Fuzzy Controller based Closed Loop Control for Single Stage Single Phase Grid Integrated PV System with Novel Configuration of 7 Level Hybrid Inverter

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Abstract: Grid integrated renewable energy sources are greatly benefiting from the use of multilevel inverters, as they inject less total harmonic distortion (THD) and improve the quality of inverter voltage. However, these inverters face challenges due to their high number of switches and complex control. Therefore, it is necessary to explore new configurations with simpler and more effective control methods. In addition, Photovoltaic (PV) systems are being installed in numerous apartments and houses, typically connected to a single phase utility grid. It is crucial to ensure power quality through the use of an inverter connected between the PV system and the utility grid, controlled by the inverter itself. Since PV systems exhibit non-linear behavior, a DC to DC converter is required, along with an appropriate algorithm to maximize power output. However, the inclusion of an additional DC to DC converter can increase the size, cost, and complexity of the system. As a result, single stage grid connected systems have gained popularity for low power applications. Furthermore, the use of a Fuzzy controller has shown superior performance compared to PI controllers, thanks to its ability to adjust gains based on changes in solar irradiance and load. Therefore, this paper introduces a new configuration of a 7 level inverter for single phase single stage grid connected PV systems, incorporating a Fuzzy controller for control. This new configuration only consists of seven switches, making it more streamlined. The paper includes extensive results to validate the effectiveness of the proposed methodology.

Keywords: Photovoltaic, Multilevel Inverter, Single Stage, Fuzzy.

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1. INTRODUCTION

The utilization of renewable energy systems, particularly photovoltaic (PV) based electrical power production systems, is steadily increasing due to growing public awareness of global warming and the numerous benefits of installing PV systems. Recently, there has been a significant interest in small-scale PV systems for offices, apartments, houses, and hospitals. These systems are typically connected to the utility grid, allowing for the transfer of excess power produced by the PV system to the grid, while also enabling the grid to supply the required power when there is insufficient power from the PV panels [1-2]. Consequently, an inverter is necessary to interface the PV system with the utility grid. However, conventional inverters tend to introduce significant harmonic content into the utility grid, thereby compromising the power quality on load buses where other loads are connected [3]. Moreover, normal inverters are unable to produce a pure sine wave even under the pulse width modulation (PWM) method. To address these issues, multilevel inverters are commonly employed in various systems connected to the utility grid.

There are numerous options available for multilevel inverters, but these options often require a larger number of switches, resulting in increased size and cost of the system. Additionally, controlling these inverters becomes more complex when generating pulses for a larger number of switches. In a study by the authors, a new configuration of a 7 level single phase inverter was proposed, which only requires seven switches. However, in order to connect the PV system to the utility grid using this inverter, an effective closed loop controller is necessary. In comparison to a PI controller, a Fuzzy controller can provide more accurate outputs due to its adjustable gains that can adapt to variations in system parameters such as temperature, solar irradiances, and various loads. Therefore, this paper implements a Fuzzy based closed loop controller.

In the distribution system, the majority of loads are connected in single phase [6-7]. Fortunately, the PV system is also connected to the same single phase line. The voltage drop in the distribution feeder or line varies depending on the load current, which is determined by the consumers' needs, due to the resistance property. Consequently, voltage drops may occur multiple times for different houses during peak load demand. Additionally, the consumption of reactive power by the load also contributes to voltage drops. To ensure a constant voltage under all conditions, especially during load demand, proper control of the inverter connected to the same feeder or line is necessary [8-9]. The proposed system aims to achieve the following objectives outlined in this paper.

- A closed loop control method has been implemented for a unique 7 level inverter configuration.
- In order to achieve a more optimal response, it is necessary to employ a fuzzy-based controller.
- To create the controller that ensures a consistent RMS voltage at the load bus.
- To deploy a grid integrated PV system with a single stage and single phase, one must fulfill the requirements.

The subsequent document is structured by presenting the system description in Section-2. Detailed description of the Fuzzy controller is presented in Section-3. The description of the proposed controller can be found in Section-4, while the results are illustrated in Section-5. The conclusions and references are provided at the end of the work.

2. SYSTEM DESCRIPTION

Figure 1 illustrates the proposed system, comprising a new arrangement of a 7 level inverter, a PV system, and a single phase AC grid. The PV system is composed of multiple PV panels which arranged in series and parallel combinations to fulfill the necessary criteria. The unique configuration of a 7 level inverter utilizes only 7 switches for a single phase. To eliminate the need for an additional converter for MPPT operation, the inverter functions as an MPPT device for the PV unit. It achieves this by regulating the voltage at DC link at its reference signal which is generated using the perturbed and observed (P&O) algorithm.

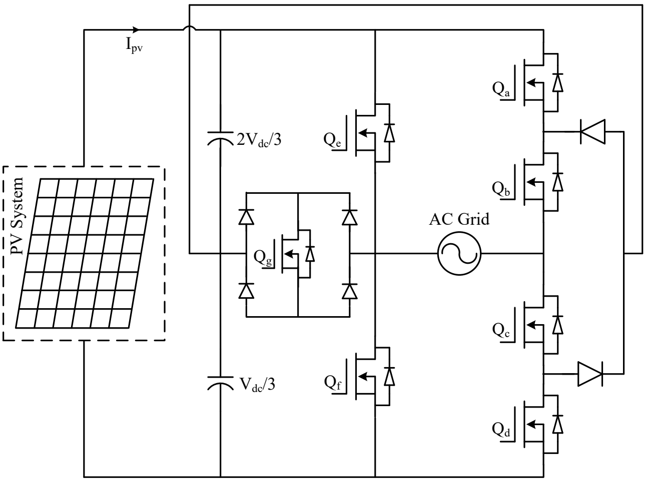


Fig. 1: Proposed Single Stage PV System.

Several scholars have recently presented similar work, and a few of them are listed here. In [10], the authors propose a modular multilevel inverter control method for a single stage grid connected PV unit. In [11-12], novel controllers for a single phase single stage grid integrated PV unit are implanted. The authors in [13] have developed frequency regulation in a single stage grid connected PV unit. In [14], an implementation of a novel P&O algorithm for a 3-phase single stage grid integrated model is presented. Authors in [15] utilize a T-type grid connected inverter for a single stage grid connected system. In [16], authors implement a P-Q based power flow controller for a single stage grid connected PV system. However, there is still a significant amount of research that needs to be done in the single phase single stage grid connected model to improve power quality and achieve better response with a Fuzzy controller.

3. FUZZY SYSTEM

The Fuzzy controller possesses the capability to adapt the output based on variations in the system. Consequently, opting for the Fuzzy controllers instead of the PI controllers can enhance the system's performance amidst different alterations. The design of a Fuzzy controller is accomplished by adhering to a specific procedure.

A. Input/ Output variables

The Fuzzy controller's output is determined by the design, which is based on the variations in input, specifically the error signal. The Fuzzy controller receives the error and its derivative with respect to sample time as inputs, in order to generate the corresponding output. At each sampling instant, error and its derivative, two input variables, etc are calculated.

e(k)=Target value(k)-actual value(k)

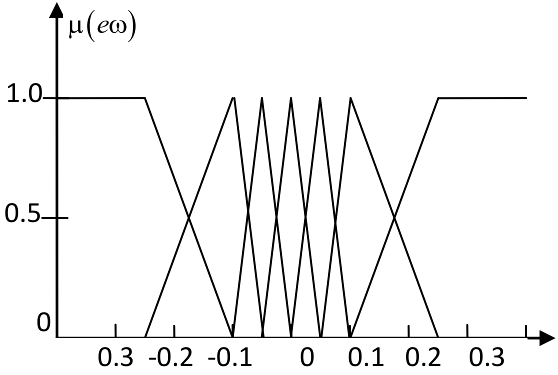
Change in e(k)=e(k)-e(k-1)

Where ‘k’ is a sample instant. $i_{qs}^{*}\left(k\right)$ is estimated by.

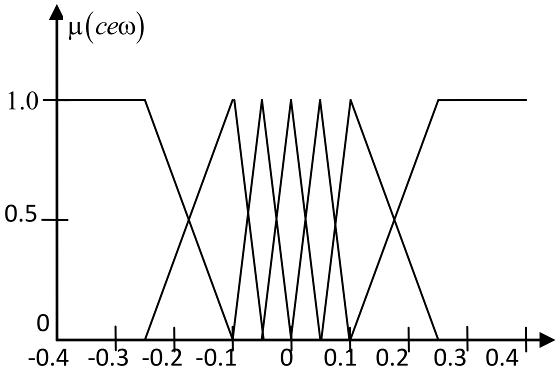
$$i_{qs}^{*}(k) = i_{qs}^{*}(k-1) + ci_{qs}^{*}(k)$$

B. Fuzzification

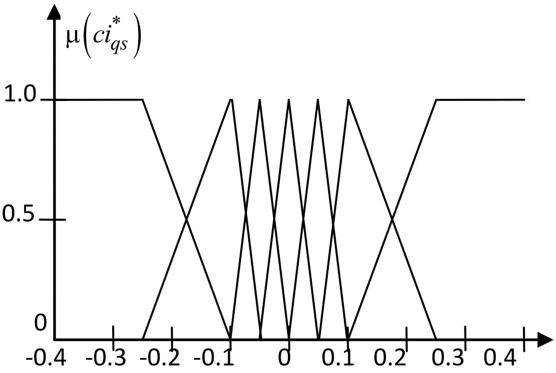
The error and its derivative are transformed into the variables of the fuzzy system. The control variables have triangular-shaped membership functions, as depicted in Figure 2. The input and output variables are constrained within the range of (-0.8, 0.8). To ensure this, appropriate scaling factors are meticulously chosen. The fuzzy set function is then partitioned into several subsets, namely A (Negative Large), 0 (Zero), B (Positive Small), C (Positive Medium), D (Positive Large), E (Negative Medium), and F (Negative Small). Each fuzzy variable is assigned a membership degree ranging from 0 (non-member) to 1 (full-member) within these subsets. The membership functions of all variables exhibit an asymmetrical shape, with a higher concentration of values near the origin (steady state).



(a)



(b)



(c)

Fig. 2: Membership functions of voltage (a) error (b) change in error (c) Changes in command current.

C. Knowledge base and Inference Stage

In the same manner, each Fuzzy set is constructed based on its own rule base function and possesses its own importance. The knowledge base consists of rules that are defined as IF-THEN statements, which govern the relationship between input and output variables with respect to membership functions. The variables, error and change in error, are processed by an inference engine that executes a total of 49 rules (7x7), as illustrated in Table-I. Each rule within the Fuzzy set holds its own significance. IF (error in voltage is Negative Large) AND (change in error of voltage is Positive Large) THEN . (ci_{qs}^{*} is Zero). Every Fuzzy set is constructed based on its unique rule base function and possesses its own level of importance.

TABLE-I: RULES

e/ce	A	E	F	0	C	B	D
A	B	A	A	A	F	E	0
E	A	A	A	E	0	F	B
F	A	A	E	F	B	0	C
0	A	E	F	0	C	B	D
B	E	F	0	B	D	C	D
C	F	0	B	C	D	D	D
D	0	B	C	D	D	D	D

D. Defuzzification

The crisp signal of the output variable $ci_{qs}^{*}(k)$ is achieved with the help of height defuzzufication method. During this stage, the evaluation of the centroid of each output membership function for every rule is noted. The ultimate output is determined by calculating the average of the individual centroids, taking into account their heights (degree of membership) in a weighted manner as described below.

$$Ci_{qs}^{*}(j)=\frac{\sum_{i=1}^{n}\mu\left[\left(ci_{qs}^{*}\right)_{i}\right]\left(ci_{qs}^{*}\right)_{i}}{\sum_{i=1}^{n}\mu\left[\left(ci_{qs}^{*}\right)_{i}\right]}$$

4. PROPOSED CONTROLLER

The proposed controller has been specifically designed to ensure that the DC-link voltage remains at the reference voltage corresponding to the MPPT level generated by the P&O algorithm. Additionally, it is designed to maintain a constant RMS voltage even under variable load conditions and to inject or compensate reactive power as required by the load connected to the same feeder as the inverter.

To achieve this, the reference voltage signal corresponding to the MPPT of the PV system is estimated using the current and voltage of the PV panels through a P&O algorithm. This generated reference signal is then compared with the actual PV voltage to generate a reference direct axis current using Fuzzy controller-1, as depicted in Figure 3.

The real component of the current (id) indicates the active power, which is also reflected by the DC-link voltage. Therefore, the real component of the current is obtained from the DC-link voltage. Similarly, the reactive component of the current (iq) can be obtained by comparing the RMS voltage with its reference value (i.e., 220V).

The obtained direct and quadrature currents are then further transferred to the phase current.

The hysteresis controller utilizes the generated phase current to produce the necessary pulses for the inverter. This is achieved by comparing the generated current with the actual inverter current. Typically, the reactive power required by the load can result in a drop in RMS voltage along the line or feeder. Therefore, the controller can compel the inverter to compensate for the reactive power demanded by the load through the proposed inverter controller. This is accomplished by comparing the RMS value with 220V, which aids in generating the quadrature axis current. The required pulse sequence can be obtained by following the sequence listed in Table-2.

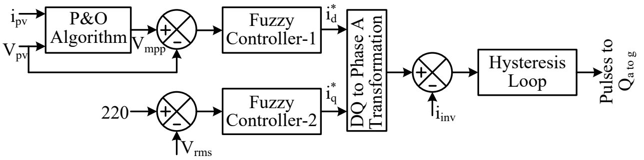


Fig. 3: Proposed controller of 7 level inverter.

TABLE-II: Voltage sequence

Level of Voltage	Pulses for Switches
+ E_{dc}	S_a, S_b, S_f
+(2/3)E_{dc}	S_a, S_b, S_g
+(1/3)E_{dc}	S_b, S_c, S_f
0	S_b, S_c, S_g
-(1/3)E_{dc}	S_c, S_d, S_g
-(2/3)E_{dc}	S_b, S_c, S_e
-E_{dc}	S_c, S_d, S_e

Direct and quadrature axis currents are essential for maintaining the DC-link voltage and RMS voltage at their reference values. This closed-loop controller also aids in compensating for reactive power, ensuring that the grid is not burdened with supplying reactive power demanded by the load connected to the corresponding feeder.

5. RESULTS

The simulation in Fig. 1 was conducted using MATLAB/Simulink to analyze the responses under different conditions. Initially, the performance of the MPPT was evaluated under varying irradiance levels. The solar irradiance was adjusted from 1000 to 750W/m2 at t=5sec. The corresponding voltage for 1000 irradiance was measured at 350 and decreased to 332 at 750. These voltage references were generated using the P&O algorithm, and the controller successfully tracked these values, as shown in Fig. 4. The figure demonstrates that the controller effectively maintains the PV system at its MPPT level even when there are changes in irradiance.

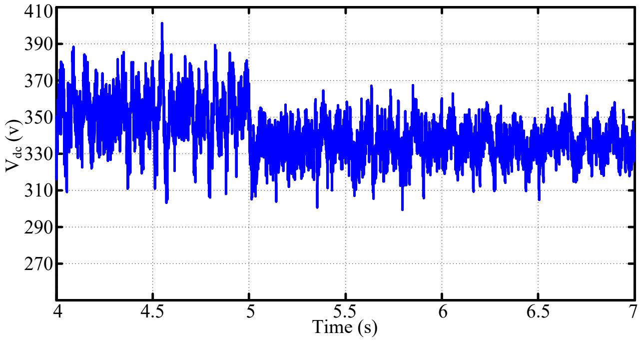


Fig. 4: DC-link voltage under change in solar irradiance to enhance the MPPT operation.

Figure 5 illustrates the output voltage of a 7 level inverter prior to the filter. It is evident from Figure 5 that the inverter is capable of generating a 7 level output instantaneously under PWM conditions. However, once the voltage passes through the filter, it transforms into a pure sine wave. This 7 level voltage effectively reduces the harmonics introduced to the utility grid by the inverter, resulting in a total harmonic distortion (THD) that remains within acceptable limits.

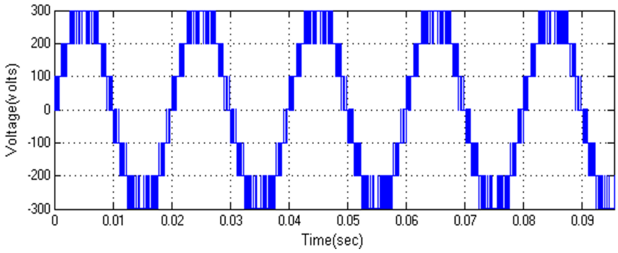


Fig. 5: Voltage profile of a proposed 7 level inverter.

Typically, the load connected to the feeder undergoes constant changes, making it challenging to maintain a consistent RMS voltage. However, the inverter that is linked to the feeder has the capability to uphold a steady RMS voltage even when there are fluctuations in the load current. By implementing a closed loop controller, the voltage drop can be compensated by generating various modulation indexes. At t=1.0 sec, a change in load current of 100% is taken into account. Nevertheless, thanks to the proposed closed loop controller, the feeder's voltage remains constant at 220V. The corresponding RMS voltage response can be observed in Figure 6.

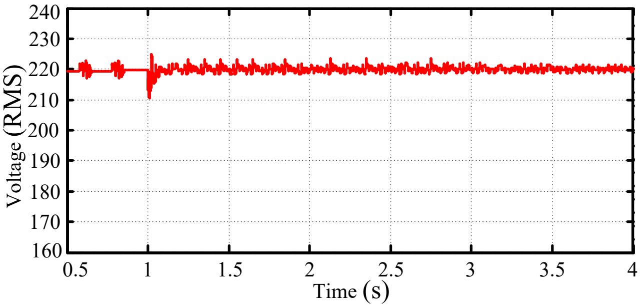


Fig. 6: RMS voltage under change in load current.

The current system has undergone testing with the addition of a reactive power load at the feeder, where an inverter is also connected in parallel. At t=2.0 sec, a sudden connection of 4kVAR reactive power is made to the feeder, as depicted in Figure 7. The controller is then compelled to compensate for the reactive power required by the load through the inverter. Upon observing Figure 7, it is evident that the inverter successfully meets the demanded reactive power by the load, resulting in a zero supply of reactive power from the utility grid. This not only aids in enhancing power quality but also improves the power factor of the utility grid. Additionally, the compensating reactive power contributes to stabilizing the RMS voltage of the feeder at its reference value.

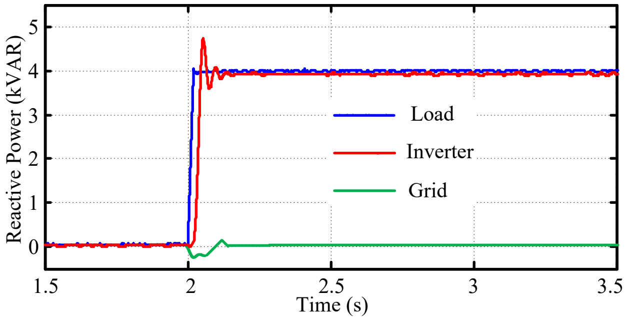


Fig. 7: Compensation of the reactive power demanded by the load.

The power quality of the system can be determined by the Total Harmonic Distortion (THD) of the voltage. In order to measure the THD of the inverter, harmonics are injected into the utility grid, which in turn affects other loads. Therefore, it is essential for the proposed controller to keep the THD below 5% in order to achieve optimal power quality. This is illustrated in Figure 8 of the proposed system.

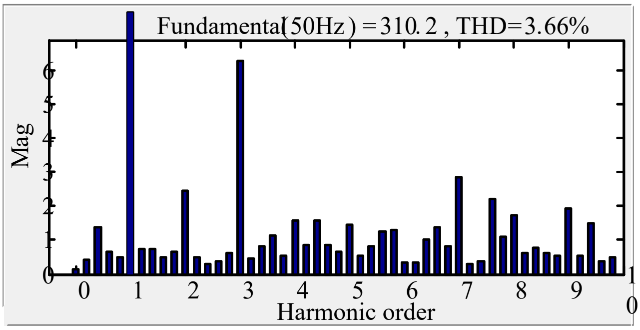


Fig. 8: THD of the voltage.

6. CONCLUSIONS

This paper presents a novel controller for a 7 level inverter in a single stage grid connected PV system. The controller is designed to eliminate the need for an extra converter for MPPT of the PV unit. Instead, it forces the inverter to act as an MPPT converter by regulating the DC-link voltage based on the signal generated by the P&O algorithm. This approach makes the system single stage and more cost effective. Additionally, the controller regulates the RMS voltage at its reference value even under changes in irradiance and variable load conditions. It also compensates for reactive power through the inverter. The effectiveness of the proposed controller is validated through extensive results obtained under various conditions.

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