A combined control method of supply harmonic current and source harmonic voltage for series hybrid active power filter

Chau Minh Thuyen, Hoai Thuong Nguyen, Phan Thi Bich Thao
Faculty of Electrical Engineering Technology, Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam

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ABSTRACT

The series hybrid active power filter (SHAPF) is known as a very effective harmonic filtering model in power systems. Typically, SHAPF is controlled by a control method based either on the harmonic voltage of the load or on the supply harmonic current. However, the above two methods have the disadvantage of requiring the control coefficient much be large enough, which easily causes system instability. Therefore, this paper presents a new control method for SHAPF. It is a combined control method of the supply harmonic current and the source harmonic voltage. The advantage of the proposed method is the ability to reduce the total harmonic distortion of the supply current and voltage applied to the load with a control coefficient that is not too large. A fuzzy-proportional integral controller is designed for the proposed control method to reduce the compensation error in steady state under variable load conditions. Mathematical models and simulation results have demonstrated the effectiveness of the proposed method in reducing the total harmonic distortion of the supply current, voltage applied to the load and minimize the compensation error at steady state.

Corresponding Author:

Chau Minh Thuyen
Faculty of Electrical Engineering Technology, Industrial University of Ho Chi Minh City
12 Nguyen Van Bao Road, Go Vap District, Ho Chi Minh City 700000, Vietnam
Email: chauminhthuyen@iuh.edu.vn

1. INTRODUCTION

Today, due to the characteristics of manufacturing industries, electrical equipment is required to operate in many different modes, with most loads being controlled by power electronic devices. As a result, the loads generate current harmonic components, which distort and shift phase compared to the source voltage. From there, a shunt active power filter (Shunt APF) was born to filter current harmonic components [1]. However, harmonic components are not only generated by power electronic loads, they are also generated by sources. The harmonics generated by the source will impose a harmonic voltage on the load, which is very dangerous. Therefore, the series active power filter (series APF) was born as a necessity [2]–[4]. However, the series APF is only capable of filtering harmonic components from the source, but it is not capable of filtering harmonic components generated from the load. For this reason, series hybrid active power filter (SHAPF) was born. It is a combination of the series APF and passive power filters (PPFs) [5], [6]. PPFs have the function of filtering load current harmonics while the series APF filters voltage harmonics emitted from the source. Therefore, research on SHAPF has practical significance, it contributes to improve the power quality of the power system.

Published research on SHAPF focusing on the design of PPFs for SHAPF is carried out in [7]–[9]. Research on control strategies for SHAPF based on the load harmonic voltage and supply harmonic current is cited in [10]–[13]. Many studies on control for SHAPF have also been carried out such as dead-beat control

[14], sliding control [15], fuzzy sliding control [16], fuzzy-neural control [17], [18], neural network control [19], [20]. To increase the adaptability of the controller when the load changes and reduce the compensation error at steady state, some studies have hybridized controllers together such as proportional integral (PI)-neural controller, fuzzy-neural controller [21]–[23]. Stability assessment of the control algorithm using Laplace transform in the frequency domain is given in [24]. In [25]–[27] use a neural controller to online adjust the parameters of the fuzzy controller's membership function to reduce output error every time the load changes. However, this analysis is only performed for the control strategy based on the harmonic voltage on the load. In summary, previous studies on SHAPF only used control methods based on the supply harmonic current or harmonic voltage on the load. With the control method based on the supply harmonic current, the control coefficient must be large enough, and the voltage applied to the load contains the harmonic component of the source voltage. With the control method based on the harmonic voltage on the load, the control coefficient must be large enough to eliminate the harmonic component of the voltage on the load but cannot eliminate the harmonic component in the supply current. Thus, the disadvantage of the above two methods is that the control coefficient must be large enough, which can easily cause system instability.

From the above analysis, this article proposes a new control method for SHAPF. It is a control method based on the supply harmonic current and the source harmonic voltage. The advantage of this method is that it can reduce the harmonic content in the supply current and the harmonic voltage applied to the load with a control coefficient not too large. The harmonic voltage applied to the load will not be affected by the harmonic component of the source voltage. This can increase the stability of the system and improve the harmonic filtering efficiency of SHAPF. However, the actual load will vary. Therefore, to respond well to load changes, a fuzzy-proportional integral (Fuzzy-PI) controller is designed for SHAPF with the proposed control method.

The structure of the article includes five sections. An overview of SHAPF is presented in section 1. Structure and control of SHAPF are introduced in section 2. Fuzzy-PI controller design is given in section 3. Simulation results and discussion are performed in section 4. Finally, the research results are summarized in section 5.

2. STRUCTURE AND CONTROL OF SHAPF

The structure of a SHAPF is shown in Figure 1. SHAPF consists of two main parts: PPFs and the active part (inverter, output filter and transformer). PPFs are designed to filter harmonic components emitted by the load, while the active part is designed to compensate for the remainder. The active part can be viewed as an impedance. It has a value of zero at the fundamental frequency and equal to infinity at the harmonic frequency. It prevents harmonic components from the source into the load.

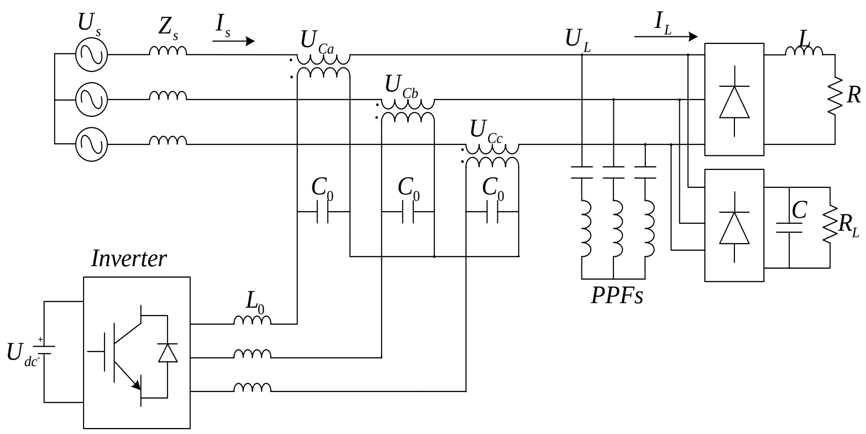

Figure 1. The structure of a SHAPF

In which: U_s and Z_s are the voltage and impedance of the source. The nonlinear load is modelled by two three-phase uncontrolled bridge rectifiers with loads R, L, C, and R_L. PPFs are passive power filters designed to suppress the high harmonics of the nonlinear load. U_{Ca}, U_{Cb}, and U_{Cc} are the compensation voltages from the inverter. L_0C_0 is output filter of the inverter and U_{dc} is power supply voltage for the inverter.

SHAPF consists of two main parts: PPFs and the active part (inverter, output filter and transformer). PPFs are designed to filter harmonic components emitted by the load, while the active part is designed to compensate for the remainder. The active part can be viewed as an impedance. It has a value of zero at the fundamental frequency and equal to infinity at the harmonic frequency. It prevents harmonic components from the source into the load. The single-phase equivalent circuit in the harmonic domain of SHAPF is shown in Figure 2. To reduce harmonic components from the nonlinear load and source, the compensation voltage from the active part of APF can be based on the supply harmonic current or the load harmonic voltage. Therefore, U_c can be considered as a dependent voltage source. From Figure 2, control methods for SHAPF can be listed as follows:

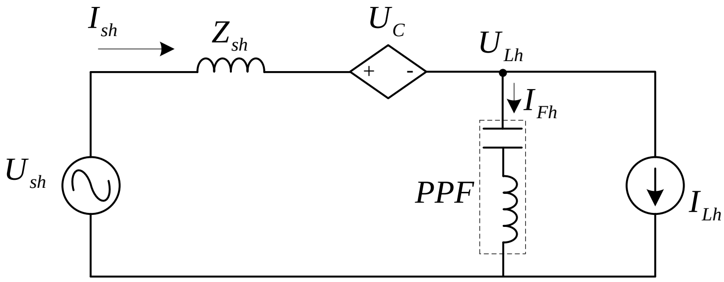

Figure 2. The single-phase equivalent circuit in the harmonic domain of SHAPF

a. Control method $U_C = KI_{sh}$ [11]

From Figure 2, I_{sh} and U_{Lh} can be calculated as (1) and (2).

$$I_{sh} = \frac{U_{sh}+Z_{PPFh}I_{Lh}}{Z_{sh}+K+Z_{PPFh}} \tag{1}$$

$$U_{Lh} = U_{sh} - (K + Z_{sh})I_{sh} \tag{2}$$

From (1) and (2) we can see that: if K is large enough, the supply harmonic current I_{sh} will decrease to zero. However, the voltage applied to the load will have harmonic components of sources U_{sh} and $U_{sh} - (K + Z_{sh})I_{sh}$ will not decrease but increase. On the other hand, if K is too large, it can easily cause system instability.

b. Control method $U_C = KU_{Lh}$ [11]

From Figure 2, I_{sh} and U_{Lh} can be calculated as (3) and (4).

$$I_{sh} = \frac{U_{sh}+(1+K)Z_{PPFh}I_{Lh}}{Z_{sh}+(1+K)Z_{PPFh}} \tag{3}$$

$$U_{Lh} = \frac{U_{sh}-Z_{sh}I_{sh}}{1+K} \tag{4}$$

From (3) and (4) we can see that: if K is large enough, U_{Lh} will decrease to zero and prevent harmonic components into load from the source. However, this method cannot reduce harmonic components in the supply current. In short, this method is only used to reduce harmonic components of the source voltage applied to the load but is not capable of reducing the harmonic content of the supply current.

c. Proposed control method

From the above two methods, this paper proposes a new control method. It is a combination of the supply harmonic current and the source harmonic voltage $U_C = K_1 I_{sh} + K_2 U_{sh}$. From Figure 2, I_{sh} and U_{Lh} can be calculated as (5) and (6):

$$I_{sh} = \frac{(1-K_2)U_{sh}+Z_{PPFh}I_{Lh}}{Z_{sh}+K_1+Z_{PPFh}} \tag{5}$$

$$U_{Lh} = (1 - K_2)U_{sh} - (K_1 + Z_{sh})I_{sh} \tag{6}$$

From (5) and (6) we can see that: if we control them so that $K_2 = 1$ and K_1 are not too large (they do not need to be too large as in method $U_C = KI_{sh}$), we can reduce I_{sh} and U_{Lh}. In particular, this method has the ability to eliminate the influence of source harmonic voltage U_{sh} on I_{sh} and U_{Lh}, and it can avoid instability due to too large K control coefficient as in method $U_C = KI_{sh}$. K, K_1 and K_2 are controllable coefficients.

The reference signals I_{sh}, U_{Lh} and U_{sh} are determined from I_s, U_L and $U_s$using the i_p-i_q method [7] as shown in Figure 3. The components I_{sa}, I_{sb}, I_{sc} are converted from the *abc* rotation coordinate system to the stationary coordinate system *dq0*, then pass through a low-pass filter to block the high-order harmonic components and pass the fundamental components. Finally, the *dq0→abc* inverse transform is used to obtain the fundamental frequency components I_{sfa}, I_{sfb}, and I_{sfc}. The reference harmonic components are obtained:

$$\begin{cases} I_{sha} = I_{sa} - I_{sfa} \\ I_{shb} = I_{sb} - I_{sfb} \\ I_{shc} = I_{sc} - I_{sfc} \end{cases} \tag{7}$$

The transformation between coordinates is shown through formulas (8) and (9).

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\,\theta\ cos(\theta - 2\pi/3)\, cos(\theta + 2\pi/3) \\ sin\,\theta\ sin(\theta - 2\pi/3)\, sin(\theta + 2\pi/3) \\ 1/21/21/2 \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} i_{sfa} \\ i_{sfb} \\ i_{sfc} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\,\theta\ sin\,\theta\ 1 \\ cos(\theta - 2\pi/3)\, sin(\theta - 2\pi/3) 1 \\ cos(\theta + 2\pi/3)\, sin(\theta + 2\pi/3) 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{9}$$

θ (rad) is the angle between the a and q axes or the angle between the a and d axes. Components U_{Lh} and U_{sh} are also determined similarly.

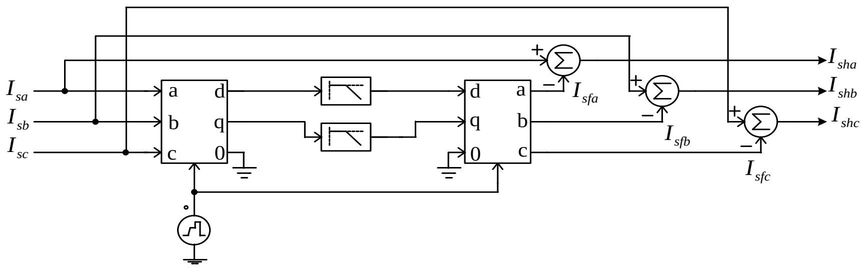

Figure 3. Determination of reference harmonic signal using the i_p-i_q method

3. DESIGN OF FUZZY-PI CONTROLLER FOR SHAPF

Because the load changes during control, the K_P and K_I parameters of the PI controller need to be continuously adjusted according to the load change. This paper designs a fuzzy regulator to adjust the parameters K_P and K_I of the PI controller. The control diagram for SHAPF using the Fuzzy-PI controller is shown in Figure 4.

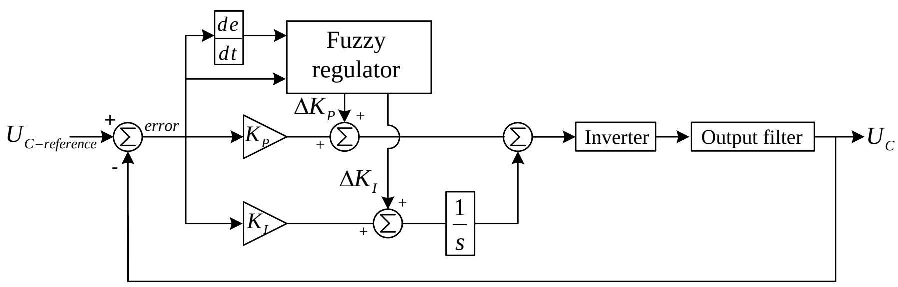

Figure 4. Control diagram of SHAPF using Fuzzy-PI controller

The initial K_P and K_I parameters are determined according to the Ziegler-Nichols method. The outputs of the fuzzy regulator are ΔK_P and ΔK_I. They are adjusted based on the error between the reference signal and the real signal and the change of this error.

$$\begin{cases} K_P^{new} = K_P + \Delta K_P \\ K_I^{new} = K_I + \Delta K_I \end{cases} \quad (10)$$

The inputs and outputs of the fuzzy regulator are represented as seven membership functions: negative big (NB), negative medium (NM), negative small (NS), zero (Z0), positive small (PS), positive medium (PM) and positive big (PB) as shown in Figures 5(a) and 5(b).

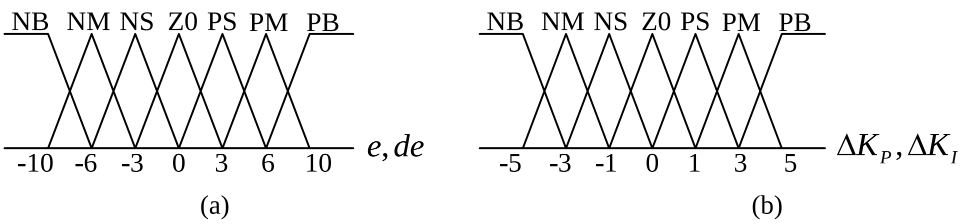

Figure 5. Membership functions of the fuzzy variable: (a) membership functions of the e, de and (b) membership functions of the ΔK_P and ΔK_I

Fuzzy rules are the core of the fuzzy adjustor and it is built based on the following principles:
- If $|e|$ is large, a large ΔK_P value is needed; If $|e|$ is small, a small ΔK_P value is needed
- If $|e|$ is approximately zero then the current K_I value is appropriate
- If $e.de > 0$ then a large ΔK_P value is needed; If $e.de < 0$ then a small ΔK_Pvalue is needed
- If $|e|$ and $|de|$are large, a large value of $\Delta K_P$and $\Delta K_I = 0$ is needed

The fuzzy rules are shown in Table 1. The inference method uses the MAX-MIN method. The centroid method is used for defuzzification.

Table 1. Fuzzy rules of $\Delta K_P$and ΔK_I

$\Delta K_P/\Delta K_I$		de						
		NB	NM	NS	ZO	PS	PM	PB
	NB	PB/ZO	PB/ZO	PM/NB	PM/NM	PS/NM	PS/ZO	ZO/ZO
	NM	PM/ZO	PM/ZO	PM/NM	PS/NM	PS/NS	ZO/ZO	ZO/ZO
	NS	PM/ZO	PM/ZO	PS/NS	PS/NS	ZO/ZO	NS/ZO	NM/ZO
e	ZO	PM/ZO	PS/ZO	ZO/NS	ZO/NM	NS/PS	NM/ZO	NM/ZO
	PS	PS/ZO	PS/ZO	ZO/ZO	NS/PS	NS/PS	NM/ZO	NB/ZO
	PM	ZO/ZO	ZO/ZO	NS/PS	NM/PM	NM/PM	NB/ZO	NB/ZO
	PB	ZO/ZO	NS/ZO	NB/NS	NM/PM	NM/PB	NB/ZO	NB/ZO

4. SIMULATION RESULTS AND DISCUSSION

To demonstrate the effectiveness of the proposed control method. The simulation results are performed on a SHAPF system as shown in Figure 1. The parameters of a SHAPF system are given in Table 2.

Table 2. Parameters of a SHAPF system

Parameters	Value
Source	($U_{s\text{-}rms}$=220 V; f=50 Hz) + (U_{peak}=25 V; f=1000 Hz)
Source impedance	Rs = 0.1 Ω; Ls = 0.2 mH
Load	R = 20 Ω; L = 30 mH; C = 500 μF; R_L=50 Ω
Transformer ratio	1:1
PPF: Consists of branches L and C connected in parallel	L =16.9 mH; C = 600 μF
Output filter	L_0 = 2 mH; C_0 = 60 μF
Inverter DC voltage	300 V

The waveforms that need to be considered include: source voltage U_{sa}, load current I_{La}, supply current I_{sa}, voltage applied to load U_{La} and compensation error of phase a. At *t*=0.3 s the load changes in the direction of increasing total harmonic distortion (THD).

– With control method $U_c = KI_{sh}$ using a PI controller. Control coefficient *K*=50. The simulation results of the waveforms with control method $U_c = KI_{sh}$ are shown in Figure 6.
– With control method $U_c = KU_{Lh}$, PI controller is used. Control coefficient *K*=50. The simulation results of the waveforms with control method $U_c = KU_{Lh}$ are shown in Figure 7.
– With control method $U_c = K_1I_{sh} + K_2U_{sh}$ using a PI controller. Control coefficient *K*=20. The simulation results of the waveforms with control method $U_c = K_1I_{sh} + K_2U_{sh}$ using a PI controller are shown in Figure 8.
– With control method $U_c = K_1I_{sh} + K_2U_{sh}$ using Fuzzy-PI controller. Control coefficient *K*=20. The simulation results of the waveforms with control method $U_c = K_1I_{sh} + K_2U_{sh}$ using a Fuzzy-PI controller are shown in Figure 9.

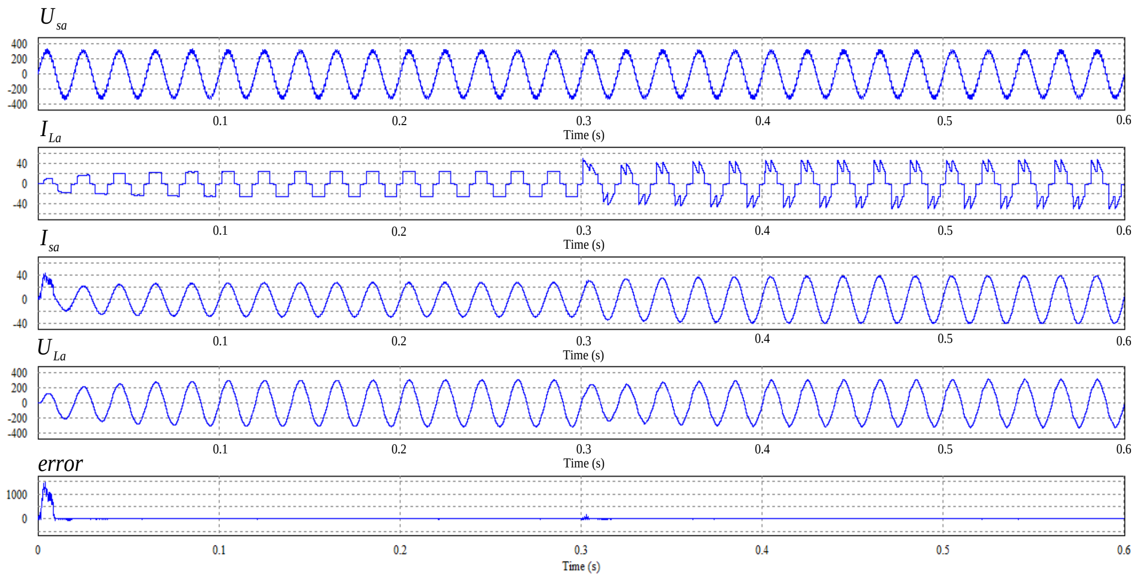

Figure 6. Simulation results of the waveforms with control method $U_c = KI_{sh}$

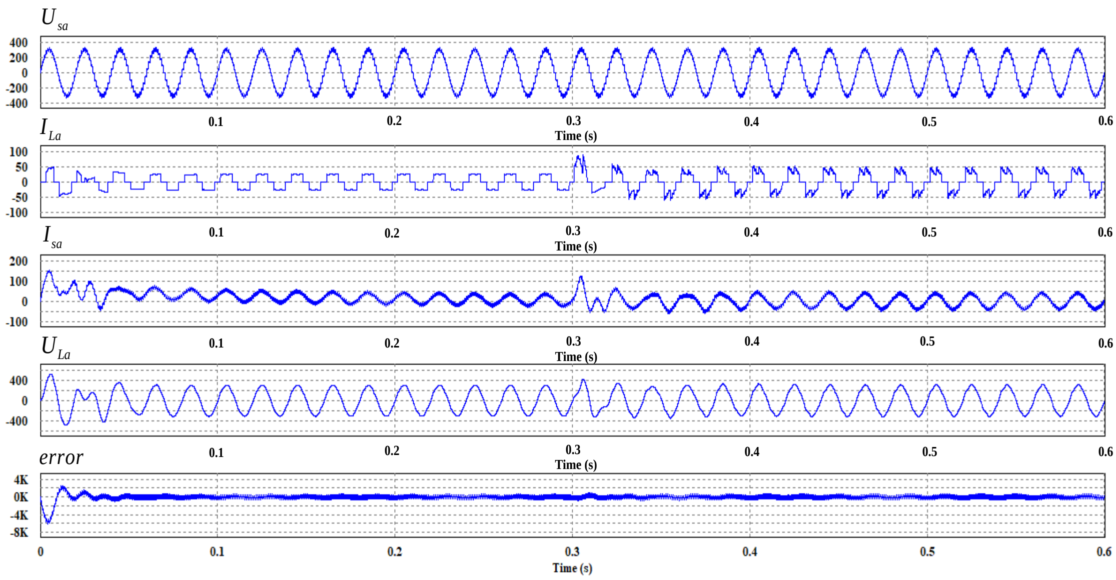

Figure 7. Simulation results of the waveforms with control method $U_c = KU_{Lh}$

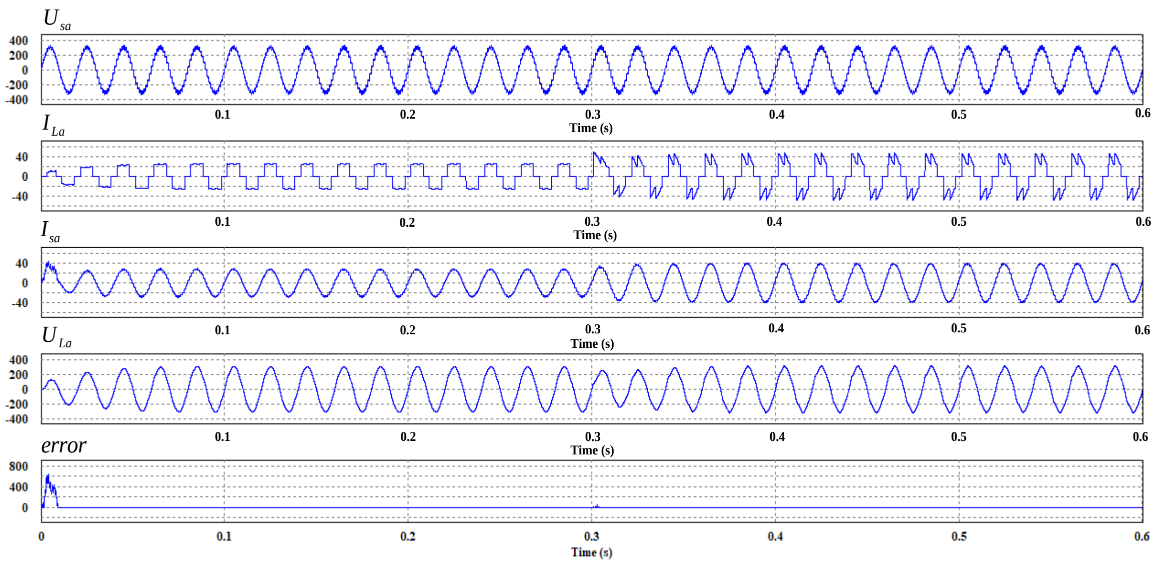

Figure 8. Simulation results of the waveforms with control method $U_c = K_1 I_{sh} + K_2 U_{sh}$ using a PI controller

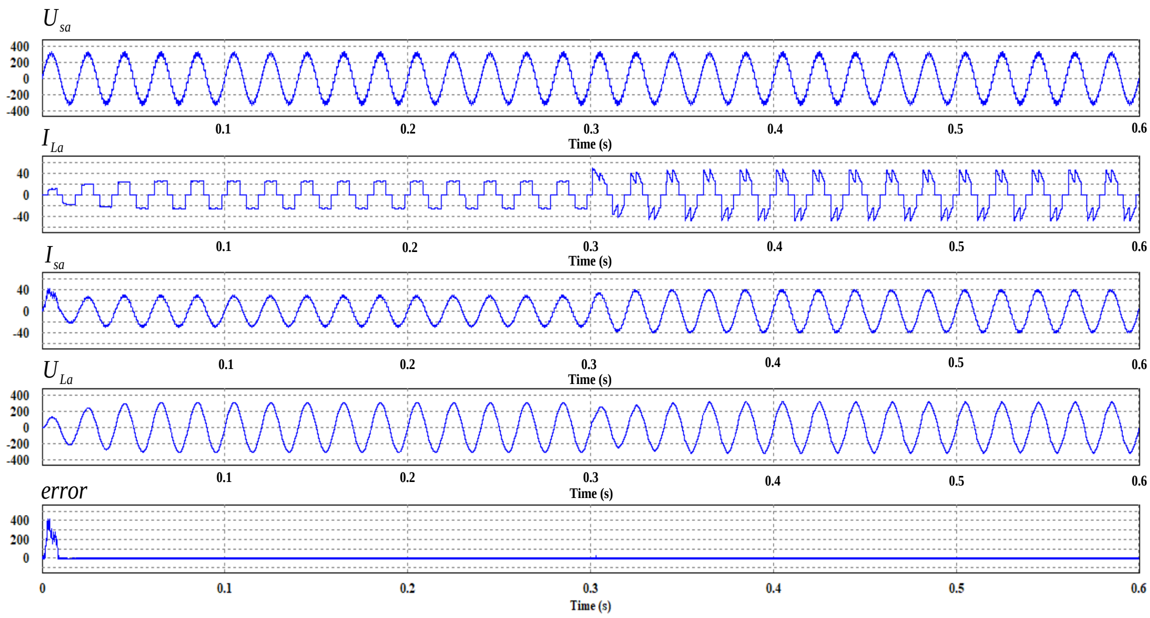

Figure 9. Simulation results of the waveforms with control method $U_c = K_1 I_{sh} + K_2 U_{sh}$ using a Fuzzy-PI controller

The summary table of simulation results with control methods is shown in Table 3. From the results in Table 3, we can see that the control method $U_c = K I_{sh}$ with K=50 is capable of reducing THD of the supply current and voltage applied to load. However, it is only effective when the control coefficient K is large enough. Control method $U_c = K U_{Lh}$ with K=50 is only capable of reducing THD of the voltage applied to the load. However, it is only effective when the control coefficient K is large enough. Control method $U_c = K_1 I_{sh} + K_2 U_{sh}$ using a PI controller is capable of reducing THD of the supply current and the voltage applied to the load with a control coefficient K is not too large (K=20), and especially it has the ability to eliminate the influence of the source voltage harmonic on the voltage applied to the load. To further improve the efficiency of the proposed control method when the load changes suddenly, a fuzzy regulator is used to adjust the K_P, K_I parameters of the PI controller. The simulation results in Table 3 show that the proposed control method using a Fuzzy-PI controller is more effective than using a PI controller in reducing THD and compensation error at steady state.

Table 3. Summary of simulation results with control methods

Control methods	THD% U_{sa}	I_{La}	I_{sa}	U_{La}	*error*	THD% U_{sa}	I_{La}	I_{sa}	U_{La}	*error*
	0.0s÷0.3s					0.3s÷0.6s				
$U_c = KI_{sh}$	8.05	31	3.2	2.33	±15	8.05	38	3.5	4.2	±15
$U_c = KU_{Lh}$	8.05	31	23.5	2.19	very large	8.05	38	52.4	4.9	very large
$U_c = K_1I_{sh} + K_2U_{sh}$ using a PI controller	8.05	31	3.04	2.43	±10	8.05	38	3.24	4.2	±10
$U_c = K_1I_{sh} + K_2U_{sh}$ using a Fuzzy-PI controller	8.05	31	1.74	2.13	±5	8.05	38	1.98	3.81	±5

5. CONCLUSION

This paper has performed a control analysis for SHAPF and proposed a new control method for SHAPF, which is a combination of supply harmonic current and source harmonic voltage. The proposed method is capable of reducing the harmonic contents of the supply current and the harmonic voltage applied to the load with a control coefficient is not too large. This contributes to improving the stability of the system. A Fuzzy-PI controller is designed to improve the efficiency of the traditional PI controller in variable load situations. The simulation results have demonstrated the effectiveness of the proposed method compared to the control method only based on the supply harmonic current or harmonic voltage of the load.

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BIOGRAPHIES OF AUTHORS

Chau Minh Thuyen was born in Binh Dinh, Vietnam, on June 6, 1977. He received his B.S. and M.S. from the Da Nang University of Technology, Da Nang, Vietnam, and the University of Technical Education Ho Chi Minh City, Ho Chi Minh City, Vietnam, in 2001 and 2005, respectively, and Ph.D. from Hunan University, China, in 2012. Since 2004, he has been a lecturer at Industrial University of Ho Chí Minh City, Vietnam. His current research includes power electronics, electric power savings, smart grid, and active power filters. He can be contacted at email: chauminhthuyen@iuh.edu.vn.

Hoai Thuong Nguyen received the B. Sc and M.Sc. degrees in Volgograd State Technical University (Russia) in 2010 and 2012, respectively. In 2016, he received PhD degree in Voronezh State University, Russia. He is currently a researcher and lecturer in Faculty of Electrical Technology, Industrial University of Ho Chi Minh City. His research interest includes the fabrication of advanced ferroelectric-related nanomaterials which are suitable for a wide range of applications, ranging from sensors and actuators to optical or memory devices. He has authored and co-authored more than 50 papers published in ISI and Scopus indexed journals. He can be contacted at email: nguyenthuongfee@iuh.edu.vn.

Phan Thi Bich Thao received the B.Sc. and M.Sc. degrees in physics from Vinh University, Vietnam, in 2002 and 2008. She is currently a lecturer of Faculty of Electrical Engineering Technology, Industrial University of Ho Chi Minh City. She has coauthored more 10 articles. Her current research includes power electronics, electrical materials, and laser. She can be contacted at email: phanthibichthao@iuh.edu.vn.