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Fuzzy Logic Controller Design for Circulating Current Control in Three-Phase Modular Multilevel Converter Fed by Fuel Cell

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Abstract: *The Modular-Multilevel Converter (M-MC) has substantially contributed to the integration of non-conventional energy sources into grid systems, particularly Proton Exchange Membrane Fuel Cells (PEMFC). This paper proposes an M-MC system to interface PEMFC with the grid, focusing on controlling circulating currents and ensuring stability. A Fuzzy Logic is employed to mitigate circulating current (CC) harmonics. Phase-Shifted Carrier (PSC) modulation is used to improve capacitor voltage balancing, thus maintaining a constant input voltage. The boost converter enhances the input voltage to a higher level, which is essential for maintaining the necessary voltage margin in MMC. The main contribution of this paper is (I)The PSC-PWM was implemented for MMC to maintain a quality +y of output voltage by the control of capacitor voltages.(II)The proposed fuzzy logic controlled circulating current must be achieved in order to regulate the dc ripple component, arm current, and circulating current of MMC.(III)It is essential to regulate the SM capacitor voltages in order to provide a balanced and equal output while maintaining the ratings and limits of the SMs, and this will be accomplished.*

Keywords: Modular Multi-level Converter (MMC), Sub-modules (SM), Fuzzy Logic Control (FLC), Proton Exchange Membrane Fuel Cell (PEMFC), Phase with modulation (PWM), Phase Shift Carrier (PSC), Circulating Current (CC).

I. INTRODUCTION

Modular Multilevel Converters (MMCs) represent a significant advancement in power electronics, offering a highly efficient and versatile solution for various high-power applications. Essentially, an MMC consists of a series connection of numerous sub-modules, each capable of generating a specific voltage step. By precisely controlling these steps, the MMC can synthesize a near-perfect sinusoidal AC waveform, surpassing the limitations of traditional two-level converters.

The core principle lies in its modular design. Each sub-module, typically employing half-bridge or full-bridge topologies, contains its own energy storage capacitor. This modularity allows for scalability and redundancy, enabling the construction of converters with extremely high voltage and power ratings. The series connection of these sub-modules facilitates the creation of a stepped voltage waveform, which closely approximates the desired AC output. This approach significantly reduces harmonic distortion, improving power quality and minimizing stress on connected equipment.

MMCs find widespread application in diverse fields. In renewable energy, they play a crucial role in integrating solar and wind power into the grid, ensuring stable and efficient energy transfer. In high-voltage direct current (HVDC) transmission, MMCs enable long-distance power transfer with minimal losses. Electric vehicle charging infrastructure benefits from Industrial drives utilize MMCs to enhance energy efficiency and control motor speed precisely.

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Moreover, MMCs are essential in energy storage systems, hydrogen generation, aerospace applications, and medical magnetic stimulation.

The key advantages of MMCs include their high efficiency, superior voltage waveform quality, and scalability. Their ability to handle high power levels, coupled with their reduced harmonic distortion, makes them ideal for demanding applications. However, the control of MMCs is complex, requiring sophisticated algorithms to manage circulating currents and balance capacitor voltages. Despite this complexity, the benefits offered by MMCs make them a compelling solution for modern power systems.

Modular Multilevel Converters (MMCs) are a modern advancement in power electronics, offering improved performance over traditional two-level converters. Their key feature is a modular design, using interconnected sub-modules for scalability and redundancy. MMCs synthesize high-quality AC waveforms through multilevel voltage steps, minimizing harmonic distortion and enhancing power quality. This makes them ideal for high-power applications like HVDC transmission, renewable energy integration, and industrial drives. While requiring complex control to manage internal dynamics like circulating currents and capacitor balancing, MMCs deliver higher efficiency and superior waveform quality, establishing them as a crucial technology in modern power systems.

Integrating renewable energy sources like fuel cells into the power grid is attractive due to their potential for clean and reliable energy. Efficient power conversion and regulation are key challenges. Modular Multilevel Converters (MMCs) are well-suited for high-voltage, high-power applications due to their scalability and performance. However, circulating currents within MMCs can significantly reduce efficiency and system performance. These circulating currents, often caused voltage mismatches and submodule imbalances, can also cause thermal stress on components, leading to potential damage. Therefore, effectively controlling them is essential for stable and efficient grid-connected MMC operation.

Fuzzy logic control has emerged as a promising technique for handling the non-linearities and uncertainties inherent in power electronic systems. Its robustness in the face of system imbalances makes it well-suited for controlling circulating currents, especially in renewable energy systems.

This work focuses on developing a fuzzy logic-based circulating current control strategy for a three-phase MMC powered by a fuel cell. Fuel cells offer high efficiency and low environmental impact but pose challenges related to dynamic power delivery and voltage regulation when integrated with MMCs.

The goal is to design a fuzzy logic control algorithm that mitigates circulating currents, ensuring stable and efficient MMC operation when connected to a fuel cell. This approach aims to improve overall converter performance, enhance power quality, and extend system lifespan.

II. SYSTEM ARCHITECTURE: THREE-PHASE GRID-CONNECTED MMC-FED PEMFC

A fuel cell-built power plant provides electrical power, which can only be supplied to a distribution location, whereas the dc electricity produced on the FC side cannot be directly distributed toward the electrical network. Thus, the fuel cells are connected to the grid interface via PE converters and electrical components. In general, the interface aspects are a 6kW PEMFC, a dc–dc boost converter, a three-phase MMC (dc–ac converter), an inverter-side output filter, and a grid. In most cases, a boost converter is used to boost the PEMFC's output voltage. As more current is required from the cell, the output voltage

waveform quality and reducing distortion through controlled capacitor charging and discharging. SMs are selectively activated to generate a near-sinusoidal AC waveform. Two primary topologies exist: Full-Bridge, offering enhanced voltage control, and Half-Bridge, used in lower-power applications.

The MMC offers scalability, high efficiency due to minimized switching losses, improved power quality through multilevel voltage generation, fault tolerance through SM bypass, and reduced harmonics. Applications include HVDC transmission, FACTS for enhanced grid stability, renewable energy integration, and potentially EV drive systems.

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grid. In most cases, a boost converter is used to boost the PEMFC's output voltage. As more current is required from the cell, the output voltage tends to decrease. To extract the maximum available power from the PEMFC, a control system is needed to regulate the output voltage by controlling the boost converter using the MPPT algorithm. LCL filters are used to reduce absorbed harmonics in power converters with rectifier input stages. The LCL filter is frequently connected to the distribution system network. The PEMFC's dc bus output voltage is coupled to the three-phase MMC via the dc–dc boost converter. The ability to adjust and increase the fuel cell voltage is essential. The PSC modulation for the MMC is mathematically studied to identify the PWM harmonic aspects of the output voltage and CC. The proposed fuzzy logic controller is integrated into the circulating current to consider each component of the circulating currents under unbalanced voltage. The next section discusses the modelling of the PEMFC and three-phase MMC with grid interface systems. Figure 1 depicts the grid-connected MMC-fed PEMFC

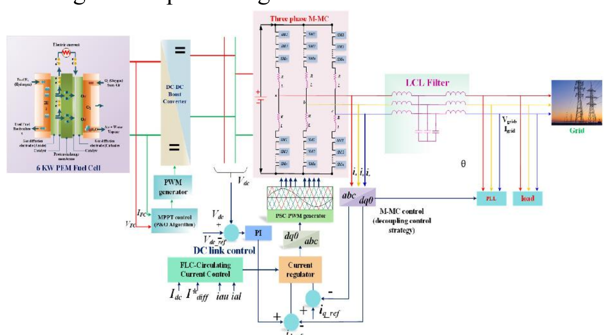

Figure 1. Thesystem architecture of three-phase grid connected MMCfed PEMFC.

Description and Modelling of PEMFC

Anelectrochemicalreactioncontinuouslytransformsthechemicalenergyofafuel into electrical energy in a fuel cell, which generates electrical power. The fuel cell is a quiet and dependable power source because it has no moving parts [1].Fuel cells use hydrogen as the fuel and oxygen (usually from air) as the oxidant in an electrochemical reaction [2]. Asabyproduct,thereactiongenerateselectricity,water,andheat.Whenhydrogengas is introduced into the system, the membrane's catalyst surface separates hydrogen gas molecules into protons and electrons [3]. Protons pass through the membrane and react withoxygenintheenvironment(formingwater).Becauseelectronscannotpassthroughthe membrane, they must go around it, resulting in a source of direct current electricity [4,5]. The following equations describe the chemical reactions that take place in a fuel cell [6].

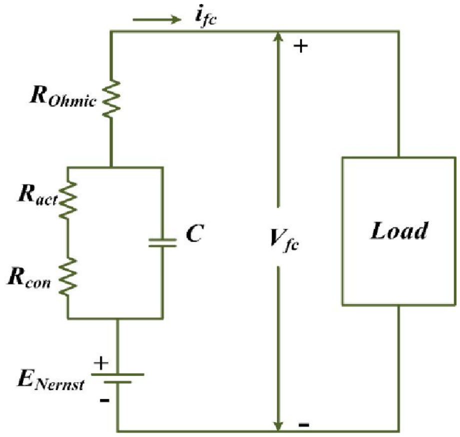

Figure 2. Equivalent Circuit of PEMFC.

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Table 1. PEMFC model parameters

PEMFC model parameters	
Rated power	6KW
Nominal operating voltage	45V
Nominal operating current	133.3A
Number of cells	65
Nominal air flow rate	300 lpm
Hydrogen partial pressure	1.5 bar
Oxygen partial pressure	1 bar
Temperature	298K

PEMFCDC–DC Boost Converter

When a fuel cell is effectively connected to an external load, the output power impacts both the internal electrochemical process and the impedance of the external load [7]. The output power of a PEMFC is not constant and varies significantly depending on the partial pressures of cell temperature, hydrogen, membrane water content, and oxygen gas. Figure 3 depicts a PEMFC dc–dc converter with an MPPT controller. Because of its simplicity, perturb and observe (P&O) is the most widely used MPPT method. This technique is used to calculate the maximum power point, calculate the actual power of the PEMFC, and quantify the voltage and current. By describing the present and preceding states of power and voltage, the P&O method can anticipate when the operating voltage is approaching the maximum power point voltage [8,9]. If there is still an increment in power, the MPP remains the same.

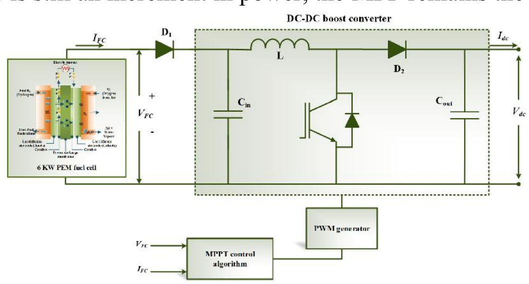

Figure 3. PEMFC and dc-dc boost converter.

Basic Circuit Operation of MMC

It employs a cascade connection of SMs to meet the optimum device voltage while providing a high multilevel output voltage waveform [10,11]. Figure 4 presents the grid- connected method of a three-phase MMC dc–ac converter. The SM is an element of the MMC which can be intended in a variety of forms using IGBT devices and dc capacitors [12]. SMs are monitored to produce the desired ac voltages throughout the standard MMC operation [13]. SM is a voltage source that can be operated. The half-bridge circuit or chopper cell is the most prevalent SM circuit topology [14]. This is due to the huge energy consumption as well as the low number of parameters in the aforementioned SM.

The arm inductor is connected in series with each set of SMs to minimize the current caused by the input voltage difference between arms [7,14]. Accordingly, in the occurrence of a dc-side short circuit, the arm inductor neutralizes the leakage current by delivering low di/dt [15,16].

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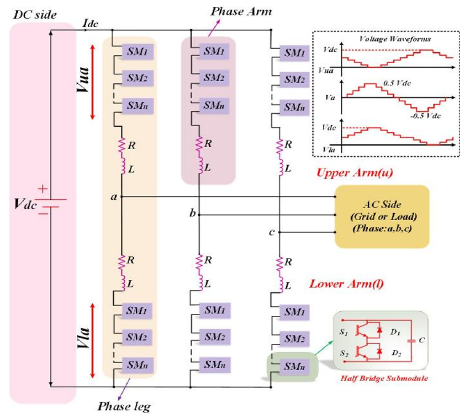

Figure 4. Three-phase MMC structure.

III. MATHEMATICAL MODELLING OF MMC

Implementation of Phase Shift Carrier PWM Technique in MMC

The triangular carrier signals can be placed horizontally or vertically within the linear modulation range. Phase-shifted carrier modulation is a modulation system in which identical triangular carrier signals are arranged horizontally (PSC-PWM) [17]. Although there is a phase shift among adjacent triangular signals in PSC-PWM, all triangular signals have same frequency and peak-to-peak amplitude.

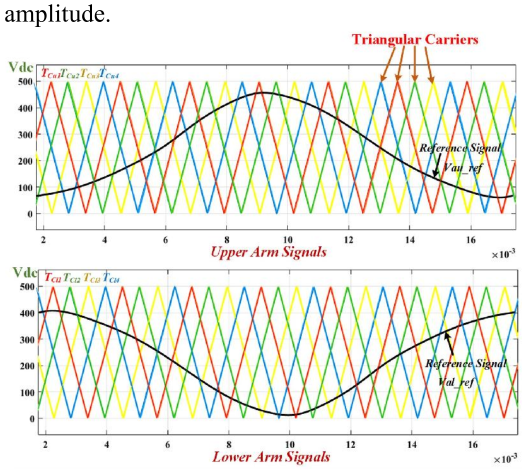

Figure 5. Simulation result for PSCPWM technique of MMC.

The output phase voltage does have positive and negative voltage levels, with a peak value of $\pm 2V$ as seen in Equation (18). The output voltage has a maximum of 2N + 1 = 9 voltage levels. Vab seems to be the line-to-line voltage assessed over phases (a and b) and also has a maximum of 4N + 1= 17 voltage levels with a step of = 62.5 V. Each SM is changed at a frequency f_{SM} of 625 Hz, which is the carrier frequency. MMC utilizes fsw = N × fc = 5000 Hz as its switching frequency. Each arm of the three-phase MMC is governed to produce unidirectional voltage which varies from zero to Vdc, where Vdc is the input dc voltage. Each arm is made up of both ac and dc elements. The arm voltages of phase a is depicted in Figure 6. Under normal circumstances, it was shown that the three-phase MMC works well. Furthermore, the converter can generate significant waveforms. In the case of lower arms, the dc element corresponds to 0.5 Vdc, whereas the ac element corresponds to the connected output phase voltage, and in the case of upper arms, it corresponds to the antiphase of the connected output phase voltage.

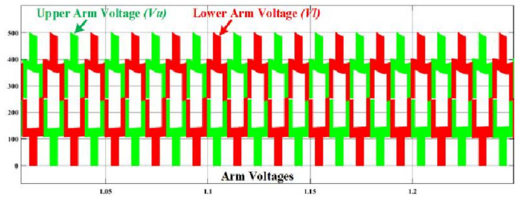

Figure 6. Simulation results for arms voltages of Phase a (V_u, V_l) in MMC.

IV. PROPOSED FUZZY LOGIC CONTROLLER INTEGRATED TO CIRCULATING CURRENT IN MMC

The capacitor voltage fluctuation is a single source of CC that has a frequency double that of the output. ac output voltages and currents are influenced by the CC.. However inadequate circulating current control increases the arm current peak/RMS value, which subsequently affects the SM capacitor voltage's ripple, device power losses, and device rating. To control the current control voltage source, the three-phase circulating current suppression is proposed. Figure 7 depicts the proposed fuzzy logic control of CC in an MMC. The fuzzy controller is the optimum solution for decision making. For nonlinear loads or large industrial applications, fuzzy provides more precision.

The FLCs are advanced expert systems. To solve a problem, an FLC uses a knowledge base described in terms of fuzzy inference rules and a fuzzy inference engine [20]. A fuzzy system is defined by a set of linguistic description rules based on expert knowledge in an FLC. Expert knowledge is often described as IF (a set of criteria are met) THEN (a set of consequences can be inferred) [18]. A fuzzy controller works by repeating the procedures described in Figure 8: all variables representing the relevant circumstances of the controller process are measured (inputs). Fuzzification [19] is the process of converting measurements into suitable fuzzy sets in order to communicate measurement uncertainty.

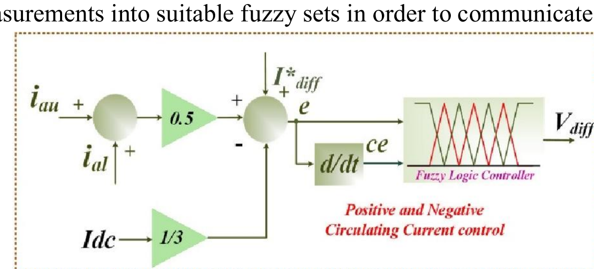

Figure 7. Proposed fuzzy logic control of circulating current in MMC.

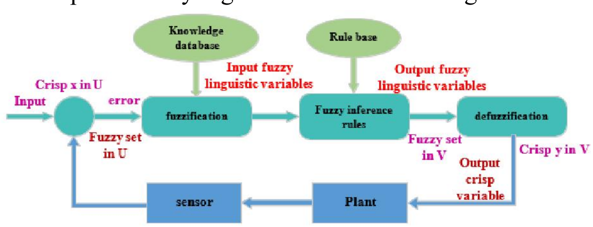

Figure 8. Block diagram of fuzzy logic controller.

V. RESULTS AND DISCUSSIONS

The conclusive architecture was implemented in MATLAB/SIMULINK and tested using the real-time simulation field for system process and control of the MMC. Figure 11 depicts the HIL configuration. The entire system referring to Figure 1 is a built-in RT lab simulation which was dumped into the OP-5700 real-time HIL simulator to validate system performance and the validity of the PSC-PWM of MMC as well as the proposed fuzzy logic for circulating current suppression in the MMC. The MMC system control parameter values are tabulated in Table 3. On the other hand, PEMFCs have a low operating temperature of around 80 ◦C (353.15 K). A low-temperature operation enables them to start faster (because of a reduced warm-up time) and reduces stress on the components of the system, resulting in increased dependability.

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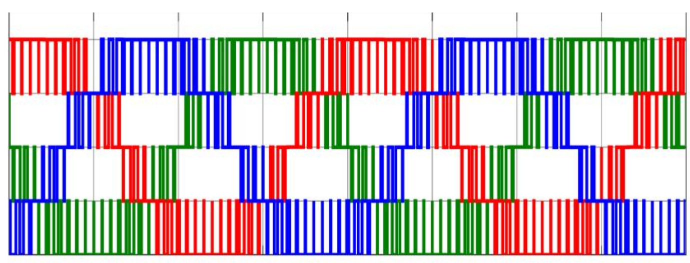
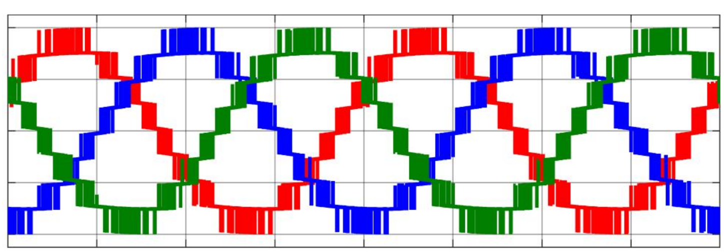
The amount of power produced by a fuel cell method is determined by water and heat management, pressure control, hydrogen, and oxygen flow. One of the fundamental process issues is reactant utilization, which is connected to the fuel cell stack current. The control system must regulate the hydrogen flow rate when a load is attached to a fuel cell system to prevent FC voltage depreciation. The power produced by the PEMFC temperature was 289 K in this scenario. In this regard, the PEMFC generated 6 kW of power, 45 V of fuel stack voltage, and 133.3 A of current was generated at temperature T = 332 K.

The boost converter regulates and controls the fuel cell's output power. The boost converter accepts the fuel cell's unregulated output voltage. Despite variations in hydrogen flow rate, load, or fuel cell operational parameters, the PI controller changes the MPPT duty ratio of the converter to deliver the appropriate output voltage. The MPPT technique is only used for tracking the maximum power attained via the fuel cell that may indirectly aid in enhancing the system performance. The PEMFC boost converter provides the highest output voltage required to maintain a constant dc bus voltage of 500 V. The produced dc-link power was 6kW and the dc-link current was 12 A at T = 298 K.Impacting voltage of an SM capacitor: the upper and lower arms of the SM capacitor voltage on an individual basis are depicted a–c. As a result, with a peak value of $\pm 2V_* = 250$ V, the output phase voltage contained positive and negative voltage levels.The output voltage had a total $2N + 1 = 9$ voltage levels with a step of $V_{ac} = 125$ V. By balancing the voltages of individual SM capacitors, a sorting method for maintaining their voltages in the MMC was established. These sorting approaches might produce a tremendously asymmetrical switching frequency among the SMs, resulting in higher converter losses. The average capacitor voltage regulator oversees confirming that the incoming dc is distributed evenly across the MMC leg and that the excess voltage of every leg's SM capacitor equals the average voltage value. In this regard, the line-to-line voltage V_{ab} was measured across phase (a and b) and had a total of $4N + 1 = 17$ voltage levels with a step of $V_{ac} = 62.5$ V. The voltages of SM capacitors deviate from their stable values when a load is connected to the grid. Voltage fluctuations were reduced dramatically, and voltages were at an acceptable level. The SM capacitor voltages were balanced, with a peak voltage ripple of 62.5 V at the base frequency.

VI. SIMULATION RESULTS

Simulation is shown with 4 cells in each arm. Upper and Lower arm voltages are identical. They have a DC and an AC component.





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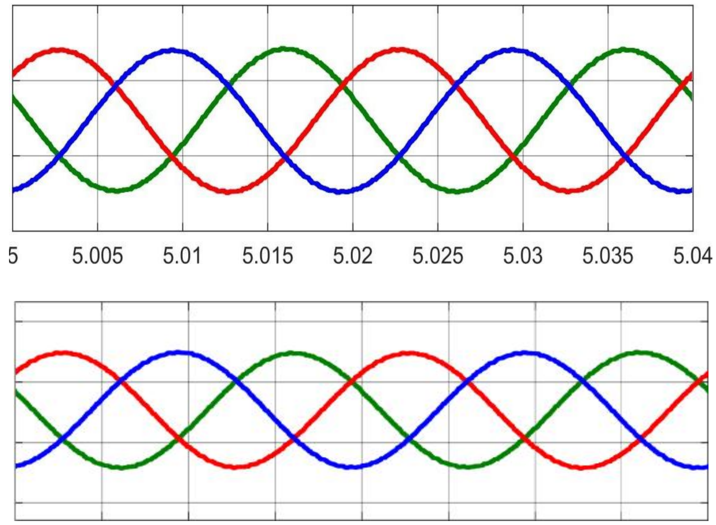

Figure 9 Three phase MMC output

VII. CONCLUSION

This chapter proposes an FLC system for reducing the peak value of circulating current in M-MC. The effectiveness of the proposed circulating current-based PSC-PWM for M-MC topology has been simulated and the performance has been analyzed. The elementary working principles of the PSC-PWM are incorporated in M-MC to obtain the capacitor voltage balancing in it. Further, the PSC-PWM technique is capable of increasing the switching frequency which in turn reduces the size of the required filters. During a phase of operation, to maintain a constant number of inserted SMs in the arm, a constant differential voltage is provided for the upper and lower arms. Consequently, the proposed method mitigates the magnitude of the CC as effectively as the existing method. At the same time, The SM capacitor voltages are balanced, with a peak voltage ripple from the DC bus voltage control of 12.5%, which is the same as at the base frequency. Using the analytical expression for a PSC-PWM-based M-MC configuration, it was determined that the THD value for M-MC phase voltage is 1.89% and the grid current is 2.30%.

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