

DESIGN OF REPETITIVE CONTROLLER FOR MODULAR MULTILEVEL CONVERTER

P.SAI ARAVIND¹, K. VINDHYA SMITHA²

¹ PG STUDENT, Department of EEE, Gudlavalleru Engineering College, Gudlavalleru, Andhra Pradesh, India

² Associate Professor, Department of EEE, Gudlavalleru Engineering College, Gudlavalleru, Andhra Pradesh, India

Abstract - Modular multilevel converters (MMCs) have emerged as the most promising topology for high and medium voltage applications for the coming years. However, one particular negative characteristic of MMCs is the existence of circulating current, which contains a dc component and a series of low-frequency even-order ac harmonics. If not suppressed, these ac harmonics will distort the arm currents, increase the power losses, and cause higher current stresses on the semiconductor devices. Repetitive control (RC) is well known due to its distinctive capabilities in tracking periodic signals and eliminating periodic errors. In this paper, a novel circulating current control scheme based on RC is proposed to effectively track the dc component and to restrain the low-frequency ac harmonics. The integrating function is inherently embedded in the RC controller. Therefore, the proposed circulating current control only parallels the RC controller with a proportional controller. Thus, conflicts between the RC controller and the traditional proportional integral (PI) controller can be avoided. The design methodologies of the RC controller and a stability analysis are also introduced. The validity of the proposed circulating current control approach has been verified by simulation and extension can be done using Fuzzy Logic Controller.

Key Words: Modular multilevel converters (MMCs), Even-order AC harmonics, Repetitive control, Fuzzy Logic Controller, Stability Analysis.

1. INTRODUCTION

Multilevel converters have successfully made their way into industrial high-power applications [1]. Among the multilevel topology family, the modular multilevel converter (MMC) is attracting increasing interests for the advantages of modular structure, inherent redundancy, distributed and reliable dc capacitors, improved power

quality, four-quadrant operation, freedom from multiple isolated dc sources, ease of expandability.

In a modular multilevel converter, the chief ripple component of the sub module (SM) capacitor voltage is the fundamental one. It can produce second-order harmonic in the output voltage of the SMs. The latter then causes second-order harmonic in the circulating current that flows through the dc source and the phase leg. Without proper control, the amplitude of the second order circulating current can be significant, and it can trigger a series of higher, even-order current harmonics. The harmonics in the circulating current increase power losses and reduce service life of power devices. More seriously, if left uncontrolled, they may cause instability during transients. The authors present open-loop methods for circulating current control and harmonic suppression. A drawback of these methods is parameter sensitivity. A FUZZY controller is used to suppress the circulating current harmonics. However, it cannot totally remove the harmonics due to its limited gains at those harmonic frequencies.

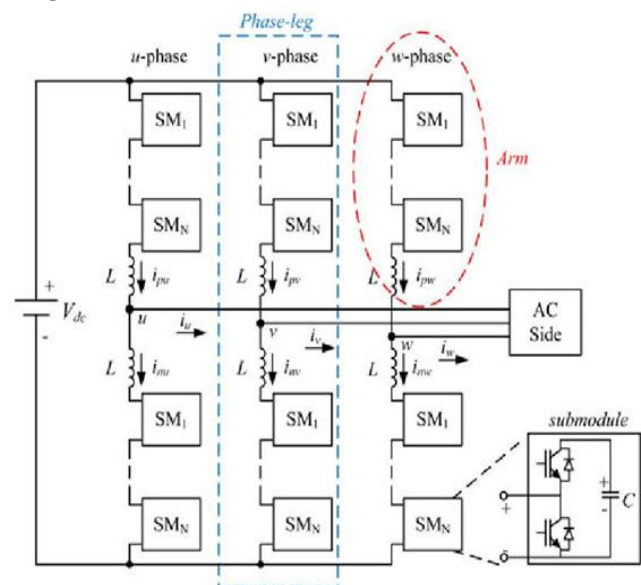


Fig -1: Topology of a three-phase Modular Multilevel Converter (as an inverter)

Pair of FUZZY controllers based on double line-frequency, negative-sequence rotating frame, is utilized to eliminate the second-order harmonic. Such rotating frames are difficult to define in single phase systems. In addition, this method may need some modification under unbalanced three-phase conditions. Proportional resonant (PR) controllers are applicable to both single phase and three-phase systems. However, implementation of PR controllers becomes difficult when multiple harmonics are to be eliminated.

2. MODELLING OF A MODULAR MULTI-LEVEL INVERTER

Modular multi-level inverter for a single phase out of three phases has shown in Figure 2

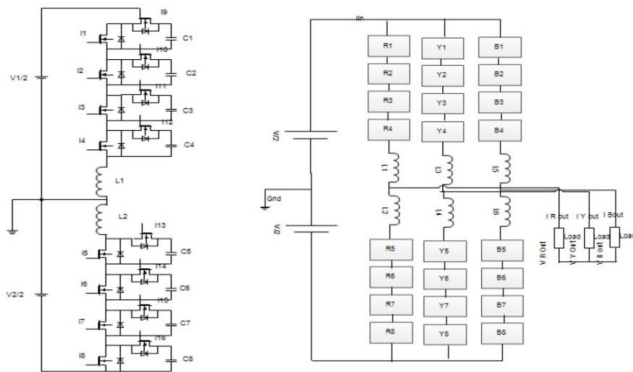


Fig-2: Five Level Modular MLI with chopper cells and details of its three phase system

By applying basic KCL and KVL in Figure 2. Whereas, i_{tr} is the current passing through 'R' phase top limb, i_{br} is the current passing through 'R' phase bottom limb; i_{cir} is the circulating current passing in 'R' phase between top and bottom of the limb. 'n' indicates number of limbs connected in MLI .

$$i_{tr} = i_{cir} + \frac{i_r}{2} \tag{1}$$

$$i_{br} = i_{cir} - \frac{i_r}{2} \tag{2}$$

$$i_{cir} = \frac{1}{2} (i_{tr} + i_{br}) \tag{3}$$

$$i_{cir} = \overline{i_{cir}} + \tilde{i}_{cir} \tag{4}$$

This circulating current is the unique feature of this topology. This current consists of both DC & AC component, where the DC (i_0) component is

$$\overline{i_{cir}} = \frac{i_0}{3} \tag{5}$$

For the phase 'R', which is shown in above, if we apply Kirchhoff's law for both the upper to lower

$$V_{tr} = \frac{V_{dc}}{2} - \sum_{n=1}^N V_{ntr} - L_{top} \cdot \frac{di_{tr}}{dt} - R_{top} \cdot i_{tr} \tag{6}$$

$$V_{br} = -\frac{V_{dc}}{2} + \sum_{n=N+1}^{2N} V_{nbr} + L_{bot} \cdot \frac{di_{br}}{dt} + R_{bot} \cdot i_{br} \tag{7}$$

Whereas, V_{tr} is the voltage across 'R' phase top limb and neutral, V_{br} is the voltage across 'R' phase bottom limb and neutral, L_{top} and L_{bot} are the arm inductors in 'R' phase top and bottom of the limb. By applying equations (1) and (2) in equations (6) and (7), we have the total voltage V_R phase is (6) + (7),

$$V_{Rphase} = \frac{1}{2} [\sum_{n=N+1}^{2N} V_{nbr} - \sum_{n=1}^N V_{ntr}] - L_{top+bot} \cdot \frac{di_r}{dt} - R_{top+bot} \cdot i_r \tag{8}$$

By this it clearly shows that the output voltage depends upon the current 'i_r' and difference of voltage injected by the cells. From equation (8), as long as the $L_{top+bot}$ (L_{tot}) presents in the circuit, then the losses will be there and the voltage output will always vary. Whereas $R_{top+bot}$ represents as R_{tot} . The circulating current can be expressed as:

$$L_{tot} \cdot \frac{di_{cir}}{dt} + R_{tot} \cdot i_{cir} = \frac{V_{dc}}{2} - \frac{[\sum_{n=N+1}^{2N} V_{ntr} - \sum_{n=1}^N V_{ntr}]}{2} = \frac{V_{cir}}{2} \tag{9}$$

3. CONTROL SYSTEM FOR CIRCULATING CURRENT

The overall control system for circulating current is shown in Fig. 3. The proposed control system consists of the Fuzzy Logic controller and a repetitive controller, which

will be discussed in the next section. For a three-phase MMC inverter, three such control blocks are needed. The circulating current reference consists of a dc component coming from total energy control, and a fundamental component coming from the differential energy control. Since the dc component i_{zx-0}^* in the current reference can be easily corrupted by the harmonics in the capacitor voltages, a moving average filter (MAF) is inserted in the i_{zx-0}^* path.

A. Control System Configuration:

A repetitive controller is paralleled with the Fuzzy controller to improve harmonic suppression. The final control structure is shown in Fig. 3. Such a parallel configuration of a repetitive controller and the existing high-dynamic controller (the Fuzzy controller in this case) can also found in [17]–[20].

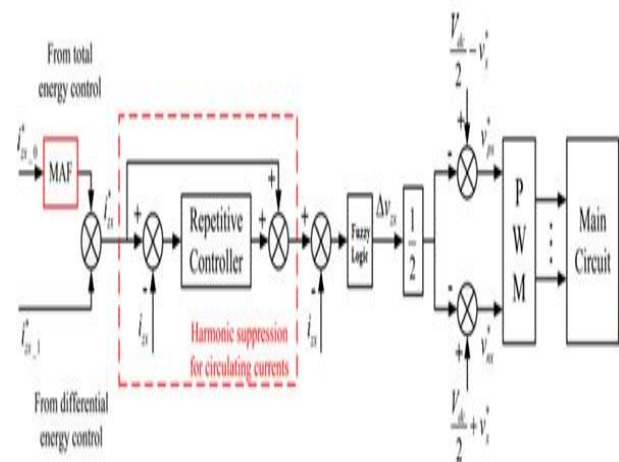


Fig-3: Overall circulating current control of MMC (for phase x)

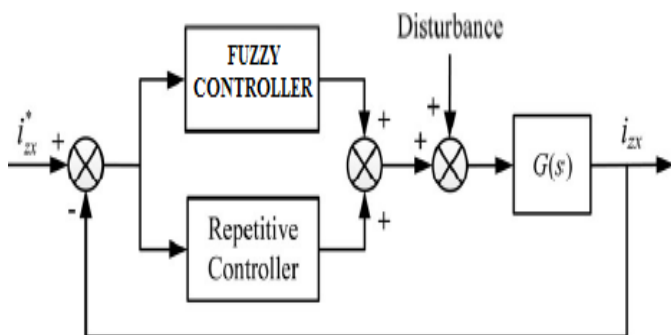


Fig-4: Proposed control structure

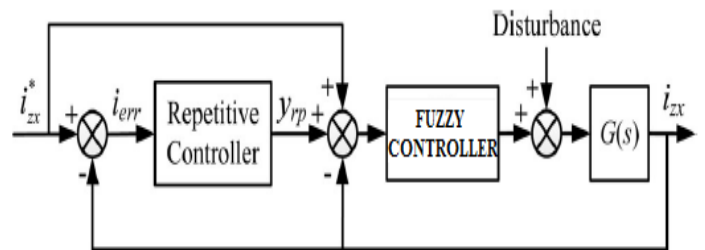


Fig-5: Proposed plug-in repetitive control structure

In this paper, however, a different structure as shown in Fig. 5 is adopted.

An important consideration behind a parallel structure is the transient performance. avoid this. With the feed forward path of current reference, the control structure in Fig. 5 is equivalent to the classical “plug-in” structure [21]–[24] as shown in Fig. 6.

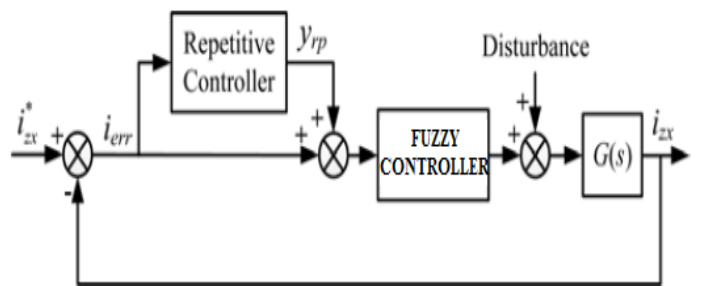


Fig-6: Equivalent form of Fig. 5

From Fig. 6 the plug-in repetitive controller is more separated from the Fuzzy controlled circulating current loop. Therefore, the Fuzzy controller can be designed independently, and the dynamics of the whole system will not be hold back by the repetitive controller. The plug-in repetitive controller only deals with the residual, repetitive error left by the Fuzzy controller. The proposed control structure also provides a more friendly “plant” for the repetitive controller.

4. FUZZY LOGIC CONTROLLER

A fuzzy logic controller has four main components as shown in Figure 7 fuzzification interface, inference mechanism, rule base and defuzzification interface. FLCs are complex, nonlinear controllers. Therefore it’s difficult to predict how the rise time, settling time or steady state error is affected when controller parameters or control rules are changed. On the contrary, PID controllers are simple, linear controllers which consist of linear combinations of three signals.

Implementation of an FLC requires the choice of four key factors: number of fuzzy sets that constitute linguistic variables, mapping of the measurements onto the support sets, control protocol that determines the controller behaviour and shape of membership functions. Thus, FLCs can be tuned not just by adjusting controller parameters but also by changing control rules, membership functions etc. The main advantages of adaptive fuzzy control over non adaptive fuzzy control are: better performance is usually achieved because the adaptive fuzzy controller can adjust itself to the changing environment, and less information about the plant is required because the adaptation law can help to learn the dynamics of the plant during real time operation. However, these approaches still have some problems. The adaptive control scheme proposed by Wang [13] guarantees the uniform boundedness of all signals of the control system but it is applicable only to single-input single-output system. In many applications, the structure of the model of the plant may be known, but its parameters may be unknown and/or change with time. Recently, the concept of incorporating fuzzy logic control into the model reference adaptive control has grown into an interesting research topic [18-20].

In a repetitive-plus-FUZZY control scheme is proposed. It is applicable to both single-phase and three-phase systems. Moreover, it can eliminate multiple harmonics in the circulating current with a single repetitive controller. However, the repetitive controller and the FUZZY controller are paralleled. Such an arrangement imposes unnecessary limitation on the FUZZY controller design and also complicates the repetitive controller design.

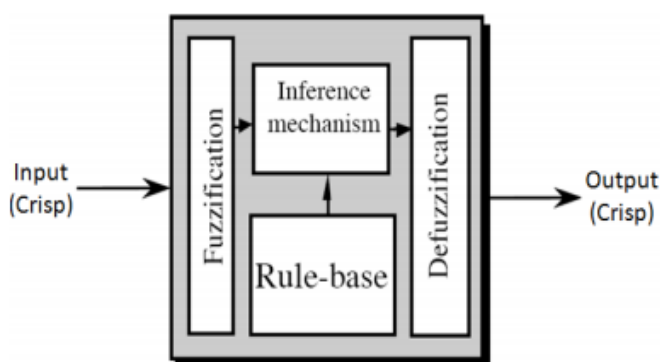
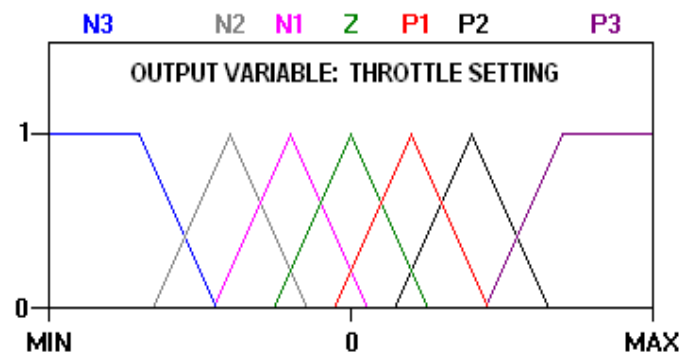


Fig-7: Fuzzy Logic Controller

This paper proposes a different repetitive-plus-FUZZY control scheme. The improved plug-in configuration of the repetitive controller avoids the above problems while keeping all the advantageous features.

Fuzzy control system design is based on empirical methods, basically a methodical approach to trial-and-error. The general process is as follows:

- Document the system's operational specifications and inputs and outputs.
- Document the fuzzy sets for the inputs.
- Document the rule set.



N3: Large negative, N2: Medium negative, N1: Small negative, Z: Zero, P1: Small positive, P2: Medium positive, P3: Large positive.

Determine the defuzzification method.

- Run through test suite to validate system, adjust details as required.
- Complete document and release to production.

In some control tasks, such as those in robot manipulation, the systems to be controlled have constant or slowly-time varying uncertain parameters. Unless such parameter uncertainty is gradually reduced on-line by an appropriate adaptation or estimation mechanism, it may cause inaccuracy or instability for the control systems. In many other tasks, such as those in power systems, the system dynamics may have well known dynamics at the beginning, but experience unpredictable parameter variations as the control operation goes on. Without continuous redesign of the controller, the initially appropriate controller design may not be able to control the changing plant well. The problem of adaptation of dynamical systems having parameter uncertainty has attracted a lot of research efforts in all times. In particular, for nonlinear systems, several approaches have been proposed to deal with this important problem [5-7].

On the other hands, as a model free design method, fuzzy logic systems have been successfully applied to control complex or mathematically poorly understandable systems. However, the fuzzy control has not been regarded as a rigorous science due to the lack of guaranteed global stability and acceptable performance. To overcome these drawbacks, during the last decade, there has been growing interest in systematic analysis and

design of fuzzy control systems such as stability and robustness [8-12]. One of the motivations in this research is the success developed in [9] where the authors provided a sufficient condition for the asymptotic stability of fuzzy control system based on Takagi-Sugeno (TS) model [8] in the sense of Lyapunov through the existence of a common Lyapunov function for all subsystems. In recent years, in order to deal with the uncertainties of nonlinear systems in the fuzzy control system literature, a lot of effort has been put to adaptive fuzzy control system such as neural network based approaches, and the TS model based approaches.

Rule base, inference mechanism and defuzzification methods are the sources of nonlinearities in FLCs. But it's possible to construct a rule base with linear input-output characteristics. For an FLC to become a linear controller with a control signal $U = E + CE$. Where E is "error" and CE is "change of error", some conditions must be satisfied:

1. Support sets of input linguistic variables must be large enough so that input values stay in limits.
2. Linguistic values must consist of symmetric triangular fuzzy sets that intercept with neighbouring sets at a membership value of so that for any time instant, membership values add to 1.
3. Rule base must consist of -combinations of all fuzzy sets.
4. Output linguistic variables must consist of singleton fuzzy sets positioned at the sum of the peak positions of input fuzzy sets.
5. Should be multiplication and defuzzification method must be "centre of gravity" (COGS).

Table-1: Parameters of the Single Phase MMC

Items	Values
Rated Power :P	1 KW
Load Resistor : R_L	14 Ω
Modulation Index : M	0.9
Rated Frequency : f_i	50Hz
DC Link Voltage : V_{dc}	400V
Arm Inductance : L	4.6 mH
Arm equivalent Resistance : R	0.05 Ω
Number of SMs in Each arm : N	4
SM Capacitor : C	560 μ F
Rated Capacity Voltage: V_c	100V

PWM Strategy	Phase Disposition PWM
SM Switching Frequency	1 kHz
MMC Equivalent Switching Frequency	4 kHz
PI Parameters	$K_p=16, K_i=20$

5. SIMULATION RESULTS

Repetitive control (RC) is well known due to its distinctive capabilities in tracking periodic signals and eliminating periodic errors. In this paper, a novel circulating current control scheme base on RC is proposed to effectively track the dc component and to restrain the low-frequency ac harmonics. The integrating function is inherently embedded in the RC controller. Therefore, the proposed circulating current control only parallels the RC controller with a proportional controller. Thus, conflicts between the RC controller and the traditional proportional integral (PI) controller can be avoided. The design methodologies of the RC controller and a stability analysis are also introduced. The validity of the proposed circulating current control approach has been verified by simulation and extension can be done using Fuzzy Logic Controller.

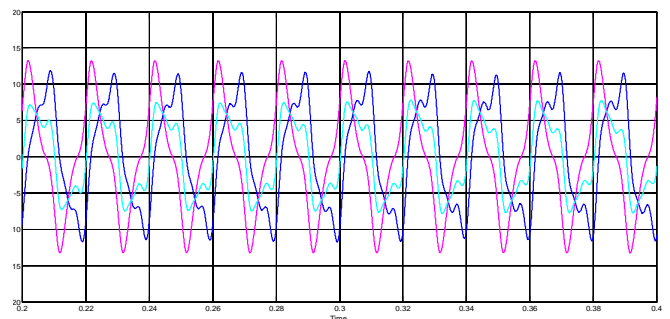


Fig-8: Currents of PI Controller

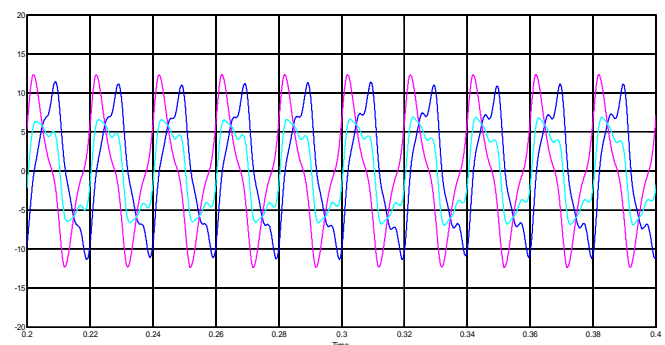


Fig-9: Currents of MAF + PI Controller

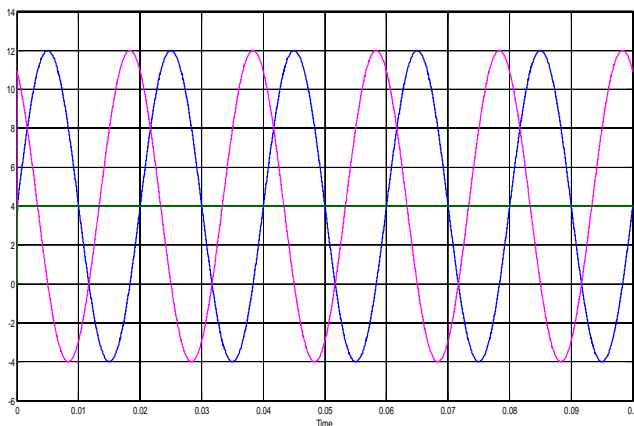


Fig-10: Current of MAF + PI + Repetitive controller

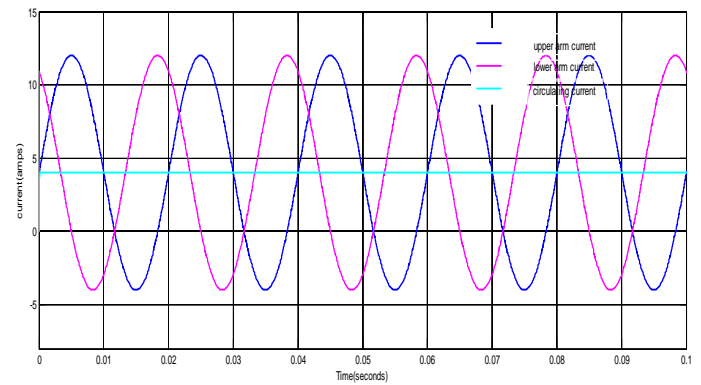


Fig-13: Currents of MAF + Repetitive + Fuzzy Controller

Table-2: Comparison of THD

PI Controller	32.77	Fuzzy Controller	27.47
PI+MAF Controller	27.34	Fuzzy+ MAF Controller	4.61
PI+MAF+ Repetitive Controller	0.41	Fuzzy+ MAF+ Repetitive Controller	0.08

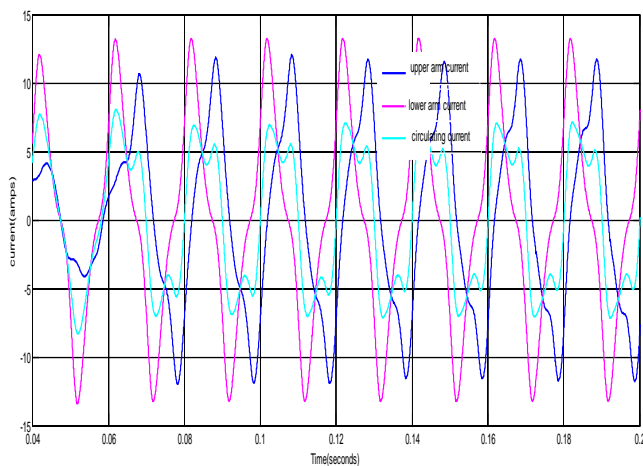


Fig-11: Currents of Fuzzy controller

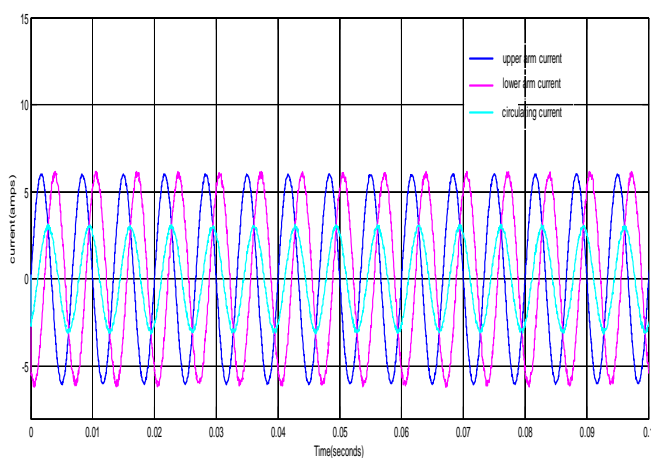


Fig-12: Currents MAF + Fuzzy Controller

6. CONCLUSIONS

The second-order as well as other higher order harmonics in circulating current brings extra power losses and may affect stable operation of the MMC. This paper proposed a “Fuzzy + Repetitive” control scheme to suppress these harmonics in the circulating current. It greatly improves the harmonic suppression of the conventional Fuzzy controller. It is applicable to both single-phase and three-phase systems, and is able to eliminate multiple harmonics with a single controller. Compared with another “Fuzzy + Repetitive” control scheme in which the two controllers are paralleled, the control structure proposed in this paper results in a more friendly plant for the repetitive controller, and poses no design limit on the Fuzzy controller. Simulation and experiments are made on a single-phase MMC inverter. The results show good harmonic suppression of the proposed control scheme, and indicate that the plug-in repetitive controller does not affect the transient performance of the Fuzzy controller. The results also show that after the second-order harmonic in the circulating current is cut out, there is no significant increase of second-order ripple in the SM capacitor voltages.

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