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Performance Enhancement of Three-Phase PWM Rectifiers Using an Intelligent Fuzzy Direct Power Control Strategy[1]

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Abstract

Many companies use three-phase Pulse Width Modulation (PWM) rectifiers in modern power conversion systems. Some examples where they are used are new energy interfaces, charging stations for electric cars, and complex industrial drives. This is because it can control the flow of voltage on the DC link. Even more important, it can keep the power clean. Due to simple structure and fast dynamic, the conventional control strategy based on the Direct Power Control (DPC) principle is preferred. Due to the variable switch frequency, high power ripple, and power input, classical DPC has several drawbacks. The total harmonic distortion (THD) of the current is high, which limits the rectifier's ability to work in some applications. An intelligent Fuzzy Logic–Based Direct Power Control (FDPC) strategy is proposed to control the three-phase PWM rectifier as a solution to the aforementioned problems. The main goal is to keep the DC-link voltage steady, reduce the harmonic distortion of the current, and keep the power factor at unity under both steady-state and dynamic conditions. In the proposed FDPC strategy, the hysteresis comparators and switching table are replaced with a fuzzy inference system, which takes the active power error, reactive power error, and grid voltage vector position as inputs and produces an optimal voltage vector selection as an output. The FDPC scheme is implemented and investigated through MATLAB/Simulink and Fuzzy Logic Toolbox. Simulation results illustrate that the proposed controller shows significant improvement of system performance over conventional DPC. The DC-link voltage

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follows the reference value with fast dynamics response and smaller ripple. Moreover, the input current THD is reduced from 4.78% to 1.93% which meets IEEE 519 requirement, and the reactive power is also regulated to zero for near-unity power factor operation. The simulation results validate the robustness of the proposed FDPC strategy for high-performance PWM rectifier in applications with high power quality requirement.

Keywords

Fuzzy Logic Control;Direct Power Control;PWM Rectifier;Power Quality

1. Introduction

In recent years, the increasing concentration of modern power-electronic-based energy conversion systems has made powering high-quality, reliable, and efficient AC–DC conversion technology critical in many engineering applications such as renewable energy, electric vehicle charging stations, uninterruptible power supplies, and high-performance industrial drives [1-3]. Among many AC–DC conversion topologies, three-phase Pulse Width Modulation (PWM) rectifiers enjoy the advantage of their controllability, bidirectional power flow, DC-link voltage regulation, and the capability to draw nearly sinusoidal input currents with a controllable power factor [4-6]. The above-mentioned advantages render PWM rectifiers capable of satisfying strict grid codes and power quality requirements such as IEEE 519, which places very tight restrictions on current harmonic distortion level and reactive power consumption. The successful utilization of the mentioned advantages, however, depends largely on the adopted control strategy as the rectifier's dynamic characteristics, steady-state performance and robustness to disturbances are directly defined by the control scheme [7-9]. The control of a three-phase PWM rectifier has been extensively investigated in the past and the most popular control methods fall into two categories: Voltage-Oriented Control (VOC) and Direct Power Control (DPC). The VOC method is based on synchronous reference frame transformations and cascaded proportional–integral controllers to control the grid currents and DC-link voltage. Although VOC has proven to deliver very accurate steady-state performance, it has several shortcomings: high computational load, high sensitivity to parameter variations and the requirement of a high-quality system model. On the other hand, the DPC method, which is based on the concept of Direct Torque Control, is a very simple control structure that changes the instantaneous active and reactive power directly without the need of current control loops and coordinate transformations, thus providing very fast dynamic response [10-12]. Despite all these advantages, the conventional DPC schemes suffer from some inherent drawbacks, such as variable switching frequency, large power ripple, high input current total harmonic distortion (THD), which restricts its application for high performance and grid-connected application. Therefore, integrating some intelligent techniques into DPC is the most recent trend to improve the performance while maintaining simplicity and fast response characteristics of the original scheme. Artificial intelligence based (including fuzzy logic control, neural networks and hybrid intelligent algorithms) have attracted a great deal of attention in recent years, as to deal with the nonlinearities, natural parameters variations and the unmodelled dynamics of the system without the need of a precise system model. It has been proved that fuzzy logic control is a very suitable technique for the real-time power electronics problems, due to its rule-based architecture, intuitive and is easy to design for real-time applications, robustness, etc. A considerable number of studies have been carried out, showing enhanced dynamic behaviour with improved power, reduced power ripple and power quality improvement when fuzzy logic replaces the hysteresis comparator or switching table in the DPC-controlled PWM rectifier [13-15]. In addition, recent advances on fuzzy adaptive systems , fuzzy-sliding-mode controller and fuzzy-assisted model predictive controller have shown significant potential to achieve constant switching frequency operation and maintain robust performance in the presence of unbalanced or distorted grid voltage. Although these methods showed some promising results, most of the existing approach increases the algorithmic complexity, requires extensive tuning procedures and/or relies on predictive models which may become a major drawback for their deployment in cost-sensitive or industrial scenarios [16-18]. Furthermore, in the above-mentioned literature, the achieved improvement in power quality comes at the cost of computational complexity and/or opaque controller design, which is in direct conflict with the original philosophy of the DPC as a simple and fast computing control strategy. Thus, a significant gap exists in designing an intelligent but structurally simple DPC-based control scheme that can simultaneously guarantee low current total harmonic distortion, stable DC-link voltage regulation and unity power factor operation while being simple to implement and robust. Guided by the aforementioned research gap, the main goal of this paper is to develop an intelligent Fuzzy Logic–Based Direct Power Control (FDPC) strategy for a three-phase PWM rectifier which not only mitigates the above-mentioned drawbacks of the conventional DPC but also provides improved power quality and dynamic performance. In particular, this paper aims at improving power quality and dynamic performance by replacing the conventional hysteresis controllers and the fixed switching table with a fuzzy inference system which determines the optimal voltage vector directly from the active power error, reactive power error and grid voltage vector position. The proposed FDPC exploits the power handling and system control capabilities of fuzzy logic along with the simplicity of the DPC to achieve the best of both worlds. One of the most interesting features of fuzzy logic is the ability to easily incorporate the heuristic knowledge and ability to handle nonlinear control behavior to control the power trajectory, ripple and harmonic distortion. The main novelty of the present work is the incorporation of a simple Mamdani type fuzzy inference system, a small rule base and analytically defined membership functions into the DPC framework to control the power into the load. The proposed FDPC is a simple, simple to implement, and low cost system as it does not require any complex predictive or adaptive scheme. The performance of the system under both steady state and dynamic operating conditions (voltage spikes) is presented through MATLAB/Simulink simulations and discussed. The performance of the system under different operating conditions is measured in terms of DC link voltage regulation, current distortion and power factor. The rest of the paper is organized as follows: in Sec. 2 the mathematical modeling of the three-phase PWM rectifier and the proposed fuzzy logic–based direct power control strategy is described; in Sec. 3 the simulation setup and the results obtained for the proposed control strategy are discussed and compared with the conventional DPC; and in Sec. 4 the paper is concluded by a short summary and some perspectives for further research.

2. Materials and Methods

In this paper, we explore the performance improvement of a 3-phase Pulse Width Modulation (PWM) rectifier by means of a fuzzy logic–based direct power control (FDPC) strategy, and the whole methodology has been developed following a procedure composed of modeling, design of the control strategy, and simulation-based validation. A 3-phase voltage source PWM rectifier is connected in series to inductive filters with the balanced AC grid as the source, and it feeds a resistive DC load through a DC-link capacitor. The rectifier topology is modeled in the reference frame of the grid, and the electrical part of the grid-side currents dynamics is described by a system of differential equations linking the phase voltages of the grid, the converter output voltages, and the characteristics of the filtering components. The converter phase voltages are represented as functions of the DC-link voltage and the discrete switching states of the semiconductor devices, so that the power flow can be directly controlled by selecting the appropriate voltage vector. The instantaneous active and reactive power exchanged between the grid and the rectifier are estimated directly from the Clarke transformation of the three-phase voltages and currents into orthogonal α–β components, so that estimation of the power can be performed in real-time, without the need for transformations in a synchronous reference frame. In the conventional direct power control strategy, the estimated instantaneous active and reactive powers are compared with their corresponding active and reactive power references, the former being produced by an outer DC-link voltage regulation loop and the latter being set to zero in order to obtain unity power factor operation. The resulting power errors are often processed by means of hysteresis comparators, and the comparison result together with the instantaneous grid voltage vector position are used to choose, from a switching table, the appropriate switching states of the rectifier. This strategy naturally provides a fast dynamic response and an elegant structure, but at the price of a variable switching frequency, high power ripple and high current harmonic distortion. In this methodology, the hysteresis-based decision logic and switching table are replaced by an intelligent fuzzy logic controller to directly select the optimal voltage vector command to minimize the power errors. The fuzzy logic controller is designed based on the Mamdani fuzzy inference structure and consists of three processes: fuzzification, inference and defuzzification. The input of the proposed fuzzy rules are the active power error, the reactive power error, and the discrete position of the grid voltage vector. The discrete position of the grid voltage vector is divided by twelve sectors, which are based on the angular position of the grid voltage in the α–β plane. The power error signals are first normalized and then transformed into three linguistic fuzzy sets: negative, zero and positive by using triangular and trapezoidal membership functions for smooth transition and robust representation of the errors. The position of the voltage is represented by twelve evenly-distributed fuzzy sets, which also correspond to the sector of the voltage vector. This preserves the directional awareness of the classical DPC, while enhancing it with smooth decision process. The output of the fuzzy controller is the voltage vector command which is represented by seven fuzzy sets. These fuzzy sets are equivalent to the seven basic switching states of the three phase PWM rectifier, including the zero-voltage vector and six active voltage vectors. By combining the likely states of active power error, reactive power error, and voltage sector position, the proposed FDPC approach aims to minimize power ripple, suppress current harmonics, and stabilize the DC-link voltage simultaneously, and therefore establishes a comprehensive fuzzy rule base containing 108 inference rules. The fuzzy rules in the rule base are processed by logical operators in an inference engine, and the fuzzy output is aggregated and then defuzzified by centroid method to generate a crisp voltage vector command, as it provides a good compromise between the smoothness of control and dynamic responsiveness.

The proposed FDPC strategy is implemented and tested in MATLAB/Simulink using Simscape Electrical and Fuzzy Logic Toolbox in order to accurately model the switching behavior of power electronic devices and the execution of control logic. The simulation model of Fig. 16 provides a detailed representation of the PWM rectifier system, with subsystems for voltage and current measurement, Clarke transformation, instantaneous power calculation, fuzzy inference processing and gate signal generation for rectifier switches. The system electrical parameters given in Table 2 are chosen to reflect realistic scenarios in many industrial power conversion applications. Simulation analysis of the system can be performed under steady-state or transient operating conditions, including DC-link voltage regulation performance and power quality. Indices such as the DC-link voltage ripple factor, the dynamic responding speed of the DC-link voltage, the active and reactive power tracking performance, and the input current total harmonic distortion are first extracted and analyzed. Moreover, the harmonic performance of the input current is also assessed by the fast Fourier transform analysis subject to the IEEE 519 guidelines to guarantee the compliance of the system with the established power quality standards. By incorporating the fuzzy logic decision making processes within the DPC structure, the proposed fuzzy direct power control methodology not only retains the fast response characteristics of the classic DPC but also significantly improves its steady-state power quality performance and parameter variation sensitivity.

2.1 Model of the 3-Phase PWM Rectifier

The rectifier consists of a three-leg voltage-source converter connected to the grid via L–R filters (Figure 1). This was explained by [19] who showed that the following system of differential equations can be used to explain the electrical dynamics of the rectifier:

$$\begin{bmatrix} Ea \\ Eb \\ Ec \end{bmatrix} = R \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} + \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \qquad (1)$$

Where: E $_{a,b,c}$ represents the source voltages, **I** $_{a,b,c}$ the currents in each phase, and $\mathbf{V}_{a,b,c}$ the phase voltages relative to the neutral point (N). These phase voltages are related to the DC-link voltage $\mathbf{V}_{dc}$ and the switching states **S** $_{a,b,c}$ (where 1 is ON and 0 is OFF) by the relations:

$$\left.\begin{aligned} V_a &= V_{dc}.\left(2S_a - \frac{S_b + S_c}{3}\right) \\ V_b &= V_{dc}.\left(2S_b - \frac{S_a + S_c}{3}\right) \\ V_c &= V_{dc}.\left(2S_c - \frac{S_a + S_b}{3}\right) \end{aligned}\right\} \qquad (2)$$

The DC-link voltage equation is:

$$C\frac{dV_{dc}}{dt} = (S_a.I_a + S_b.I_b + S_c.I_c) - I_{dc} \qquad (3)$$

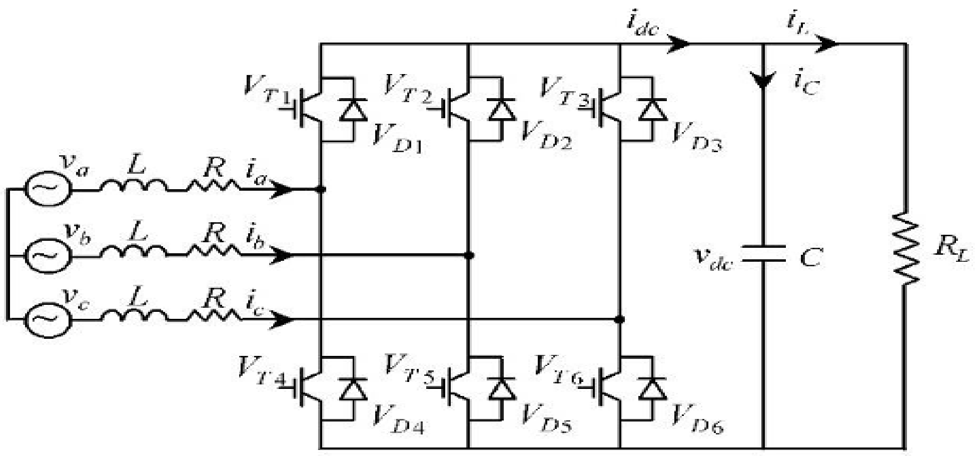


Figure 1 Topology three–Phase PWM rectifier

2.2 Fuzzy DPC for PWM Rectifier:

The structure of the conventional DPC, as illustrates in Figure (2), consists of (Bouafia et al., 2008):

1. An estimator for active (p) and reactive (q) power.
2. An outer control loop (usually PI) to regulate $\mathbf{V_{dc}}$ and generate the active power reference $\mathbf{p_{ref}}$.
3. Setting $\mathbf{q_{ref} = 0}$ to achieve unity power factor.
4. Hysteresis comparators to convert power errors ($\mathbf{e_p} = \mathbf{p_{ref} - p}$, $\mathbf{e_q} = \mathbf{q_{ref} - q}$) into digital signals ($\mathbf{d_p}$, $\mathbf{d_q}$).
5. Determining the location (vector) of the source voltage in one of the 12 sectors (Sector) illustrated in Figure 3.
6. The digital voltage phase angle, denoted as θn, along with the discrete error signals, Sp and Sq, are subsequently fed into the switching table. as illustrated in Table 1.
7. The PWM rectifier's switching sequences (Sa, Sb, and Sc) are constructed using the logical procedures shown in Table 2.

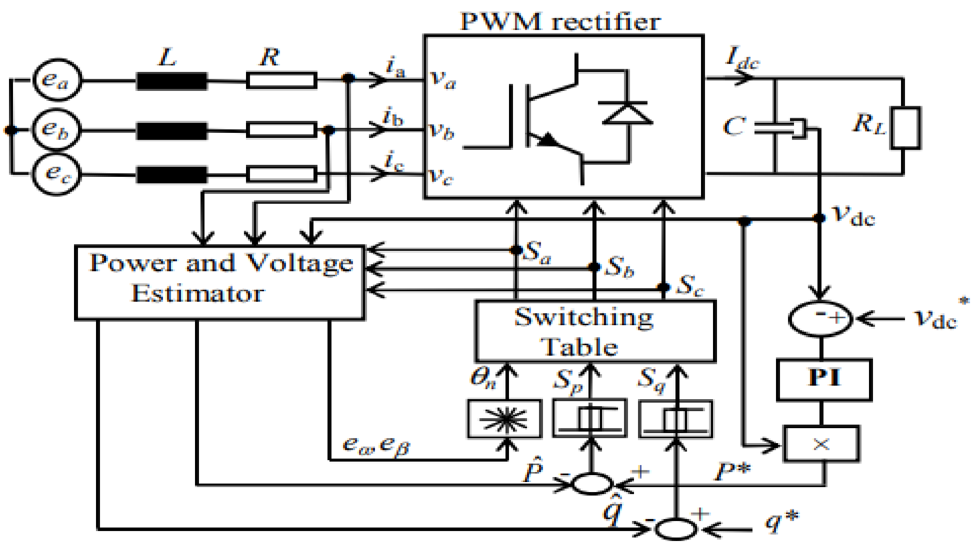


Figure 2 Conventional DPC configuration of three-phase PWM rectifier.

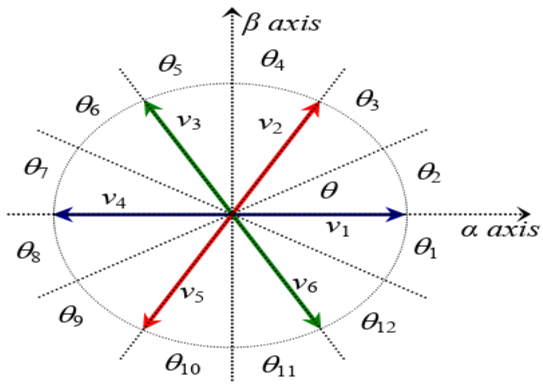


Figure 3 Rectifier voltage vectors for Twelve Sectors.

The outputs of the hysteresis comparators are defined as:

$$d_p = \begin{cases} 1, & (p_{ref} - p) \geq H_p \\ 0, & (p_{ref} - p) \leq H_p \end{cases} \qquad (4)$$

$$d_q = \begin{cases} 1, & (q_{ref} - q) \geq H_q \\ 0, & (q_{ref} - q) \leq H_q \end{cases}$$

The calculation for instantaneous active and reactive power is as follows:

$$[\,(n-2)\frac{\pi}{6} \leq \theta_n \leq (n-1)\frac{\pi}{6}\,] \;\ldots\ldots\; n = (1,2,3,\ldots 12) \qquad (6)$$

The equations of p and q are:

$$p = (v_a \,.\, i_a + v_b . i_b + v_c \,.\, i_c)$$

$$q = \frac{1}{(1.732)}[(v_b - v_c)i_a + (v_c - v_a)i_b + (v_a - v_b)i_c] \qquad (7)$$

Table 1 The Switching for DPC

S_P	S_q	θ1	θ2	θ3	θ4	θ5	θ6	θ7	θ8	θ9	θ10	θ11	θ12
1	0	101	111	100	000	110	111	010	000	001	111	001	000
	1	111	111	000	000	111	111	000	000	111	111	000	000
0	0	101	100	100	110	110	010	010	011	011	001	001	101
	1	100	110	110	010	010	011	011	001	001	101	101	100

Table 2. Several switching stages.

V	Sa	Sb	Sc
0	0	0	0
1	1	0	0
2	1	1	0
3	0	1	0
4	0	1	1
5	0	0	1
6	1	0	1
7	1	1	1

2.3 Fuzzy Logic-Based Direct Power Control (FDPC):

Figure 4 depicts the replacement of the standard switching table and hysteresis comparators with a fuzzy logic controller to increase system performance. The fuzzy control system consists of three main stages (Figure 5) (Taibi et al., 2025):

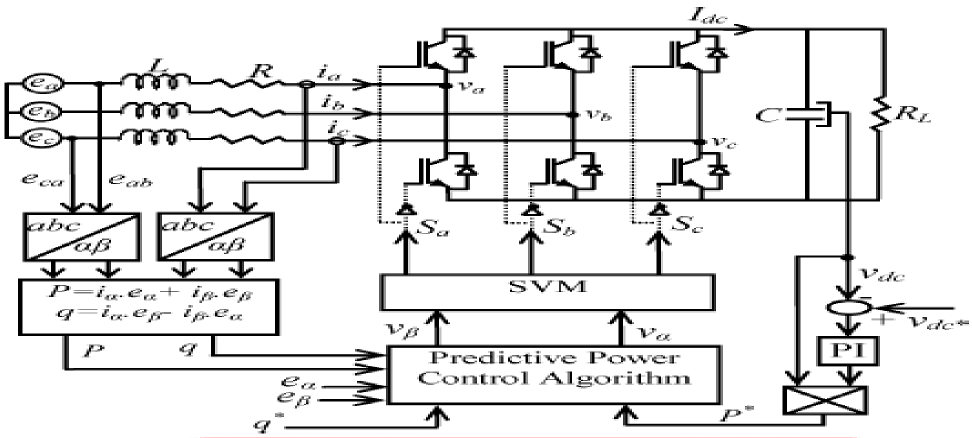


Figure 4 Predictive DPC Configuration of 3-phase PWM Rectifier Based on $\alpha - \beta$ Components.

1. **Fuzzification:** Converting numerical inputs into fuzzy sets.
2. **Inference Engine:** Applying "If-Then" fuzzy rules.
3. **Defuzzification:** Converting fuzzy outputs into an applicable numerical value.

The I/Ns to the Fuzzy Controller are:

The dynamics of the Active & Reactive Power, error are Quantified through the following Mathematical Model:

$$e_p = P^* - P \quad (8)$$

$$e_q = q^* - q$$

The mathematical representations for instantaneous Active & Reactive Power are Defined by the following Equations:

$$\begin{cases} P = e_\alpha . i_\alpha + e_\beta . i_\beta \\ q = e_\alpha . i_\beta + e_\beta . i_\alpha \end{cases} \quad (9)$$

The efficacy of the Fuzzy Logic Controller is critically depended on both the precise configuration of the membership functions and the accurate formulation of the fuzzy rule base.

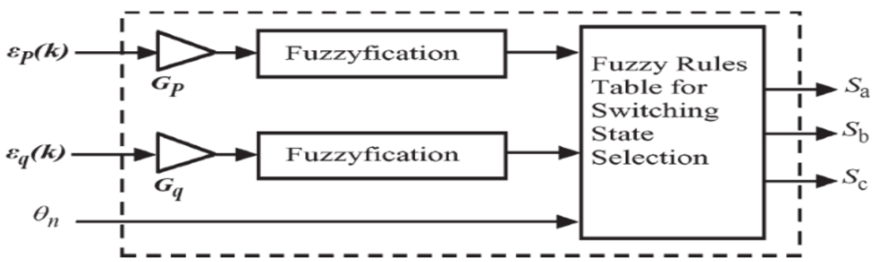
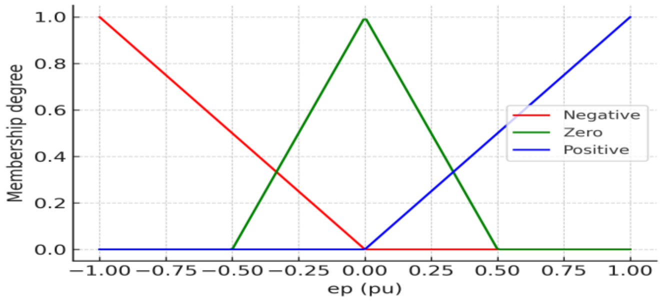
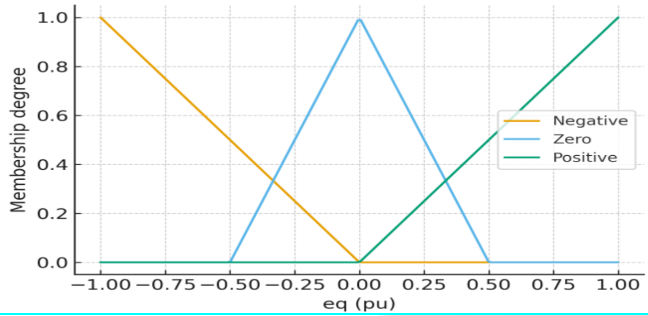


Figure 5 The Diagram of the Proposed Fuzzy Logic Based DPC Scheme.

The variables $\mathbf{e_p}$ and $\mathbf{e_q}$ are represented by Three Fuzzy Sets: Negative (N), Zero (Z), and Positive (P) (Figure 6). Meanwhile, **θn** is divided into 12 Fuzzy Sets (θ1 to θ12) representing the sectors (Figure 7).



(a) Membership Funs. for Active Power Error (ep)



(b) Membership Funs. for Reactive Power Error (eq)

Figure 6 (a & b) The Membership Functions Distributions for Fuzzy Inputs Variables

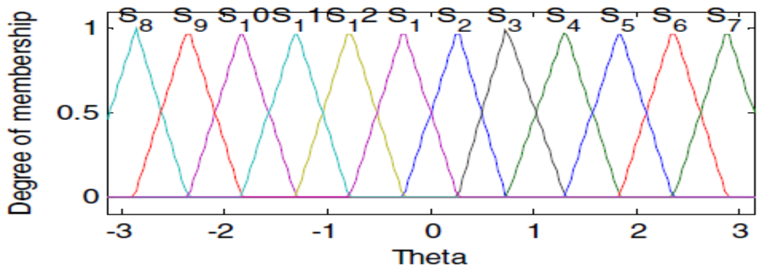


Figure 7 Membership Funs. for the Grid Voltage Vector's Phase (θ).

The fuzzy controller's O/P is the needed voltage vector for the rectifier (Vout), which is represented by seven fuzzy sets (V0 through V7) that correspond to the converter's fundamental switching states (Figure 8).

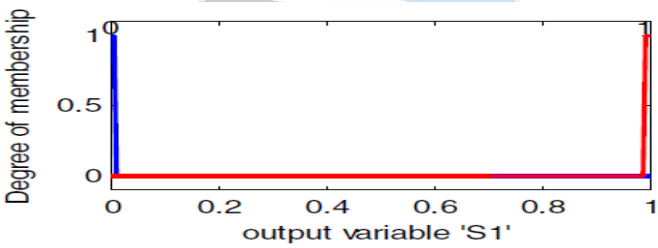


Figure 8 The states switches membership functions of output

The controller's performance depends on the membership functions and inference rules. The system has 108 rules (3 for e_p × 3 for e_q × 12 for θ), designed to minimize power errors. The Mamdani inference method and the centroid method for defuzzification are used. Figure (9) shows a flowchart of the inference process.

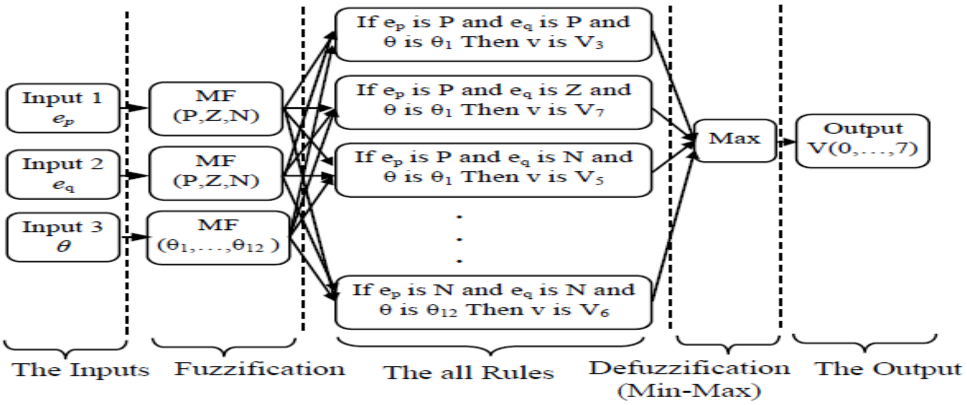


Figure 9 Flowchart of fuzzy logic system.

3. Results and Discussion

The proposed fuzzy logic–based direct power control (FDPC) strategy for the three-phase PWM rectifier has been extensively investigated by simulations run in MATLAB/Simulink, and the results clearly show significant improvements in dynamic and steady-state performance compared with conventional direct power control (DPC). The simulation model included all electrical subsystems, such as the voltage and current transformation of the grid side, the instantaneous power estimation, the control logic, and the switching signals. The system was simulated with a rated DC-link voltage reference of 250 V; the line-to-line voltage of the grid with 146 V and 50 Hz; the inductive input filter with 12 mH; the DC-link capacitor with 4000 μF; and the resistive load with 100 Ω. The system has been simulated with a maximum switching frequency of 20 kHz and a sampling time of 10 μs. These parameters allow to evaluate the power quality control strategy under realistic conditions. The ability of any PWM rectifier control strategy to regulate the DC-link voltage under both steady-state and dynamic conditions is one of the most important performance indicators. According to the proposed method, the FDPC could keep the dc-link voltage near the reference value 250 V, almost free of steady-state error and with well limited voltage ripple. It can be seen that when compared with the conventional DPC scheme, which suffers noticeable oscillation due to the power control based on hysteresis controller and variable switching frequency, the FDPC is able to generate a very smooth voltage profile with fast settling time after transient disturbance. During the dynamic operating states such as the initial startup and load variations, the regulated dc-link voltage can reach its reference value very quickly with negligible overshoot and undershoot, which demonstrates the superior transient response of the fuzzy logic controller. This improvement can be explained by the fuzzy inference mechanism, which keeps track of the power error's amplitude and orientation and selects the appropriate voltage vector in a smooth and adaptive manner, thus avoiding the sudden switching action as in classical DPC. Apart from the dc-link voltage regulation, the input current quality is another important index to evaluate the performance of grid-connected rectifiers. The simulated grid-side voltage and current waveforms with proposed FDPC are shown. The input currents are almost sinusoidal and remain in phase with the corresponding phase voltages. Assessment with the fast Fourier transform reveals a substantial decrease in input current THD. The current THD of the conventional DPC is measured to be 4.78%, while the proposed FDPC strategy reduces the current THD to only 1.93%, or more than 59%. This low harmonic distortion complies fully with IEEE 519 harmonic standards. It also proves the ability of the fuzzy logic controller to suppress low order harmonics usually caused by the switching nature of the hysteresis controller. The improvement in the THD can be credited to the removal of both fixed hysteresis bands and the switching tables because in the classical DPC as the operation of the switching table and hysteresis cause abrupt changes in the voltage vector that lead to uneven switching operation, whereas the rule-based FDPC decides the output voltage vector switches based on both the error amplitude of the power and the instantaneous position of the grid voltage vector.

The superiority of the proposed control scheme can also be seen from the instantaneous active and reactive power responses. The FDPC operation has the active power track the reference value derived from the outer dc-link voltage controller, with low ripple and swift convergence. In comparison, the traditional DPC shows significant oscillations in both active power and reactive power, especially in the transient periods. These large oscillations in real power and reactive power are directly responsible for the increase in current distortion and voltage ripple.

3.1 Simulation Results

The suggested FDPC model was implemented in the MATLAB/Simulink environment with the Fuzzy Logic Toolbox. Figure 10 depicts the basic simulation model. Figures 2-2 to 2-6 depict the essential subsystems: abc/pq modeling, voltage and current vector computation, power estimation, the control unit, and the fuzzy logic controller. The electrical parameters utilized in the simulation are listed in Table 3.

Table 3 The Electrical parameters of power circuit

DC-bus voltage	**250 V**
Line to Line voltage	146 V
Load Resistance	100 Ω
Inductance of inductor	12 mH
DC-bus capacitor	4000 μF
Resistance of inductor	0.25 Ω
Sampling times	10 μS
Switching frequency (MAX)	20 KHz
Source voltage frequency	50 Hz

Simulation results demonstrated superior performance

- **DC Voltage Regulation:** Figure 2-7 shows that the DC-link voltage was stably controlled at 250 V, with quick stability and low ripple.
- **Improved Power Quality:** The current Total Harmonic Distortion (THD) fell from roughly 4.78% in the traditional DPC system to 1.93% in the proposed FDPC system, which met IEEE 519 criteria.

- **Precise Power Control:** Excellent active and reactive power management was achieved, with an average reactive power of zero, assuring unity power factor operation.

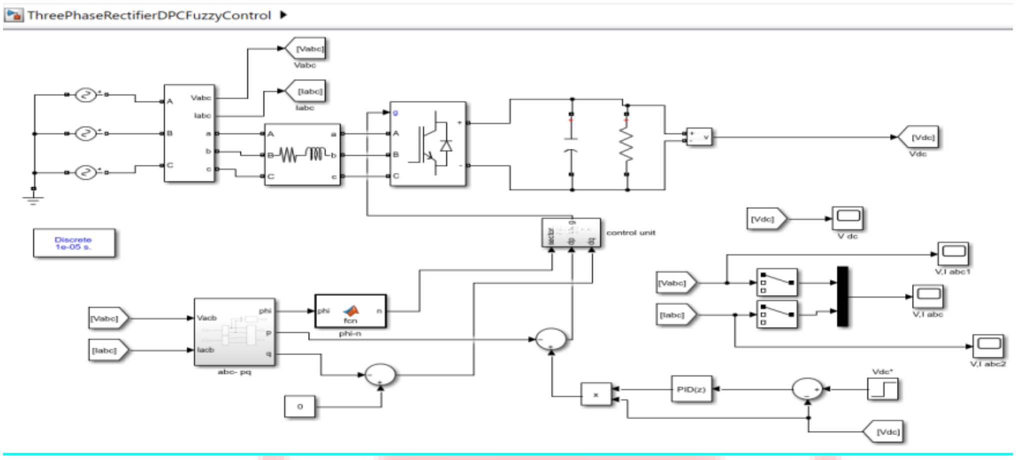


Figure 10 The main model

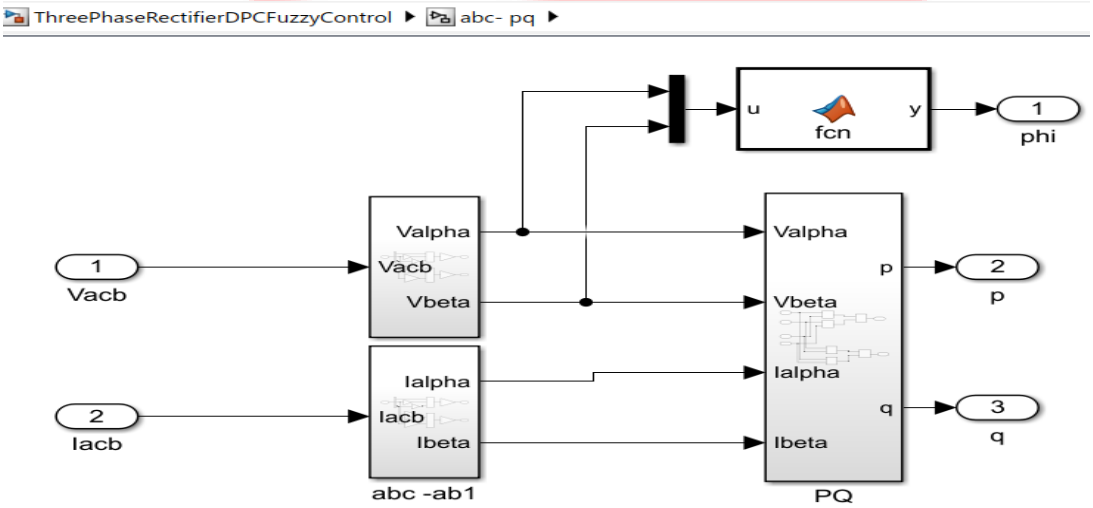


Figure 11 The (abc - pq) model

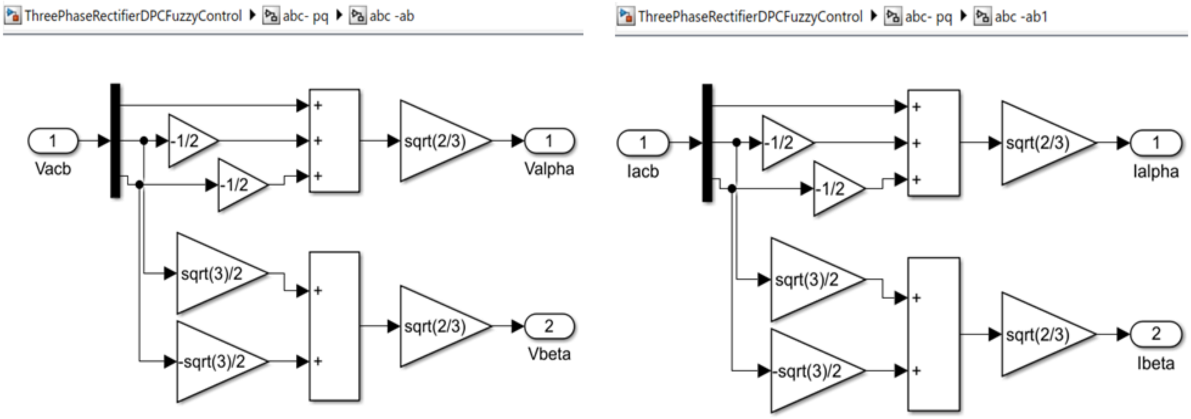


Figure 12 The (abc - ab) models (getting Valpha, Vbeta from Vabc)

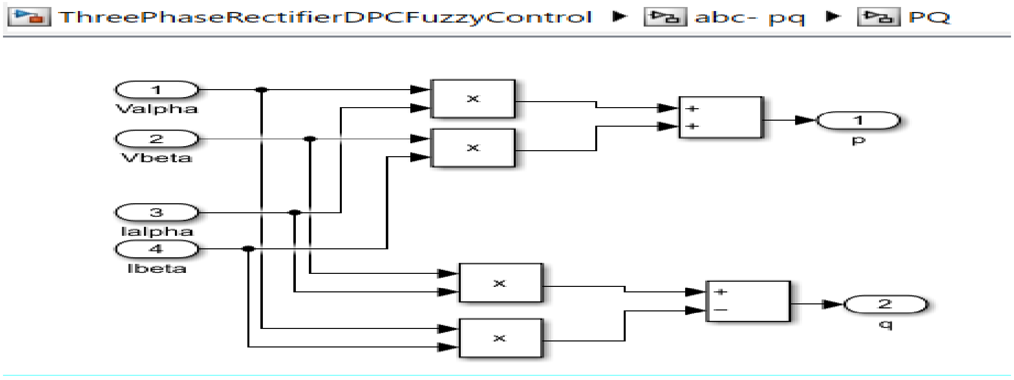


Figure 3.4 The PQ model

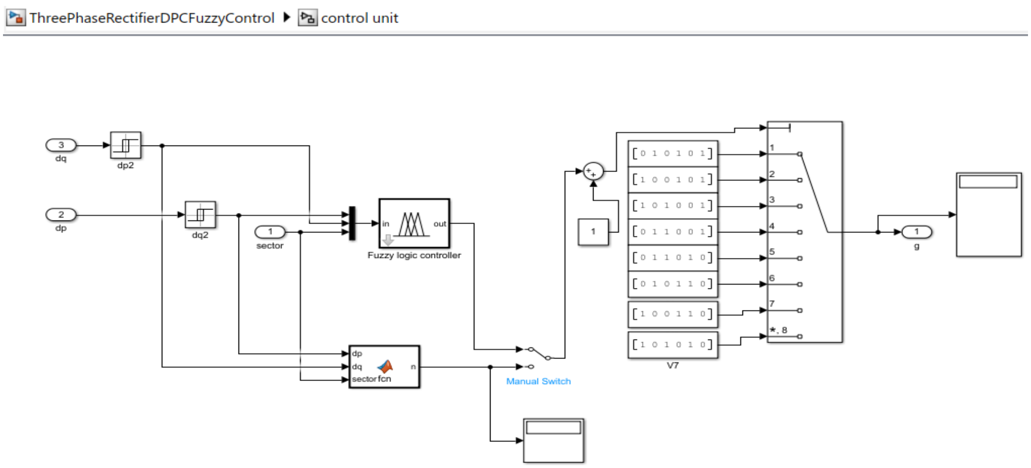


Figure 13 The Control unit

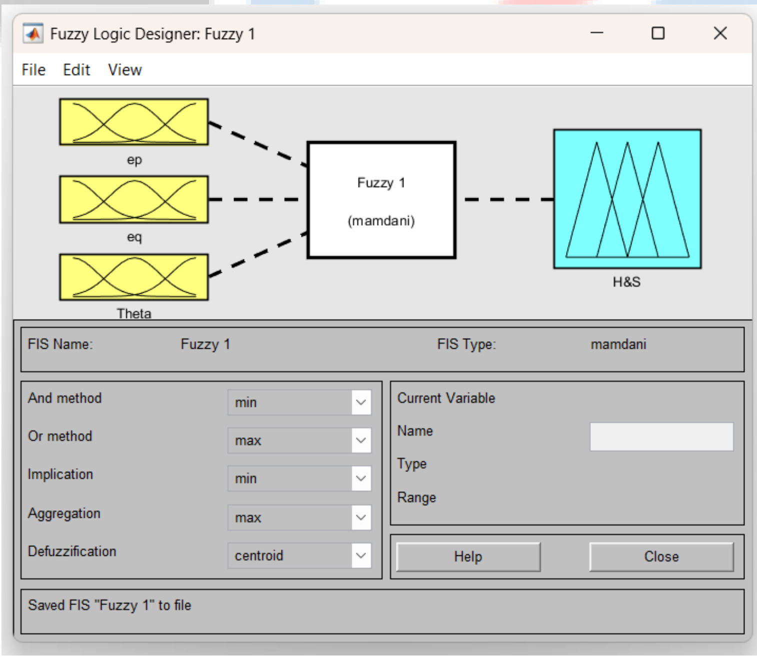


Figure 14 The Fuzzy Logic Control

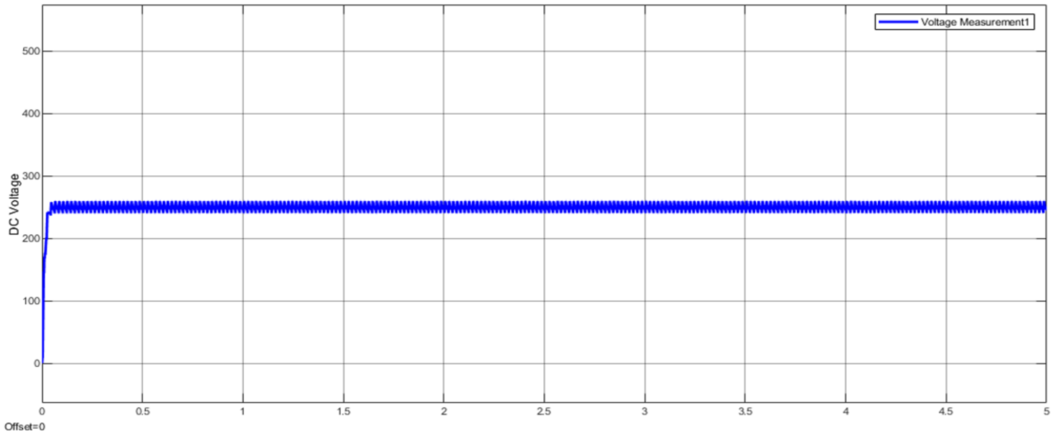


Figure 15 The Steady – State and Dynamic Performance of DC-Link Voltage Regulation

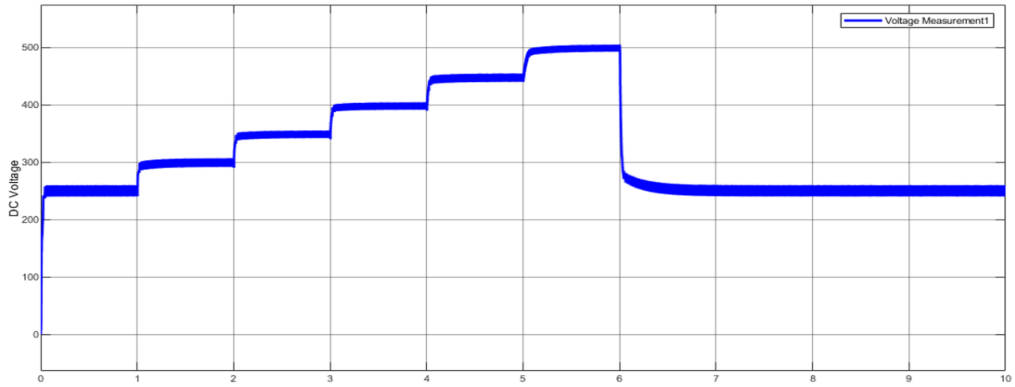


Figure 16 The DC-Link Voltage under Fuzzy Logic Based Direct Power Control

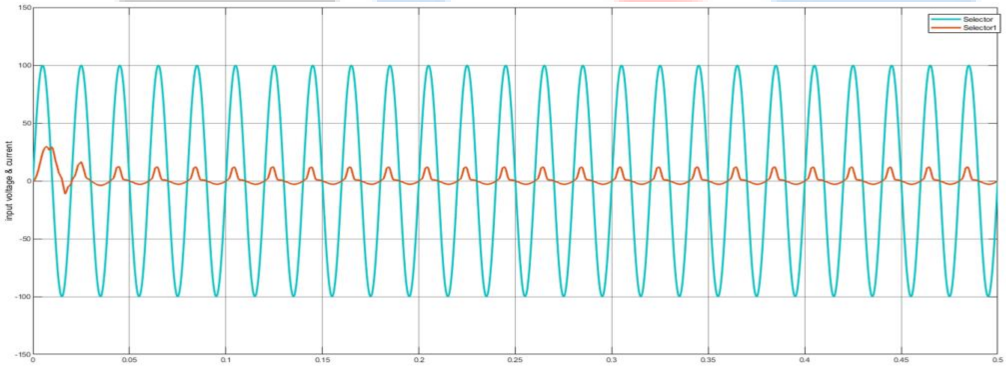


Figure 17 input voltage and current

Figure (10-17) depicts the primary measure for determining the Effectiveness of the Fuzzy Logic Control Method in Controlling the DC-link voltage & improving Power Quality in the Rectifier System.

In Direct Power Control (DPC) systems, maintaining a stable and regulated DC-link voltage across the load is a primary objective. The rectifier converts power from the three-phase AC source to a load supplied with DC voltage. The control system adjusts the rectifier's switching to achieve this goal.

The numerals from 0 to 10 in the figure (2-8) represent the measured or controlled output voltage levels, which are most likely normalized values expressed in per-unit (pu) relative to a nominal reference voltage. This allows for the evaluation of the control system's performance under various operating conditions (such as load variations or source disturbances) and its ability to regulate the output voltage at the desired setpoint (e.g., 10 pu).

The proposed fuzzy logic control algorithm has been evaluated through simulation, and the obtained results confirm its effectiveness. Specifically:

- The controller can maintain the output voltage at the desired reference level (level 10 in this case) under normal operating conditions.
- It achieves a fast dynamic response with minimal overshoot and undershoots when subjected to sudden disturbances in load demand or source voltage.

Furthermore, the algorithm significantly suppresses output voltage ripple, ensuring a highly stable DC voltage profile

The fuzzy logic controller has the ability to process active power error, reactive power error, and voltage sector information all at the same time. This unique capability helps the controller to resolve conflicting control objectives better than classical switching tables which results in better power decoupling and stability. Another interesting aspect of the results concerns the behavior of the system during steady-state operation under nominal conditions. The Fuzzy DPC- controlled rectifier is able to maintain a stable operating point with less power ripple and consistent switching behavior. This will be very helpful in reducing the stress on the power electronic components and the overall reliability of the system. The smoother control action also contributes to reducing electromagnetic interference which is an important metric in industrial power electronics. Moreover, the numerical results of DC-link voltage ripple show a clear advantage of the FDPC approach. Where conventional DPC is classically known to have pronounced ripple due to the discrete nature of the voltage vector selection and the switching irregularities due to the hysteresis band, the FDPC considerably suppresses these oscillations, resulting in a more stable DC output that is desirable for sensitive downstream loads. The performance improvement is even more pronounced during dynamic events when the fuzzy controller exhibits strong robustness against sudden variations without compromising stability or power quality. Control Perspective The simulation results presented show that the fuzzy logic based technique has successfully removed the inherent disadvantages of conventional DPC while retaining its good properties such as fast dynamic response and conceptual simplicity. In comparison with other sophisticated predictive or adaptive control based techniques, the proposed FDPC does not need an explicit plant model of the system or online estimation of system parameters. Thus, FDPC is not sensitive to parameters and it is simple to implement. The simplicity is due to use of Mamdani type fuzzy inference system with small rule set of 108 rules. A careful design of membership functions and the rule set is justified by simulation results. Having three levels of negative, zero and positive for the representation of active and reactive power errors is sufficient for representing dynamics of the system yet maintaining robustness, and having twelve sectors for the representation of the grid voltage vector ensures correct directional orientation, just as in classical DPC. In general, the numerical results across different conditions demonstrate the proposed FDPC strategy provides a balanced and efficient solution for improving the performance of three-phase PWM rectifiers. The advantages of better DC-link voltage regulation, harmonic suppression, and power factor correction together lead to better power quality and operation reliability. The results have shown that incorporating fuzzy logic into a direct power control framework is an effective way to overcome the decoficiencies of classical DPC without compromising simplicity or fast response. Therefore, the proposed FDPC approach is suitable for modern power electronic applications where high efficiency, low harmonics and robust dynamic performance are required.

4. Conclusion

This paper proposed an intelligent fuzzy logic–based direct power control (FDPC) strategy to improve the performance of a three-phase PWM rectifier with emphasis on power quality improvement and ensuring robust DC-link voltage regulation. The proposed strategy replaced the conventional hysteresis comparators and fixed switching table of the classical direct power control (DPC) by a Mamdani-type fuzzy inference system. Hence, the design of the FDPC controller using active power error, reactive power error and grid voltage vector position as input variables mitigates the limitations of the conventional DPC including variable switching frequency, high power ripple, and high current harmonic distortion. In addition, the FDPC controller allows a smooth and adaptive voltage vector selection for steady-state as well as dynamic operations. The proposed control strategy shows outstanding performance compared to the conventional DPC strategy, clearly demonstrated by the simulation results obtained in the MATLAB/Simulink environment. In particular, the DC-link voltage is tightly regulated at the reference level of 250 V with minimal ripple and faster dynamic response compared with the conventional DPC. Moreover, the proposed FDPC strategy significantly reduces the THD of the input current from 4.78% to 1.93%, thus fully satisfying the IEEE 519 power quality standards. The reactive power reached nearly zero, and the power factor was close to one. It also greatly improved the power quality on the grid side. These results show that the fuzzy logic controller can greatly improve the stability and overall performance of the system. Besides, the controller compared with other advanced control methods can improve the control performance without increasing the computational complexity or requiring an accurate mathematical model of the system.

Therefore, the proposed FDPC strategy is simple, robust and effective for high-performance application of three-phase PWM rectifier. The proposed control scheme with its easy-to-execute and high-performance nature is suitable for practical implementation in modern power electronic conversion systems. Future efforts will focus on experimental validation using a real-time digital control platform. The performance of the controller under unbalanced and distorted grid conditions will also be investigated.

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