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Design of AI based Controllers for Minimizing Low-Order Circulating Currents in MMC

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Abstract : Modular Multilevel Converters (MMC) have gained significant attention in high-voltage direct current (HVDC) transmission systems due to their superior performance in terms of voltage waveform quality and efficiency. However, one critical issue that MMCs face is the presence of low-order circulating currents among the submodule capacitors. These circulating currents can degrade system performance, increase losses, and potentially lead to module failures if not properly controlled.This paper presents the design and implementation of AI-based controllers to minimize low order circulating currents in MMCs. Both fuzzy logic and artificial neural networks (ANNs) are effective in reducing harmonic currents in DC-link systems and perform well even when the AC grid conditions are unbalanced. This makes them suitable for use in multi-frequency AC systems. Simulation results confirm that the proposed methods are accurate and reliable in controlling circulating currents

IndexTerms – Modular Multilevel inverters, AI Controllers, circulating current

I. INTRODUCTION

MMC represents a significant recent innovation in power electronics converters. By utilizing combinations of different direct current (DC) buses, they can synthesize ladder output waveforms, making them highly applicable across various Power Electronics (PE) applications. Increasing the number of DC buses in a MMC allows it to create more voltage levels, thereby approaching a sinusoidal output waveform [1].
The concept of MMC differs significantly from conventional converter topologies, as outlined by several key points [1–5]:

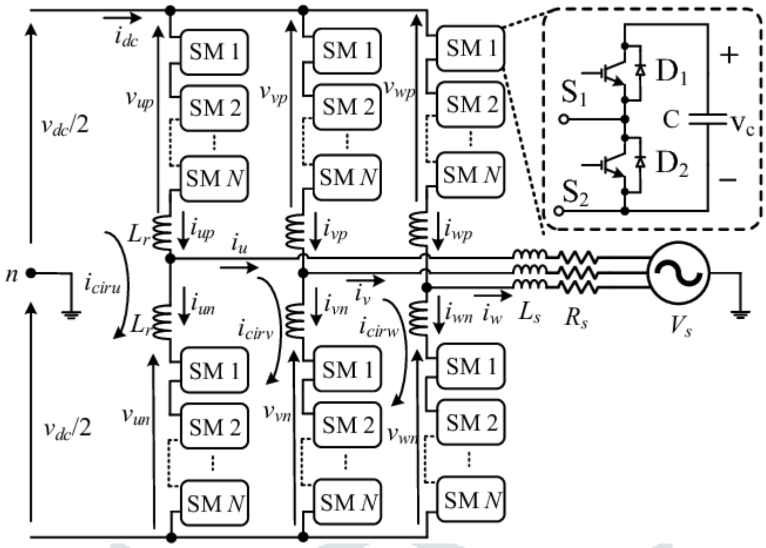
- Modularity and Expandability
- Harmonic Content
- Reduced Passive Filter Size
- Reduced Semiconductor Stress
- Lower Switching Frequencies
- Simplified Maintenance
- Integration of Renewable Energy

These characteristics make Multilevel Converters versatile and advantageous for various power electronics applications compared to traditional two-level converters. The features of Multilevel Converters (MLCs) are highly appealing, particularly for high-voltage power distribution applications. For instance, MLC integration in HVDC systems is detailed in references [5–9], with proposals for distributed control in HVDC applications discussed in [10], and fault analysis covered in [11–13]. MLCs are also extensively applied in renewable energy contexts such as solar photovoltaic systems [14–15], onshore wind farms and offshore wind farms. They play a crucial role in interfacing with Energy Storage Systems (ESS). In electric mobility, MLCs find application in railway electric systems, as active power conditioners to enhance power quality in railways and for traction purposes in EV's. They also interface with onboard ESS in EV's and are utilized in marine propulsion systems. Furthermore, MLCs serve as active conditioners, mitigating power quality. However, it has encountered issues such as circulating currents and voltage imbalances.

To enhance the MMC's performance, control strategies have been incorporated. Generally, Conventional PI controller has been incorporated to enhance the performance of the system. However, PI controllers may not perform well in systems with significant non-linearities. These controllers rely on accurate mathematical models of the system for optimal performance. Inaccuracies in these models can lead to suboptimal control. To overcome this drawbacks, this work introduced a soft computing technologies based fuzzy and neural controller for MMC. In this approach, fuzzy and ANN logic was employed to control the DC component and suppress circulating currents in the system. These techniques suppress the circulating currents involved adjusting the common mode(CM) reference value using a controller, thereby ensuring that the CM dependent source value remained predominantly DC.

II. PROPOSED METHODOLOGY

Figure 1 depicts the schematic illustration of this proposed system



III. MODULAR MULTILEVEL INVERTERS

Figure 2 depicts a MMC, focusing on one phase labeled as 'a'. Each phase in the MMC is represented as a leg, which consists of two arms. Each arm contains multiple submodule (SM) units connected in a series arrangement. The DC power source has a center tap with a voltage magnitude of 2Udc. Different configurations of SM's are utilized depending on the application. In this methodology, half-bridge SMs are specifically used.

A half-bridge SM includes two switches-IGBT or diode pairs (S1 and S2) along with a DC-link capacitor for storing energy, as shown in Figure 3. These switches are controlled by an AI based PWM controller. When S1 remains turned 'ON' and S2 in 'OFF' state, the output voltage Uac equals Udc, indicating that the SM is in the 'inserted' state. Conversely, when S1 is 'OFF' and S2 is 'ON', Uac equals to 0, indicating that the SM is in the 'bypassed' state.

Each DC link capacitor stores a voltage of Udc_{in}/N when the SM is in the inserted state, assuming the capacitor is maintained at Udc_{in}/N. As a result, the converter terminal produces a waveform with (N+1) voltage levels for each phase. Here, 'j' represents either the upper (u) or lower (l) arm, and 'n' ranges from 1 to N.

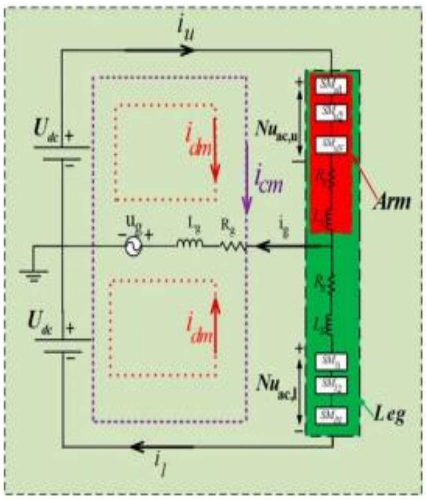


Figure 2. Proposed MMC -phase 'a'.

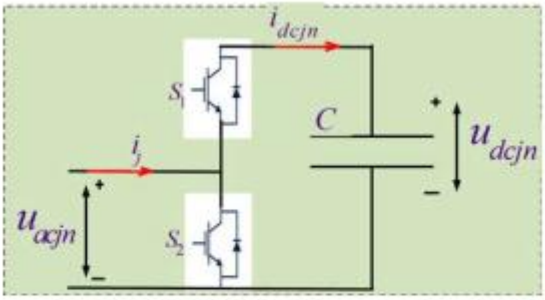


Figure 3. SM of MMC

IV. FUZZY LOGIC CONTROLLER

FLC are intelligent control systems that rely on a collection of straightforward rules derived from expert’s experience or knowledge.The process of changing exact numerical values into fuzzy values is called fuzzification. This is done using membership functions (MFs), which help define how each input belongs to different categories. One of the commonly used MFs is the triangular membership function because it is simple and easy to use.

The rule base of the FLC is designed to produce fuzzy outputs. This rule base uses linguistic variables to create its rules. The "if" part of the rule (antecedent) states a condition, and the "then" part (consequent) states the resulting action. The inputs to the FLC are the error / change in error.

In this FLC system, the membership functions (M’s) are categorized into five levels as shown in Fig. 4, 5 and 6.

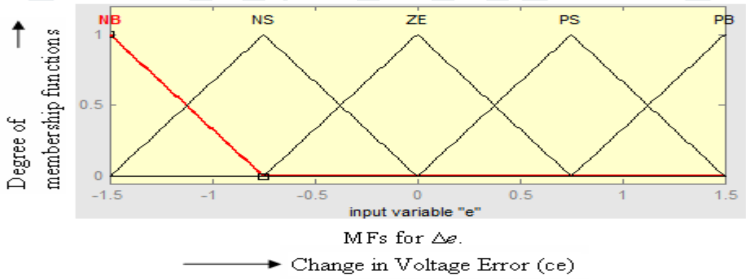


Figure.4. MFsfor e(k)

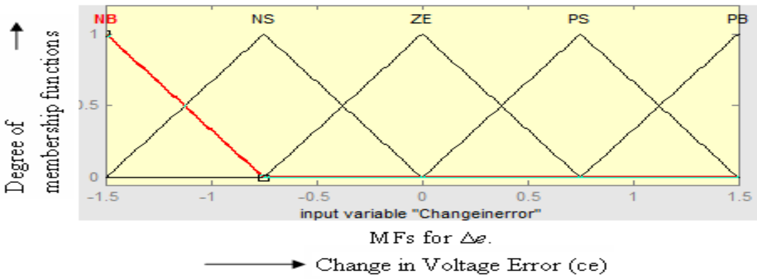


Figure. 5. MFsfor ce(k)

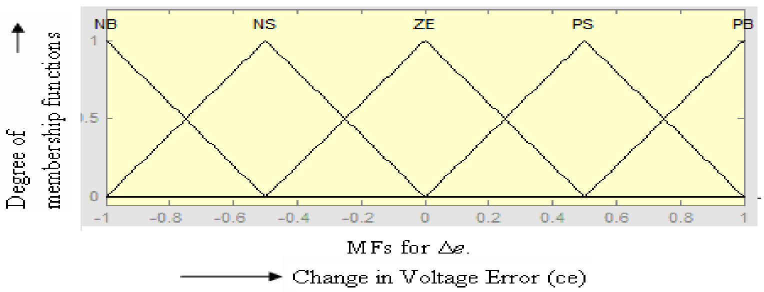


Figure.6. MFsfor cu(k)

The control rules are created using linguistic variables and stored in the rule base using a rule evaluator. The rules formed with these linguistic variables are tabulated in Table 1.

Table 1

Rule base

e(k)/ce(k)	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

The incremental change in the control signal cu(r), is the output of the FLC. The output of the FLC is the incremental change in the control signal, cu(r). These outputs are then fed into the process. Defuzzification, also known as the "rounding off" method, converts the set of membership function values into a single value. In this system, the Centroid method is used for defuzzification because it is accurate. A Mamdani fuzzy system uses fuzzy sets to form the rule consequents. Therefore, all the fuzzy systems in this work are Mamdani fuzzy systems.

V.ARTIFICIAL NEURAL NETWORK (ANN)

The main objective of designing a controller for any system is to obtain a desired output efficiently. The neural networks possess indigenous learning and self-regulating abilities, which allows them to adjust the alterations in data, these networks are used to effectively control the converters. Thus the minimum MSE is about l e-7. LEARNGDM. Gradient Descent bias learning function was utilized in this work. Thus the developed controller has three layers, input layer with one neuron, a hidden layer where four neurons are placed and the output layer with one neuron as shown in Fig 7 – 10.

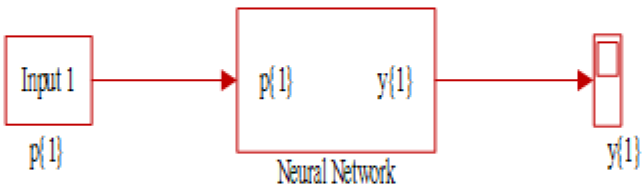


Figure.7.Neuro Controller

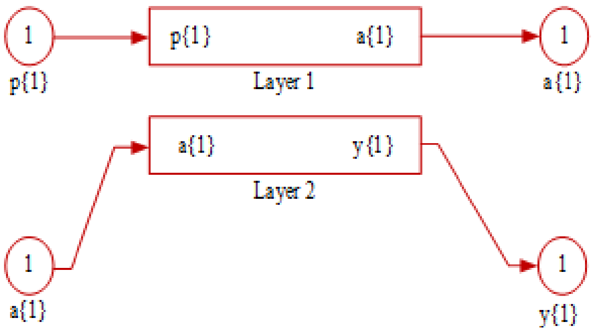


Figure.8. Design of Proposed Neural Network

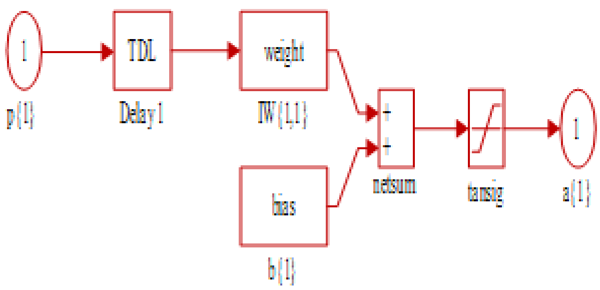


Figure.9. Hidden Layer in proposed methodology

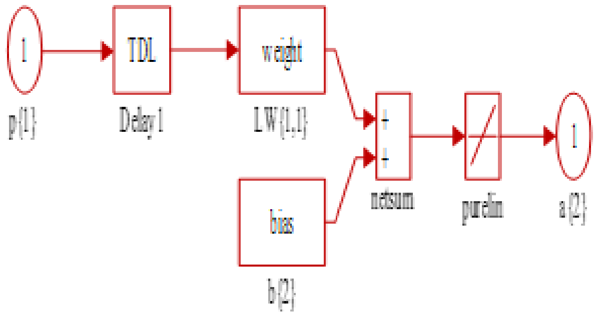


Figure.10. Output Layer

In this work, the optimum number of four hidden neurons was selected because, under this condition, the number of epochs for training the neural network can be minimized to a considerable extent and a fairly correct and satisfactory dynamical performance of the converters can be derived. At the same time, it has also been proved that using more than four hidden modes are not able to produce any significant improvement and again it may need for additional time for computation of the output.

VI.RESULTS AND DISCUSSION

To test the performance and effectiveness of the proposed system, a 3ϕ MMC connected to an AC grid was simulated using MATLAB/Simulink software. The design parameters are listed in Table 2.

Table 2. Simulation Parameters

PARAMETER	VALUE
DC supply voltage	10kv
AC grid voltage(rms)	5.77kv
AC grid frequency	50Hz

Fig 11-12 depicts the output voltage of the proposed system

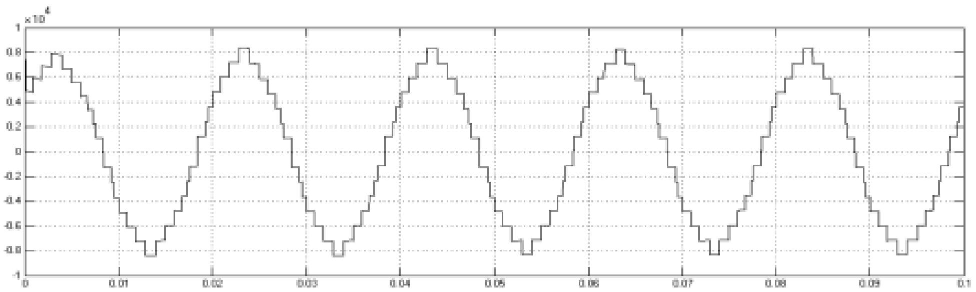


Figure. 11. Output Voltage(per phase)

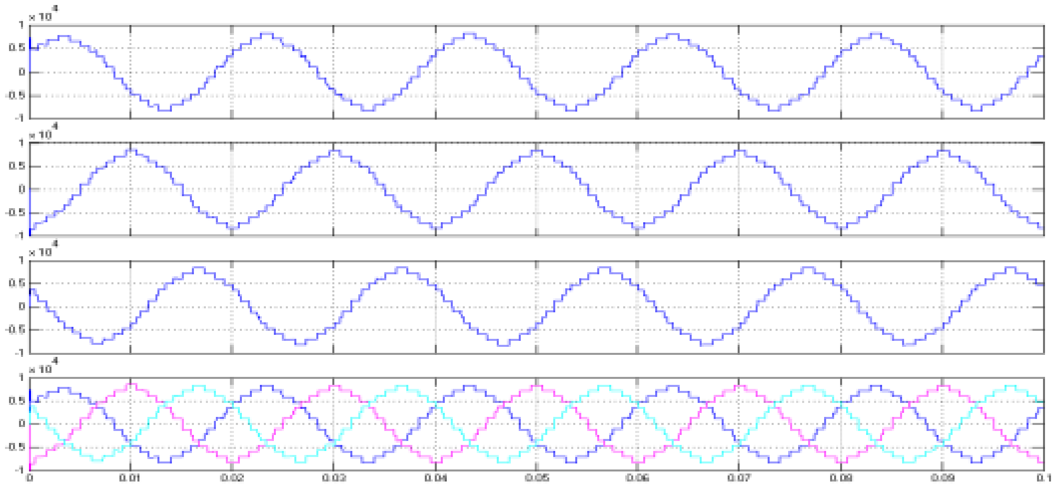


Figure .12 . Output Voltage (3ϕ)

Figure 13-14 represents the THD of the system with proposed controller.

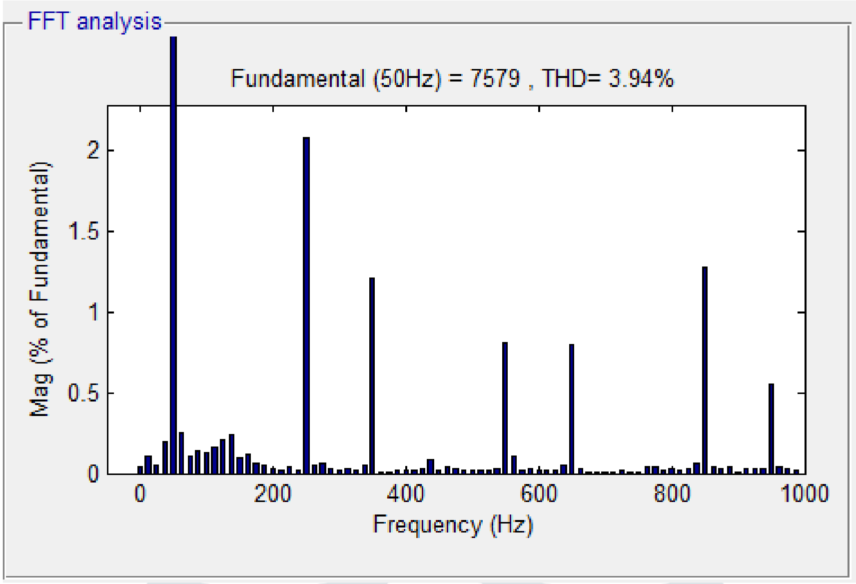


Figure.13. THD with FLC

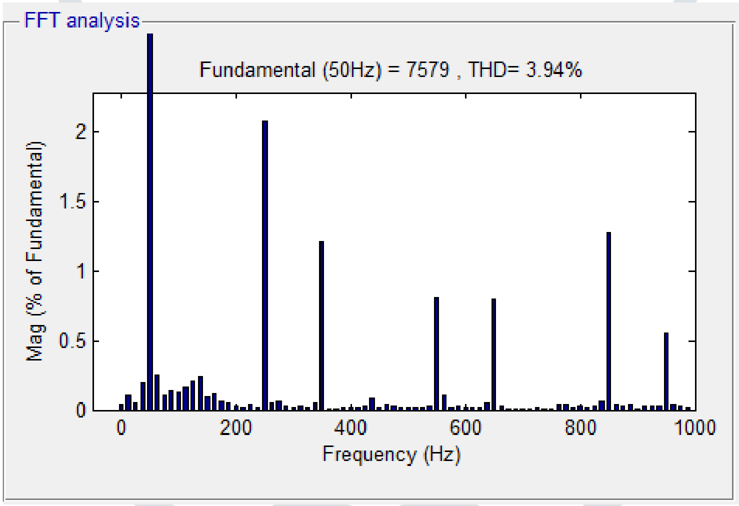


Figure.14. THD with ANN

From the above results, it is found that the ANN controller compensates harmonics perturbations quicker and with a low THD about 3.94%. Thus, ANN can be considered as the suitable controller.

VII.CONCLUSION

This article introduces a FLC and ANN controller designed to minimize the substantial second-order harmonics in circulating currents within a MMC. The FLC and ANN controllers work together reduces the harmonic currents while ensuring a balanced distribution of power between the input and output sides across various operational scenarios. Unlike traditional resonant controllers, this method naturally achieves balance by simultaneously regulating both arms of the MMC. Extensive simulations were conducted to illustrate the effectiveness and advantages of this approach under diverse operating conditions.

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