPE-2 FUZZY LOGIC SYSTEM

The conventional FLC as known as type-1 fuzzy logic system (T1FLS) might have good controlling ability in various applications, however it lags to define the uncertainties of the systems’ noises, nonlinearities and environmental variations. Type-2 fuzzy logic system (T2FLS) defines the system’s uncertainty through a bounded region in membership function (MF) as upper and lower MFs as shown in [125, Fig. 12]. The uncertainty appears due to the measurement noise in the system and can be captured by minimizing the negative effect on the system. Like T1FLS, it contains a rule-base, a fuzzifier, an inference-engine and an output processor. The output processor is comprised with defuzzifier and type reducer that produces type-1 fuzzy output as shown in [126, Fig. 13]. So, according to Hisdal [127], “increased fuzziness in a description means increased ability to handle inexact information in a logically correct manner.” According to John [128], “Type-2 fuzzy sets allow for linguistic grades of membership, thus assisting in knowledge representation and they also offer improvement on inferencing with type-1 sets.” [126]

In T2FLS, the structure of rules are same as T1FLS except that they involve in type-2, the inference process requires additionally to obtain unions and intersections of type-2 sets, and compositions of type-2 relations, the output process is involved a type-reduction process as similar process to type-1 defuzzification to generate type-1 sets from type-2 sets and then defuzzified to crisp output [126].

VI. FUZZY LOGIC INVERTER CONTROLLER

FLC (fuzzy control) can be intelligent control, knowledge-based control, or expert control [119]. A fuzzy logic may model human behavior in terms of intelligence and sense in smart machines [117]. By implementing user-defined rules in performing the system processes, FLC is considered as flexible, and rules can be added and modified easily to improve or alter system performance [129]. Fuzzy logic is the simplest to integrate among the different intelligent controllers [130]. Unlike the conventional controller, the design and application of the FLC algorithm in a highly complex system is more favorable because of its simplicity [116]. A system with fuzzy logic as the controller also provides high quality and reliable output with low cost, better system response, and excellent performance [131]. The nonlinear behavior of the fuzzy controller may result in higher system robustness. This system may comprise nonlinear elements with a simple control structure [116].

Unlike conventional controllers, such as PID controllers, which are based on the mathematical models of the process under control, the FLC uses the concept of an “inference engine.” This method is considered the heart of the system operation. The FLC utilizes the concept of fuzzy sets theory (fuzzy logic), set of IF–THEN fuzzy rules, linguistic variables, and fuzzy proposition in its system operation, such as in decision-making [116]. FLC is applicable to any nonlinear system control (e.g., the PV inverter system), which does not require any distinct process of design, such as pole placement, frequency response, and root-locus designs because of the nonlinear behavior of rules.

The design of a PV inverter control system should consider the fluctuation nature of the PV itself. This scenario ensures that the effect of the PV output variation toward the inverter output is minimized. Given DC input power fluctuation, voltage control that maintains a constant inverter output should be obtained. This role is played by the effective inverter control system. Fig. 14 presents a block diagram of the PV inverter controller that utilizes FLC.

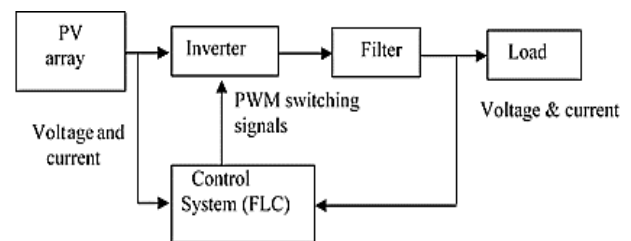


FIGURE 14. Fuzzy logic controller of a PV inverter system.

The selections of system variables, MFs, and fuzzy rules development are necessary to develop the FLC-based control algorithm for a system. The input and output variables used in the FLC system should be initially determined. In an electrical system, inputs to the FLC system are the parameters (electrical signals) originating from the “process to be controlled”. However, the FLC output is the control process

of the input parameters. Different types of system output parameters exist depending on the applications. The output network of the inverter is considered to be the plant to be controlled. The fuzzy logic inverter control algorithm is designed based on the FLC architecture as shown in Fig. 11. In the fuzzy logic-based inverter control system, an error in the discrete time, $e(k)$ [Equation (16)], and its rate of change, de/dt , are selected as input variables for the FLC. The controller output, $u(k)$, is selected as the FLC output variable as illustrated in Fig. 15. The inverter output voltage is the output variable from the process. The process output in an equilibrium or steady-state condition should be extremely close to the desired value.

$$e(k) = r(k) - y(k), \tag{16}$$

where $y(k)$ is the process (inverter) output variable, and $r(k)$ is the desired or reference signal.

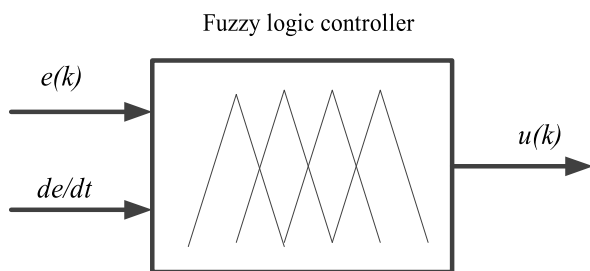


FIGURE 15. FLC input and output variables.

A. RULE-BASED FUZZY CONTROLLER

The FLC structure is a double-input-single-output type. For the proper and accurate fuzzy system operation, the input and output variables of the universe of discourse should be normalized to fit into the interval value of -1 and $+1$. Each input variable obtains five triangular-type MFs and two trapezoidal-type MFs as shown in Fig. 16. The input and output variables associated with the fuzzy sets are NB, NM, NS, ZERO, PS, PM, and PB.

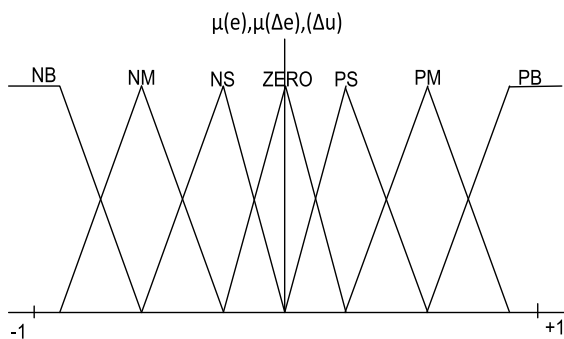


FIGURE 16. MFs for the error, change of error, and change of output.

Given that seven MFs (fuzzy sets) of each input variable exist, the fuzzy system obtains 49 possible rules. These rules are presented in table form, called the fuzzy rule table

TABLE 3. Fuzzy rule table for the rules base system.

Error → Change of error ↓	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NS	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

(Table 3), to simplify the controller design. Table 3 shows a list of rules that governs the controller decision. Several examples of the system rules are presented as follows [89]:

Rule 1: IF error is NB AND change of error is NB THEN output, u is NB

Rule 2: IF error is NM AND change of error is NB THEN output, u is NB

Rule 3: IF error is NS AND change of error is NB THEN output, u is NM

...
...

Rule 49: IF error is PB AND change of error is PB THEN output, u is PB

Equation (17) shows that the output of the fuzzy controller changes for every sample of time, T_s , as in discrete-time, $u(k + 1)T_s$, until it reaches steady-state [132].

$$u(k + 1)T_s = u(kT_s) + \Delta u(kT_s) \tag{17}$$

where $\Delta u(kT_s)$ is the new value of the controller output control at $t = kT_s$, and k is the value of (0, 1, 2, 3...).

The defuzzification process is implemented to convert or extract crisp, u , (real signal or non-fuzzy output) output value from a fuzzy controller output [116]. The process then converts the numerical output to a control signal that drives the process to meet the desired outcomes. The method of translating the rule firings into the crisp output values is the COG. The method is implemented as a value of crisp control action, which represents the fuzzy controller output as shown in [117, eq. (18)]. This method obtains the equilibrium position of the fuzzy region by determining the weighted mean of the fuzzy region [133].

$$COG = \frac{\sum_k \mu_k(u_k) \times u_k}{\sum_k \mu_k(u_k)}, \tag{18}$$

where u_k is the discrete element of output value (fuzzy set), and $\mu_k(u_k)$ is its MF (value).

B. INVERTER CONTROL ALGORITHM

The purpose of the inverter control system is to generate a desired and stabilized 50 Hz sinusoidal output waveform. Eliminating the contents of the harmonic at the output and control the constant DC input voltage are the main challenges for the inverter controller. These issues can be addressed

by generating PWM signals to gate the switching devices of the inverter. Output voltage and current waveform must be ensured to attain the phase condition called the unity power factor. These objectives are accomplished with the PWM technique. The duty cycles of the actuator or switching devices are controlled to accomplish the control objectives. The control approach is introduced to the control algorithm, which is embedded in a system controller or DSP. Fig. 17 presents the functional flowchart of the PWM control algorithm of the inverter [134].

The flowchart shows that the final process requires generation of the IGBT duty cycle, which can be accomplished through the PWM signal generation. The IGBT duty cycle of the boost converter, PWM_{boost} , is initialized to supply the desired DC voltage to the inverter input [89]. The output voltages of the three-phase inverter, v_a , v_b , and v_c , are then sensed and transformed to the direct-quadrature (dq) reference frame to improve voltage regulation. An error signal is generated by comparing voltages v_d and v_q to their respective reference voltages, v_{dref} and v_{qref} , at dq reference frame. This error signal guides the generation of the duty cycle of the inverter, PWM_{inv} , where a positive error contributes to higher duty cycle, whereas a negative error indicates a lower duty cycle [135]. This loop continues until a minimum error of the voltage is attained to reach an equilibrium state.

Fig. 17 shows the control algorithm, which is composed of different components and functional blocks, such as PLL-type frequency synchronization, three-axes abc to two-axes dq transformation, voltage regulation that utilize FLC controllers, and PWM signal generation and signal conversion. The PLL block provides a stable frequency of reference for the system control to stabilize the output frequency at its desired level. The standalone configuration provides the PV generated power directly to the local loads. The voltage-control scheme is used for inverter operation, where the output voltages with unity power factor and displaced 120° to one another are sampled and transformed to dq components. This scenario ensures that these parameters can be employed by controllers for control purposes. The three AC voltage quantities in balanced three-phase systems are transformed to two imaginary DC quantities. This transformation can conduct a simple calculation to analyze the three-phase synchronous machines or control the three-phase inverters before recovering the three-phase AC results by inverse transformation. The Park transformation [136] is utilized in this axes transformation with a 50 Hz PLL internal or local synchronizing signal.

By obtaining the output voltage or current feedback samples and implementing the control algorithm, the inverter controller can transfer the maximum PV power to the load and maintain the output voltage, current, and frequency at their desired levels. The switching signal generation that employs the voltage control approach for a standalone three-phase inverter is illustrated in [89, Fig. 18]. The fuzzy logic control strategy is implemented in the special DSP called dSPACE DS1104 [134], [135].

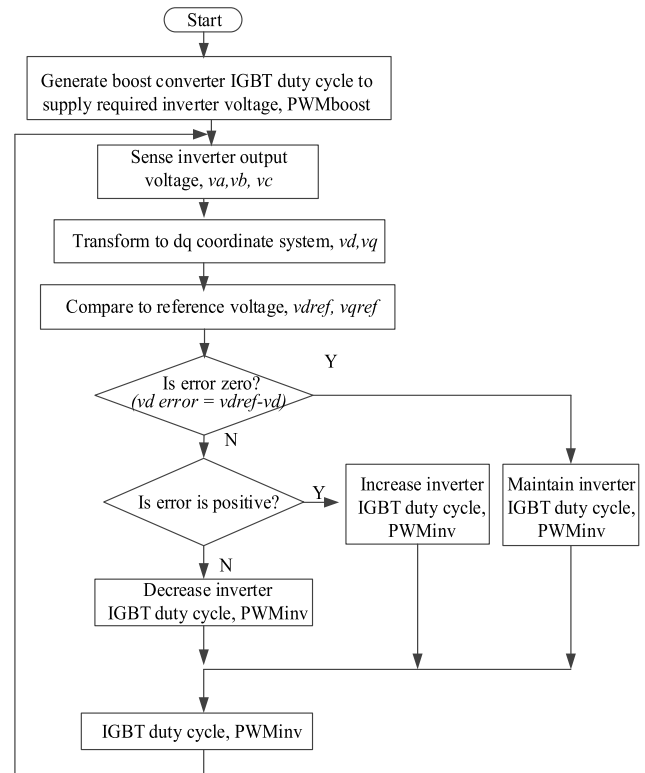


FIGURE 17. Inverter control algorithm flowchart.

Three-phase quantity-like voltages in the synchronous reference frame (abc) must be transformed into the static reference frame (dq) to apply the fuzzy controller to the PV inverter system. This mechanism simplifies the development of the control system. The three-phase coordinate system equations are expressed in a two-phase coordinate system that rotates at the fundamental angular frequency, ω and presented in Fig. 19. In most cases, the three-phase variables have no zero sequence components. However, the abc to dq transformation is reduced to d and q components only, which may be applied in the balanced three-phase load condition. Therefore, the dq coordinate frame contains v_d and v_q terms only by disregarding the v_o term. By applying the transformation matrix, the AC varying quantities become DC quantities, which are easier for the controller to address [134]. The FLCs can contain knowledge on the reference voltage in transient and steady-state conditions for error minimization. The voltages v_d and v_q are regulated at reference voltages v_{dref} and v_{qref} , respectively, by comparing the course that generates error voltages. These error voltages are fed to the FLCs to regulate the output voltage of the inverter. The dq quantities can be retransformed into the three-phase quantities by multiplying with the inverse transformation matrix [134] to ensure that the inverter produces three-phase output quantities, such as voltage and current. Therefore, the controller establishes and stabilizes the phase voltage, v_a , of $240 V_{rms}$ for instance or line voltage, v_{ab} , of $415 V_{rms}$ and frequency of 50 Hz.

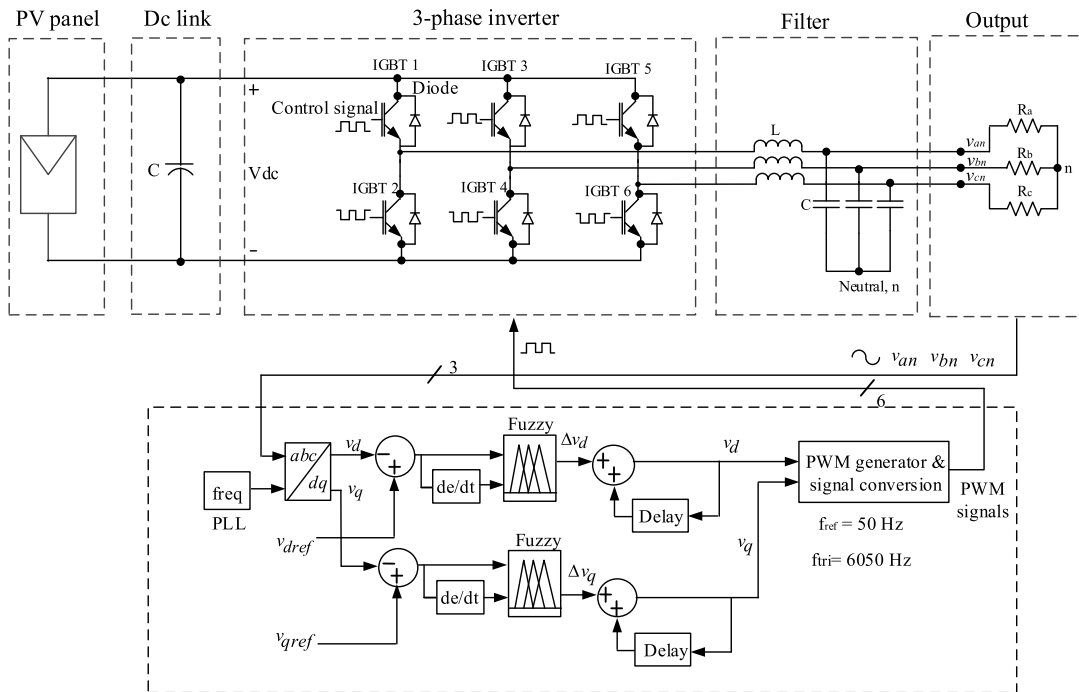


FIGURE 18. Control strategy for a standalone three-phase inverter.

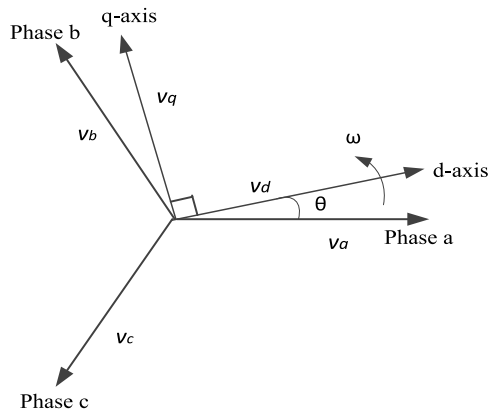


FIGURE 19. Relationship between frames abc and dq.

C. INVERTER SWITCHING SIGNAL GENERATION

At the final stage of the control algorithm depicted in Fig. 18, the dq components are converted into PWM signals. At this point, the components are retransformed to the abc coordinate frame and then compared to the 6050 Hz carrier triangular wave. The switching frequency of the inverter switches is established by this triangular wave [60], thereby generating the switching signals called SPWM. SPWM is a technique that provides switching frequency to the inverter IGBTs to produce the inverter AC outputs as a pure sine wave [36]. The duty cycles of the IGBTs switching are modulated by the sinusoidal control signal, which is the desired voltage and frequency of the inverter.

The voltage that results from the preceding action has harmonic contents that appear as sidebands around the switching frequency, which are expressed in [49, eq. (19)]. With the aid

of a filter, an output waveform of a near sinusoidal shape is obtained. This filter has low impedance characteristics for lower frequencies and high impedance characteristics for higher order harmonics. The cut-off frequency of the filter may be assigned as 1 or 2 octaves above the fundamental switching frequency of 200 Hz [137]. Thus,

$$f_{harmonic} = kM_f = k \frac{f_{triangular}}{f_{control}} \tag{19}$$

where k is an integer, $f_{triangular}$ is the frequency of the triangular waveform, $f_{control}$ is the frequency of the sinusoidal control signal, and M_f is the frequency modulation index.

The RMS value of the line-to-line inverter output voltage is described as follows:

$$V_{line, RMS} = 0.612 M_a V_{dc} \tag{20}$$

where $f_{triangular}$ is the frequency of the triangular waveform, V_{dc} is the DC input voltage, and M_a is the amplitude modulation index.

The amplitude modulation index is the control variable responsible for the RMS value of the line-line inverter output (fundamental) voltage. The modulation index is the amplitude ratio of the control signal, $V_{control}$, to the triangular signal, $V_{triangular}$, as shown in Equation (21). By varying the index from 0 to 1, the output voltage varies from 0 V_{dc} to 0.612 V_{dc} . It corresponds to the varying of the duty cycle or width of the switching time. An over-modulation phenomenon may occur due to the increase in the index value of 1. This scenario may result in excessive harmonics in the inverter outputs, which should be avoided. Thus, the index

value of 0.9 should be maintained [137].

$$M_a = \frac{A_{V_{control}}}{A_{V_{tri}}} \quad (21)$$

Using the desired three-phase RMS line output voltage of 415 V and maximum modulation index of 0.9, Equation (21) is utilized to determine the minimum requirement of the inverter DC input voltage [137]. The filter output is connected to the three-phase load. The controller manages the overall operations, including controlling the switching of the power devices and regulating the voltage and current.

D. FLC BASED ADVANCED CONTROLLER

Many research and developments have been done to control nonlinear systems with uncertainties. A controller has been developed for buck and boost converters to study the uncertainties of the system using T2FLC [130]. It has been implemented in three phase inverter to upgrade the performance of the system compared to T1FLC [138]. A design has been proposed by Bay for DC-DC boost converter that enhances the PV output voltage to three phase inverter input using Interval T2FLC (IT2FLC) [139]. It has been shown that IT2FLC utilized converter system produces superior performance that T1FLC based converter control in handling the uncertainties of the system. An adaptive neuro-fuzzy logic control has been presented to a grid connected multilevel PV inverter system [140] as a robust controller, however, it lags to define the performance to environmental sensitivities of PV modules. Fei and Zhu [141] proposed an adaptive fuzzy sliding mode controller for grid connected PV inverter system. In this adaptive fuzzy controller, T2FLC has been incorporated to estimate upper bound of uncertainties of noise due to ambient conditions that results to adjust the nonlinearities for reliable control of inverter [141]. With fast nonlinear learning capability the fuzzy neural network (FNN) has been applied to nonlinear systems in many fields of control engineering including industrial processes. A fault detection method using FNNs for nonlinear systems was demonstrated by Xue *et al.* [92]. Lin *et al.* [93] and Wen *et al.* [94] presented an adaptive FNN to control permanent magnet motor drive system and multi-input multi-output (MIMO) nonlinear systems, respectively. A novel adaptive hybrid control system was proposed by El-Sousy [95] for permanent-magnet servo drive. A wavelet Petri fuzzy neural network (WPFNN) was used for squirrel-cage induction generator system in [96]. Li *et al.* [90] presented an adaptive fuzzy output-feedback dynamic surface controller for nonlinear systems. Many advanced FLC schemes have been proposed and demonstrated in [97], [98], [142], and [143].

VII. CHALLENGES AND RECOMMENDATIONS

A potential power inverter must be able to produce a sinusoidal waveform of constant magnitude irrespective of load type. It should also provide fast recovery from transients caused by external instabilities without hampering the power quality. However, several challenges could raise difficulty in

the application of PV systems and their inverters. The details of the challenges and the corresponding recommendations are as presented as follows.

A. GRID-CONNECTED PV INVERTER

PV-based grid-tied inverters have been developed for commercial viability and practical implementation, which could enable power electronic controls to evolve to address the technical demand of interfacing PV inverters with the grid [144]. A PV inverter with grid integration could provide voltage regulation by sourcing or sinking reactive power. The traditional PV inverter requires modifications with this feature by oversizing the power electronic properly to support reactive requirements and avoid the problem of excessive ripples during high VAR production or absorption [145]. However, the voltage regulation and VAR support from the PV inverter system has yet to be defined. The addition of this feature to the PV inverter system would also incur considerable costs. Hence, determining how the capabilities of future PV inverters toward solar energy grid integration systems can be enhanced is important.

An increase in PV penetration levels increase require that certain issues be addressed, such as voltage upswing, voltage regulation for cloud-induction, transient problems due to mass tripping of PV at low voltage or frequency profiles, power quality issues for anti-islanding, undue harmonic contamination, and coordination problem of defensive relays and fuses [146]. Future solar energy grid integration system inverters should have critical capabilities to work under enhanced services and controls to microgrid integration, as well as serve as an interface with the control communication bus system of power systems [147]. Ensuring the reliability and consistency of the inverter hardware concerns is highly imperative. The mean time between inverter failure and PV module hardware has a large gap, and thus, inverters should be substituted once or twice over their life span [39]. Inverter failure also causes a missed-opportunity cost for energy not generated. Thus, enhancing the efficiency to ensure the long service life of inverters would result in lower energy generation costs.

B. INTERMITTENCY OF PV INVERTERS

Policies for injecting PV power back to the grid are challenging because of the large penetration of intermittent PV generation without fast acting inverters. Fluctuations in solar irradiance and available PV power would lead to the following issues;

- Continuous switching of active and reactive power resources;
- Decreased equipment lifetime and increased maintenance costs;
- Transient changes in PV generated voltage on a sudden trip, particularly if the system undergoes continuous voltage regulation; and

- Harmonics generation in the outputs of PV inverters, and inverter interconnection with the distribution system during a possible resonant interaction.

A sophisticated forecast model should be developed to sustain satisfactory levels of consistency and viability in power systems to address PV intermittence issues. A smart inverter with bidirectional communication capabilities should be used to curtail transient information of the forecasted model and avoid disturbances, thereby overcoming the forecasted drop in PV generation. For the load demand management corresponding to the flexible power generation in a grid-connected PV system, incentive-based demand response management may provide valuable assistance. This management system can mitigate the predicted variations or inconsistencies in PV generation.

C. INVERTER CONTROLLER AND ITS ALGORITHM

Many inverter control techniques to solve the problems of the PV system integration with AC loads and utility grids have been recommended. PI controllers are commonly employed in inverter controls [31]. However, these controllers require a trapezoidal sum approximation to transform the function from the continuous-time to the discrete-time domain for suitable processing and performance [103]. Optimization techniques have been recommended to tune the gains of the PI controller and improve the performance [148]. Artificial intelligence-based control techniques have been applied in inverters with high efficiency and superior dynamics, such as the artificial neural network and ANFIS. Nonetheless, these controllers require large training data before they are trained and implemented in the controller. Presently, FLCs are applied in inverter control design because they are simple and can be adapted to any complex systems without mathematical model. However, FLCs are implemented with several rules and MFs. Generally, these rules and MFs are determined by a trial and error procedure, which is time consuming and inefficient [149]. Therefore, the optimization algorithm is recommended to optimize FLC rules and MFs that enhance the efficiency of the FLC design and performance and maximize power generation in a grid-connected PV inverter.

D. MULTI-LEVEL INVERTER SWITCHING

The switching losses of a multi-level (ML) inverter comprise the maximum percentage of total device losses. A decrease in switching frequency produces more harmonic distortion in inverter output waveforms. ML inverters can provide output voltage waveforms with less harmonic distortion. However, more switching devices translate to lower efficiency and consistency of the power converter. Thus, optimizing switching frequencies that lessen the harmonic distortion in output waveforms is essential to ensure the high power quality and fast dynamic responses of ML inverters.

Low switching frequency methods are necessary to lower the switching losses for high power applications. However, high switching frequency methods are appropriate for high dynamic range applications with high power quality.

Different PWM modulation strategies have been developed, including carrier-based sinusoidal PWM, selective harmonic elimination, and space vector modulation, to decrease harmonics and offer flexibility to select optimal ML inverter switching. Computational complexity occurs with the increase in inverter levels. Therefore, fast computation, which conversely performs with poor accuracy, is necessary [121]. A new approach that offers possibilities of low switching frequency while maintaining acceptable THD to include advanced control strategies could be adopted [150] to address the issue. Other programming approaches, such as gradient-based methods, genetic algorithms, and search optimizations, have also been used as ML inverter control strategies. However, these approaches undergo a long computational process and suffer from optimization convergence and sensitivity at difficult levels.

The selection of a PWM switching method for an inverter is a trade-off between switching frequency and harmonic distortion. Therefore, considering the optimization of modulation techniques that allows a lower switching frequency with harmonic reduction is noteworthy. Several approaches have been considered to define these issues. Nevertheless, most of these approaches have demerits in terms of the wide modulation index use or increment in switching losses. Accordingly, SVPWM and synchronous optimal PWM, which consider low switching frequencies, algorithm simplification, and neutral-point balancing, are utilized in ML inverter controllers. These approaches synchronize the switching and fundamental frequencies, in which the optimized frequency minimizes the harmonic distortion. Thus, optimal modulation techniques are more suitable. However, the optimization technique is invalid for transient conditions and high over currents are produced subsequently along with pulse pattern changes. Thus, the challenge in minimizing switching loss and waveform distortion with an extremely low switching frequency could be an optimum switching control method that may be useful in reaching this goal.

E. COMPLEX COMPUTATION DUE TO FUZZY MF AND RULES

As a convention, the selection of MF number and limits of each MF in the FLC structure should be in a suitable position set obtained by means of a trial-and-error procedure until the FLC provides a favorable result. However, this procedure can be difficult to accomplish because it incurs long computational time and determining the MF boundaries is difficult [149]. Thus, an adaptive FLC design technique that can control the inverter system by adopting the optimization algorithm should be utilized, thereby avoiding the rigorous outdated trial-and-error approach and obtaining the minimized or best MFs [148], [151]. The generated adaptive MFs should be implemented in the input and output of the fuzzy inverter controller to solve the problems of the scalar or vector control. FLC rules are also formed by the IF-THEN condition to develop the control algorithm. These rules are executed to implement the control decisions of a controller. The more

linguistic variables with more linguistic values, the more possible rules are generated [117], [123]. Therefore, a processor with high speed and space may be required to ensure efficient intelligent control decision for FLC and its operation.

F. PASSIVE FILTER INTEGRATION

An efficient inverter system produces a stable and smooth output voltage signal with low THD value in high-power applications [150]. The three-phase inverter system faces a high harmonics problem that harms the load system [152]. Therefore, the inverter system requires filters to lower the harmonics effect to the loads. The quality of the inverter output also depends on the design and performance of the filter along with the DC input voltage quality [71]. Hence, the use of a filter at the input side of the inverter system may enhance the output quality. An LC passive filter of higher order may be utilized in an inverter system application to lower higher harmonics components and system design cost [153]. The plant parameters should be controlled to integrate the filter in the inverter system. This mechanism could also be implemented by using voltage and current sensors, which are then fed to the input of the control system to track the desired output of the filter through the control algorithm.

G. INVERTER POWER QUALITY ISSUES

In power grid applications with PV system, maintaining the power quality is an issue because of the fluctuations of the DC power source. A high value DC-link capacitor may be essential to stabilize the DC-link voltage and decrease the voltage ripple at the switching time of power devices, which can result in suitable inverter power quality [70], [71]. Maintaining the output signal of the inverter system with low THD level is another challenge for the power quality issue, which complies with the standard requirement (e.g., IEEE Std 519-1992) [22], [154]. Given the power conversion process, voltage and current qualities may be concerned with deviations from the ideal of a single-frequency sine wave of constant amplitude and frequency. Several power quality issues include harmonics, voltage dips, voltage flickers, and noise [32]. Harmonics because of waveform distortion result in equipment overheating, increased losses, decreased volt-ampere capacity, and voltage and current waveform distortion [152]. The harmonic level of the output waveforms of a system is determined by the THD value [43]. The selection of the controller is essential because it determines the amount of plant output and desired value deviation [77]. In particular, a suitable controller tracks the reference value accurately, lowers the deviation to zero or the smallest value possible, and sustains the fast transient response without overshooting (above the desired output) and steady-state response with minimal error [155]. The control system must also have a system stability criterion that allows the system natural response to decay to zero eventually as time approaches infinity or undergo oscillation. The IGBT may be considered a controllable switch for the inverter, which has the feature of lower conduction losses (in “on” state) of the BJT and the

fast turn “on” and “off” feature of the MOSFET [60]. These features are suitable for designing an inverter that employs high switching frequency to produce suitable power quality output with low conduction loss. A drive circuit is required to switch the transistor state to either the “on” or “off” state. The operation of the gate driver is essential because it affects the electrical performance of power converters, such as reliability and efficiency [156].

VIII. CONCLUSIONS

A power inverter system is utilized to serve as the interface for the DC power source from the PV to the utility grid or AC load. The optimal design of the inverter system and its robust intelligent control has vigorous PV applications. The inverter with FLC controls the fluctuation of DC power from the PV and generates the quality and state of the output to loads. This study reviews and discusses the control system technology of a three-phase inverter and PV. Many controller algorithms and methods, which have been implemented in PV power converters (e.g., boost converters and inverters), have been investigated to address issues such as system stability and output power quality. Different types of inverter system platforms have been presented, and have been utilized and incorporated for inverter improvement. The overall design concept of the fuzzy logic-based PV inverter control algorithm was also discussed. A comparison of AI control methods for PV inverter system is presented with their operations, advantages and disadvantages. Moreover, the performance of inverter systems is reviewed in tabular format to show the control robustness and the application progresses. This review includes the development of fuzzy rules and system control strategy to accomplish the control objective of converting DC input voltage to AC sinusoidal waveform to power up AC loads. The concept of PWM signal generation has also been presented to accomplish the aforementioned control objective. The current issues and challenges of a fuzzy logic inverter system in PV applications and generations have been highlighted to describe a grid-connected PV inverter, intermittency of PV inverters, inverter controller and its algorithm, multi-level inverter switching, complex computation because of fuzzy MF and rules, passive filter integration, and inverter power quality issues. This study presents several recommendations to enhance and improve the FLC-based inverter system, as well as direct the future development of intelligent inverter systems in PV applications and generations. Conventional energy sources can be exhausted, and hence, finding alternative energy sources, such as PV, has become highly significant. Inverter controllers are considered a significant field in PV systems.

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