

Analysis of 12-Pulse Rectifier with Active Inter-Phase Reactor with Fuzzy Control Based Circulating Current

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ABSTRACT: This paper analyzes the effect of circulating current with amplitude and phase on the line current of 12 pulse rectifier with the combination of the active inter phase reactor. Therefore the input line current and the total harmonic distortion will be calculated by using fuzzy controller under various amplitude and phases of the circulating current. According to the calculation results the effect of the circulating current will be analyzed. The fuzzy controller is the most suitable for the human decision-making mechanism, providing the operation of an electronic system with decisions of experts. Here fuzzy is compared with the other controller and later we analysis the performance of the system when the amplitude of the circulating current will be little less than equal the half of the load current. Therefore both the phases of lagging and leading operations are minimum, in THD of the input line current. By utilizing the simulation results we can verify the analysis of the system.

INTRODUCTION

Multi-pulse rectifier (MPR) technique is one of the most popular methods of eliminating harmonics in high power rectification [1, 2], and is widely used in aircraft power system, adjustable speed drives, electro-chemical processes and so on [3–5]. Among MPRs, 12-pulse rectifier is preferred due to its simple configuration and easy realization [6, 7]. However, the theoretical total harmonic distortion (THD) of input line current in 12-pulse rectifier is 15.2% under large inductive load, which does not. Installing an active or a passive auxiliary circuit at DC side of 12-pulse rectifier is an effective method of eliminating harmonics in input line current.

When the two bridge rectifiers are connected in parallel, an inter-phase reactor (IPR) is often used to ensure the independent operation of the two bridge rectifiers [13]. Replacing the IPR by a double-tapped IPR is typical passive auxiliary method. The THD of MPR with double-tapped IPR is 7.6% and the MPR operates as 24-pulse under ideal condition [14, 15]. However, conduction losses of double-tapped IPR are an inevitable problem in the passive method. Fig. 1 shows a 12-pulse rectifier with active IPR [8]. Compared with the IPR, a secondary winding is used in the active IPR, which is connected in series with an auxiliary circuit. The auxiliary circuit may produce an additional circulating current i_p superimposed on the output current of the two bridge rectifier, which may affect the input line current of 12-pulse rectifier.

Controlling the input current is of the auxiliary circuit can change the shape, amplitude and phase of the circulating current. The input line current of 12-pulse rectifier can be shaped as sine wave approximately by the active IPR with auxiliary circuit.

The output side of the auxiliary circuit is connected with load, which means the abstracted harmonic power by the auxiliary circuit is fed to the load. Therefore, the 12-pulse rectifier with active IPR has higher energy conversion efficiency than that of the passive method.

CIRCULATING CURRENT IN 12-PULSE RECTIFIER WITH ACTIVE INTER-PHASE REACTOR

Fig. 1 shows the 12-pulse rectifier with active IPR and auxiliary circuit. In Fig. 1, i_p is the circulating current produced by the auxiliary circuit, and I_d is the load current. A delta-connected autotransformer is used to produce two groups of three-phase voltages with 30° phase-shift angle to feed the two diode rectifiers, and a zero sequence blocking transformer (ZSBT) exhibits high impedance to zero-sequence currents and can ensure independent operation of the two rectifiers.

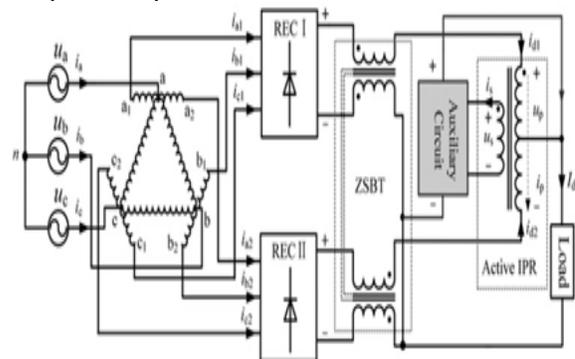


Fig.1. the 12-pulse rectifier with active IPR and auxiliary circuit

when the amplitude, and phase of the circulating current are $0.5I_d$ and 300 Hz for 50 Hz grid, respectively, the THD of input line currents is 1.06% . Fig. 2 shows the relation between the circulating current and the output phase voltage of the autotransformer.

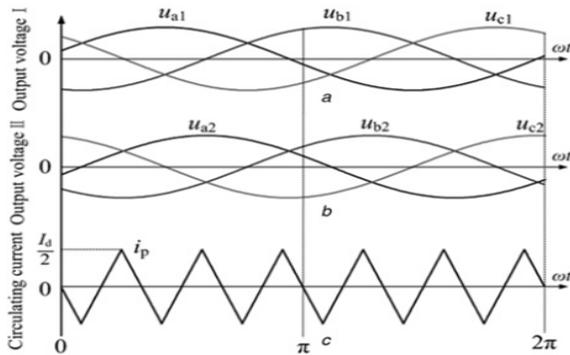


Fig. 2. Relation between the circulating current and the output phase voltage of the autotransformer a Output phase voltage I b Output phase voltage II c Circulating current

From Fig. 2, the Fourier series expansion of the circulating current is calculated as

$$i_p = I_d \sum_{n=1}^{\infty} \frac{4}{n^2 \pi^2} \sin \frac{3n\pi}{2} \sin 6n\omega t \quad (1)$$

Assume the flow direction of the circulating current as shown in Fig. 1, the output currents of the two diode bridge rectifiers are expressed as

$$\begin{cases} i_{d1} = 0.5I_d + i_p \\ i_{d2} = 0.5I_d - i_p \end{cases} \quad (2)$$

Substituting (1) into (2) yields

$$\begin{cases} i_{d1} = I_d \left(0.5 + \sum_{n=1}^{\infty} \frac{4}{n^2 \pi^2} \sin \frac{3n\pi}{2} \sin 6n\omega t \right) \\ i_{d2} = I_d \left(0.5 - \sum_{n=1}^{\infty} \frac{4}{n^2 \pi^2} \sin \frac{3n\pi}{2} \sin 6n\omega t \right) \end{cases} \quad (3)$$

Fig. 3 shows the output currents i_{d1} and i_{d2} . When the circulating current meets (1), the two diode bridge rectifiers operate under critical continuous conduction mode. If the amplitude of the circulating current is greater than the half of the load current, the diode bridge rectifiers operate under discontinuous conduction mode.

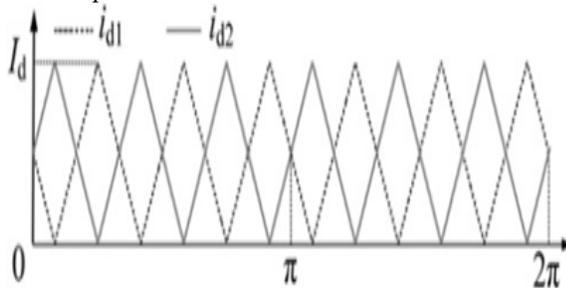


Fig. 3. Output currents of the two diode bridge rectifiers under critical continuous conduction mode

In application, the grid frequency is viewed as a constant value.

EFFECT OF CIRCULATING CURRENT'S AMPLITUDE ON INPUT LINE CURRENT

The three essential factors of the circulating current determine the harmonic elimination ability of the auxiliary circuit. If the circulating current does not meet the three essential factors, not only the harmonics are not

eliminated, but also the system may operate abnormally. Assume the expression of circulating current as

$$i_{px1} = 2\alpha_p I_d \sum_{n=1}^{\infty} \frac{4}{n^2 \pi^2} \sin \frac{3n\pi}{2} \sin 6n\omega t \quad (4)$$

where α_p describes the relation between the amplitude of circulating current and load current, and is defined as the ratio of amplitude of i_{px1} to load current I_d .

When α_p is equal to 0.5, i_{px1} is equal to i_p . From (3), i_{d1} and i_{d2} are less than zero in some intervals if α_p is >0.5 . Hence, α_p should meet

$$0 \leq \alpha_p \leq \frac{1}{2} \quad (5)$$

From Kirchhoff's current law, the input line current of phase a can be expressed as

$$i_{ax1} = 0.5A_1 I_d + A_2 i_{px1} \quad (6)$$

Where

$$\begin{cases} A_1 = S_{a1} + S_{a2} + \frac{2-\sqrt{3}}{\sqrt{3}}(S_{b1} - S_{c1} + S_{c2} - S_{b2}) \\ A_2 = S_{a1} - S_{a2} + \frac{2-\sqrt{3}}{\sqrt{3}}(S_{b1} - S_{c1} + S_{b2} - S_{c2}) \end{cases}$$

and S_{a1} , S_{a2} , S_{b1} , S_{b2} , S_{c1} and S_{c2} are the switching functions of phases a_1 , a_2 , b_1 , b_2 , c_2 and c_2 , respectively.

$$S_{a1} = \frac{i_{d1}}{i_{a1}} \quad (7)$$

where i_{d1} is the output current of rectifier I shown in Fig. 3. Fig. 4 illustrates the switching function S_{a1} .

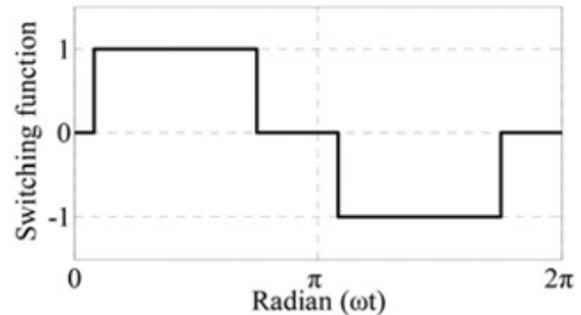


Fig. 4. Switching function S_{a1}

The Fourier series expansion of S_{a1} is calculated as

$$S_{a1} = \sum_{n=1}^{\infty} \frac{4}{(2n-1)} \cos \frac{(2n-1)\pi}{6} \sin \left[(2n-1) \left(\omega t + \frac{\pi}{12} \right) \right] \quad (8)$$

The switching functions of other phases meet

$$\begin{cases} S_{b1} = S_{a1} < -\frac{2\pi}{3} \\ S_{c1} = S_{a1} < +\frac{2\pi}{3} \end{cases} \begin{cases} S_{a2} = S_{a1} < -\frac{\pi}{6} \\ S_{b2} = S_{b1} - \frac{\pi}{6} \\ S_{c2} = S_{c1} < -\frac{\pi}{6} \end{cases} \quad (9)$$

From (6)–(9), the Fourier series expansion of i_{ax1} can be calculated as

$$i_{ax1} = I_d \frac{4\sqrt{6}(1-2\alpha_p)}{\pi(\sqrt{3}+1)} \left[\sin \omega t + \sum_{n=1}^{\infty} \frac{\sin(12n\pm 1)\omega t}{(-1)^n(12n\pm 1)} \right] + \frac{96\sqrt{6}\alpha_p I_d \sin \omega t}{\pi^2(3\sqrt{3}+5)} + \frac{96\sqrt{6}\alpha_p I_d}{\pi^2(3\sqrt{3}+5)} \sum_{n=1}^{\infty} (-1)^{(24n-1\pm 1)/2} \times \left[\frac{\sin(24n\pm 1)\omega t}{(24n\pm 1)^2} - \frac{\sin(24n-12\pm 11)\omega t}{(24n-12\pm 1)^2} \right] \quad (10)$$

To obtain the minimal THD, we may take the derivative of THD_{ax1} to α_p in (11) and set the derivative to zero.

Hence, for the minimised THD of input line current, the optimal α_p should be

$$\alpha_p = \frac{((24(3\sqrt{3}-5))x+(\sqrt{3}-1)z)}{\pi((24(3\sqrt{3}-5))(2x+z)+(\sqrt{3}-1)(2z+y))} \cong 0.4915 \quad (11)$$

where x , y and z meet

$$\begin{aligned} x &= \sum_{n=1}^{\infty} \left[\frac{(\sqrt{3}-1)}{(12n\pm 1)} \right]^2 \\ y &= \sum_{n=1}^{\infty} \left[\frac{24(3\sqrt{3}-5)}{\pi(12n\pm 1)2} \right]^2 \\ z &= \sum_{n=1}^{\infty} \frac{48 \left[\frac{1}{(24n-12\pm 1)^3} - \frac{1}{(24n\pm 1)^3} \right]}{(-1)^{(24n-11\pm 1)}(7+4\sqrt{3})\pi} \end{aligned} \quad (12)$$

In addition, from expression (11), we can draw the relation curve between the THD of input line current and α_p , as shown in Fig. 5.

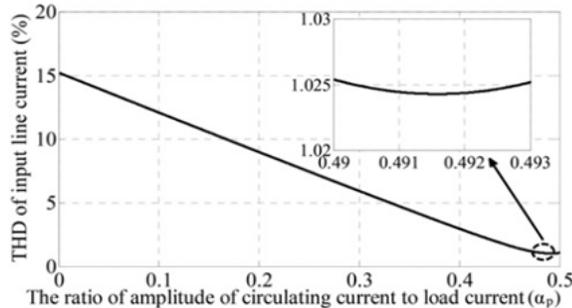


Fig. 5. Relation between THD of input line current and α_p

- (i) When α_p is equal to zero, the THD is about 15.2%, and the MPR operates as 12-pulse rectifier.
- (ii) During the interval $[0, 0.4915]$, the THD decreases as α_p increases. When α_p is about 0.4915, the THD is minimal. The minimum of THD is about 1.024%.
- (iii) During the interval $[0.4915, 0.5]$, the THD increases as α_p increases. When α_p is equal to 0.5, the THD is about 1.06%.
- (iv) Almost all previous results about the MPR with active IPR suggested that the amplitude of circulating current should be half of load current.

Fig. 6 shows the simulation results of input line currents' spectrums under different α_p . It is obvious that the input line current only contains a small quantity of characteristics harmonics when the active auxiliary circuit is utilized.

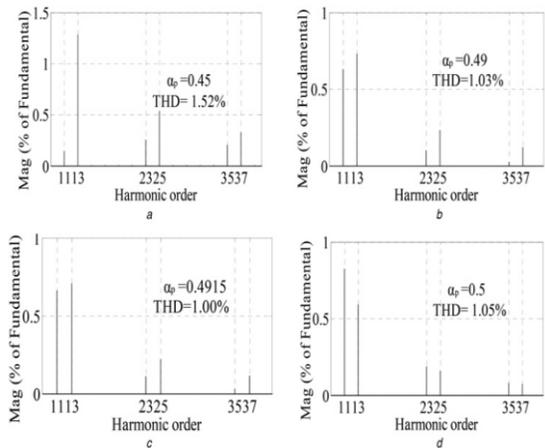


Fig. 6. Input line current and its spectrum under different α_p a $\alpha_p = 0.45$ b $\alpha_p = 0.49$ c $\alpha_p = 0.4915$ d $\alpha_p = 0.5$

During the theoretical analysis, the leakage inductance of the autotransformer, the inductances of ZSBT and active IPR, are all ignored. Therefore, there is difference between the simulation results and theoretical results. Figs. 7a and b show the output currents of the two diode bridge rectifiers

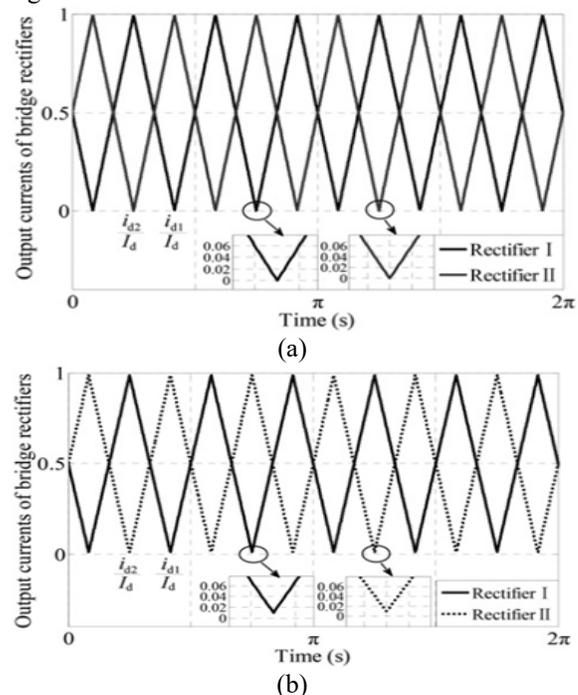


Fig. 7. Output currents of diode bridge rectifier I and diode bridge rectifier II under different α_p a $\alpha_p = 0.5$ b $\alpha_p = 0.4915$

when $\alpha_p = 0.5$ and $\alpha_p = 0.4915$, respectively. When $\alpha_p = 0.5$, the two diode bridge rectifiers operate under critical continuous current mode. When $\alpha_p = 0.4915$, the two diode bridge rectifiers operate under continuous current mode.

EFFECT OF CIRCULATING CURRENT'S PHASE ON INPUT LINE CURRENT

When analyzing the effect of circulating current's phase on input line current, assume the expression of circulating current as

$$i_{px2} = I_d \sum_{n=1}^{\infty} \frac{4}{n^2 \pi^2} \sin \frac{3n\pi}{2} \sin 6n(\omega t + \beta) \quad (13)$$

where β is the phase of i_{px2} . When β is less than zero, i_{px2} lags the synchronous signal by β electrical degree. When β is greater than zero, i_{px2} leads the synchronous signal by β electrical degree. The output line voltage of phase-shift transformer is always sampled to be the synchronous signal. When β is equal to zero, i_{px2} is equal to i_p . Generally, $-\pi/12 \leq \beta \leq \pi/12$. Similarly, the input line current of phase a can be expressed as

$$i_{ax2} = 0.5A_1 I_d + A_2 i_{px2} \quad (14)$$

Fig. 8 shows the relation between THD and phase of circulating current. Fig. 9 shows the input line currents and their spectrums under different phases of circulating current. Therefore, both the circulating current lagging and leading the synchronous signal lead to the increase of harmonic amount in input line current.

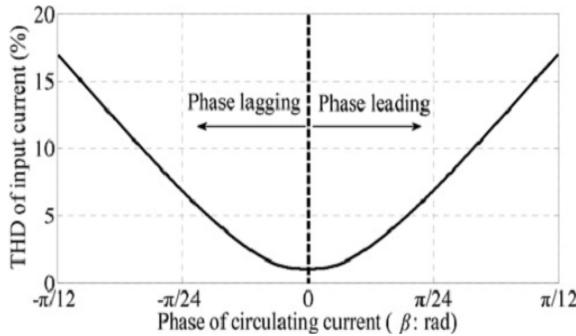


Fig. 8. Relation between THD and phase of circulating current

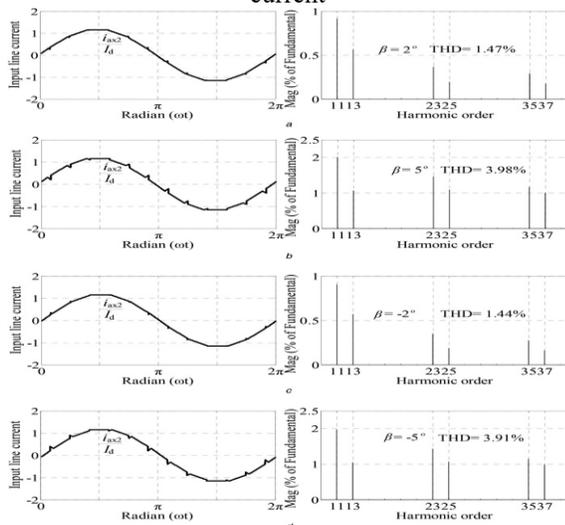


Fig. 9. Input line currents and their spectrums under different phases of the circulating current

FUZZY LOGIC CONTROLLER

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC.

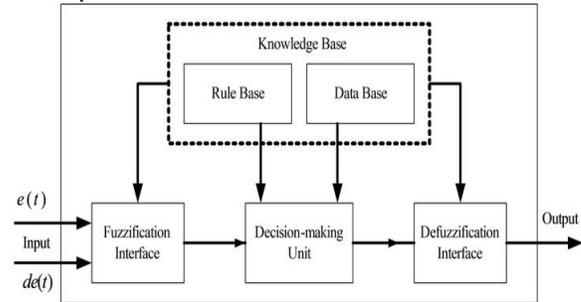


Fig. 10. Fuzzy logic controller

The FLC comprises of three parts: fuzzification, interference engine and defuzzification. The FC is characterized as i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's, 'min' operator. v. Defuzzification using the height method.

TABLE III: Fuzzy Rules

Change in error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

Fuzzification: Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The value of input error and change in error are normalized by an input scaling factor. In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular $E(k)$ input there is only one dominant fuzzy subset. The input error for the FLC is given as

$$E(k) = \frac{P_{ph}(k) - P_{ph}(k-1)}{V_{ph}(k) - V_{ph}(k-1)} \quad (15)$$

$$CE(k) = E(k) - E(k-1) \quad (16)$$

Inference Method: Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership function of each rule is given by the minimum operator and maximum operator.

Defuzzification: As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height“ method is used and the FLC output modifies the control output. Further, the output of FLC controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. The set of FC rules are derived from

$$u = -[\alpha E + (1-\alpha)*C] \quad (17)$$

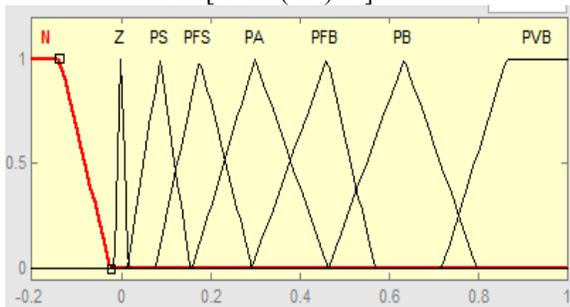


Fig 11. input error as membership functions

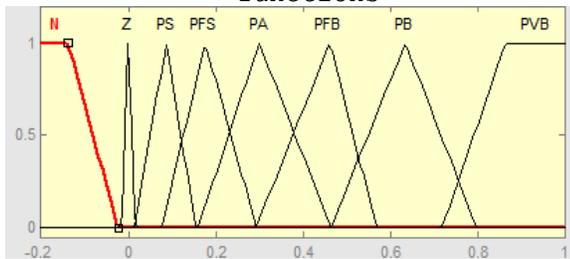


Fig 12. change as error membership functions

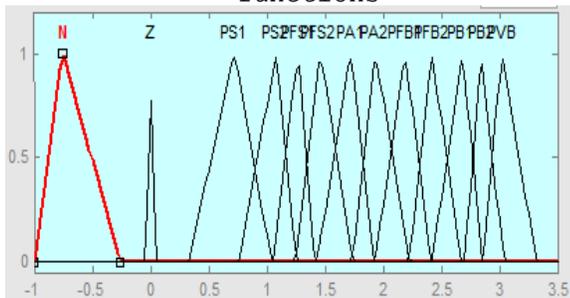


Fig 13. output variable Membership functions

Where α is self-adjustable factor which can regulate the whole operation. E is the error of the system, C is the change in error and u is the control variable

SIMULATION RESULTS

There are several topologies to realise the function of the auxiliary circuit. In this paper, we propose a two-stage auxiliary circuit which is the combination of PWM converter and boost converter, as shown in Fig. 10.

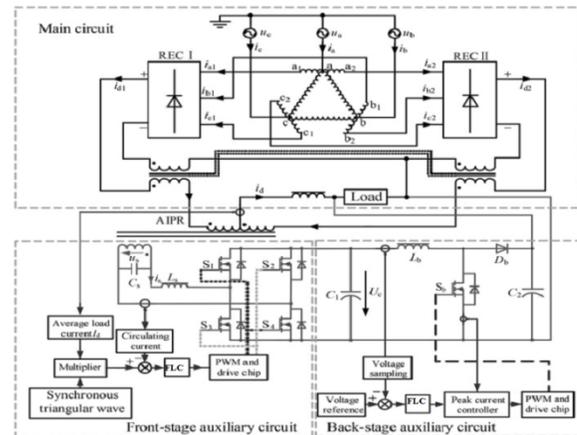


Fig. 14. Control block diagram of the proposed MPR with two-stage auxiliary circuit

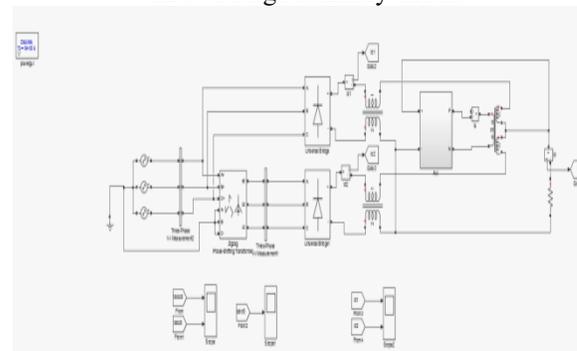


Fig. 15. Overview of the simulation block diagram

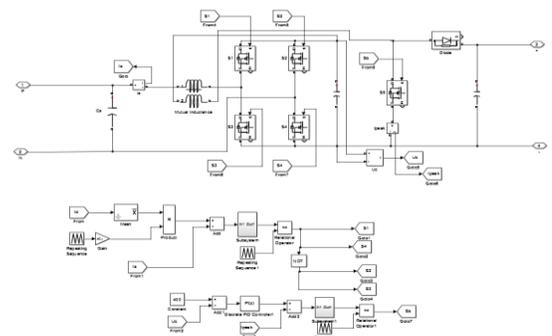


Fig. 16. Control block diagram of simulation

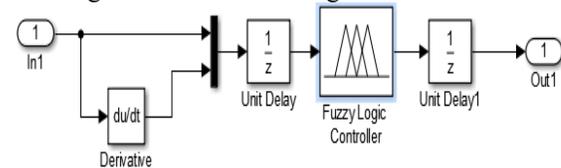


Fig. 17. Fuzzy logic controller in simulation

The front stage is a PWM rectifier, which is used to control the applicable circulating current precisely. The back stage is a DC– DC converter, which is used to feed the power absorbed by the front stage to system load and regulates output voltage of the front stage as the same as

load voltage. Table 1 shows the parameters of the MPR and auxiliary circuit for setup.

Table 1

Parameters of the MPR and auxiliary circuit

parameter	Value
Load voltage U_d	242V
Load current I_d	6A
Turn ratio of active IPR	1:1
Front stage inductor L_a	1mH
Front stage switching frequency	50KHZ
Back stage inductor L_b	350 μ H
Back stage switching frequency	50KHZ

When β is equal to 0, Fig. 12 shows the spectrum of input line current under different amplitudes of circulating current. When αp is about 0.4915, the THD is minimal.

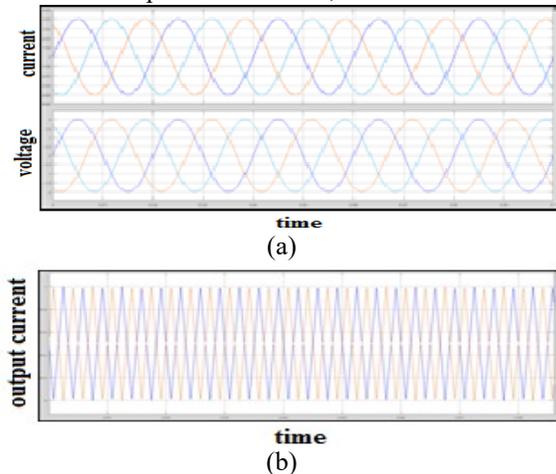


Fig. 18. a) Input line current and source voltage b) Output currents of diode bridge rectifier I and diode bridge rectifier II under different αp

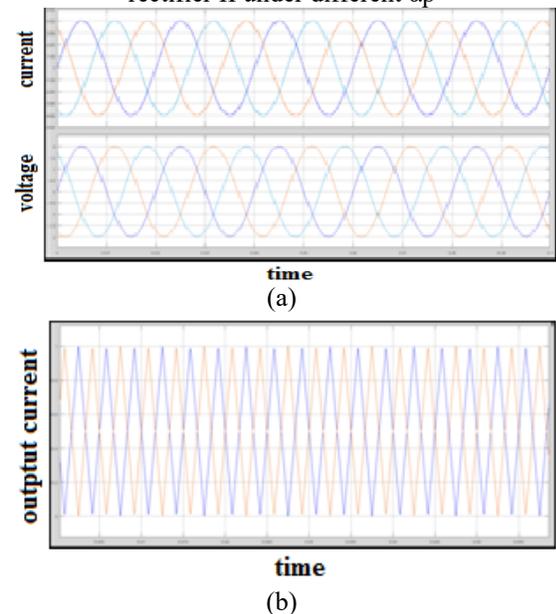


Fig. 19. a) Input line current and source voltage b) Output currents of diode bridge rectifier I and diode bridge rectifier II under different αp

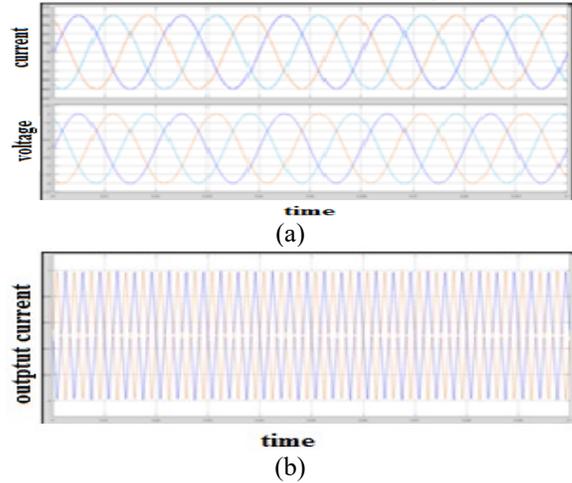


Fig. 20. a) Input line current and source voltage b) Output currents of diode bridge rectifier I and diode bridge rectifier II under different αp

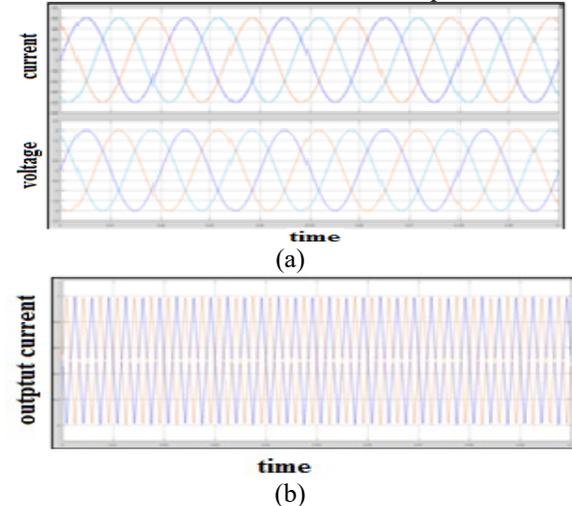
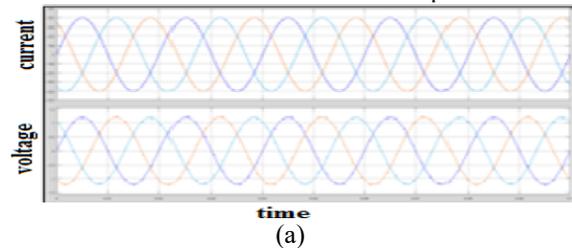


Fig. 21. a) Input line current and source voltage b) Output currents of diode bridge rectifier I and diode bridge rectifier II under different αp



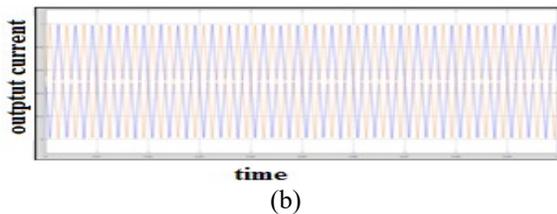


Fig.22. a) Input line current and source voltage b) Output currents of diode bridge rectifier I and diode bridge rectifier II under different α_p

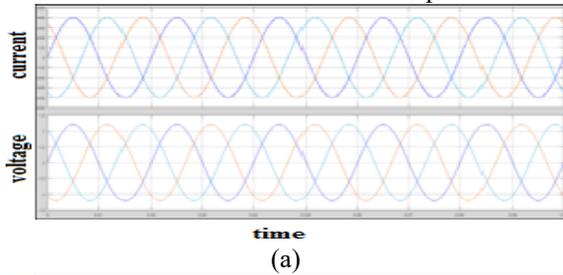


Fig.23. a) Input line current and source voltage b) Output currents of diode bridge rectifier I and diode bridge rectifier II under different α_p

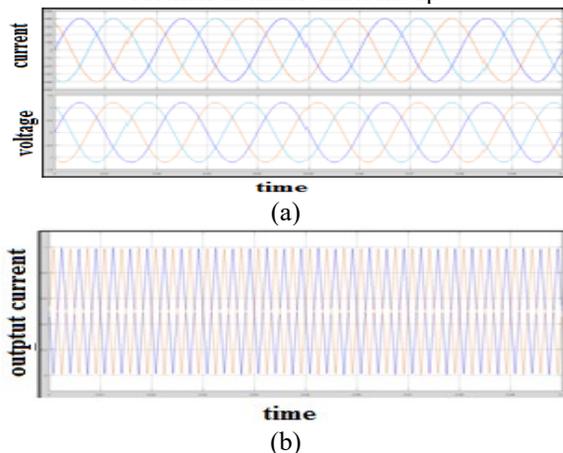


Fig.24. a) Input line current and source voltage b) Output currents of diode bridge rectifier I and diode bridge rectifier II under different α_p

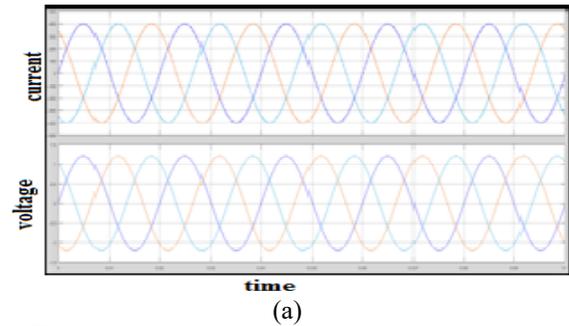


Fig.25. a) Input line current and source voltage b) Output currents of diode bridge rectifier I and diode bridge rectifier II under different α_p

In general, the THD variation trend in the results is coincident with that of theoretical analysis. When α_p is equal to 0.4915 and the circulating current leads the synchronous signal by about 3.6 electrical degrees, Fig. 13 shows the spectrum of input line current. Therefore, the phase leading of circulating current leads to increase in THD of input line current. When the circulating current lags the synchronous signal, we also obtain the similar results.

CONCLUSION

According to the paper we are implementing the effect of the circulating current which is based upon the performance of the MPR with the active IPR. In the precious section which is explained that the amplitude of the circulating current will be usually equal to the half of the load current then the THD of the input line current will be minimum. Therefore in this paper we are developing the fuzzy controller for the better performance. Here the fuzzy controller is the most suitable for the human decision-making mechanism, providing the operation of an electronic system with decisions of experts. After fuzzy controller the THD of the input current will be minimum when compare the amplitude which is slightly less than the half of the load current. By using the simulation results we can verify both the lagging and leading circulating current of the synchronous signals, which will leading to the minimize the harmonics in the input line current. Finally in this paper we can extend the other MPRs which are auxiliary circuit of the active harmonics reduction at the DC side.

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