OPTIMIZATION OF CURRENT CONTROLLER FOR GRID-CONNECTED INVERTERS USING A PSO ALGORITHM

TỐI ƯU BỘ ĐIỀU KHIỂN DÒNG ĐIỆN TRONG NGHỊCH LƯU NỐI LƯỚI SỬ DỤNG GIẢI THUẬT PSO

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ABSTRACT

Renewable energy resources - wind and solar - are increasing very strongly for sustainability and environment with enormous potential. However, their drawbacks are diluted and discontinuous. Thus, in order to become a stable, quality, and cheap power source, they need to be connected to the power grid by using power semi-conductor inverters wherein the current controllers affect significantly output harmonics. Therefore, the power quality of grid-connected inverters depends much on these coefficients of inverters. Since the closed-loop transfer function of grid-connected inverters is infinite. Thus, there are numerous values of the coefficients that can satisfy the transfer function to stabilize system. However, the manual determinations of the coefficients basing on the transfer functions like Bode diagram can provide the local minimum values. This paper proposes a method for determining the optimal coefficients of current controllers using Particle Swarm Optimization (PSO) algorithm. The proposed method does not require much time, strength, and experience of designers. To validate the performance of the proposed technique, the simulation results generated by the proposed technique are compared to those of the method relying on the transfer function.

Keywords*: current controller; distributed generation (DG); grid-connected inverter; Particle Swarm Optimization (PSO); Total Harmonic Distortion (THD).*

TÓM TẮT

Các nguồn năng lượng tái tạo như gió và mặt trời đang phát triển rất mạnh mẽ vì tính bền vững, thân thiện với môi trường trong khi tiềm năng vô cùng lớn. Tuy nhiên, nhược điểm của chúng là bị loãng và không liên tục. Do đó, để có một nguồn điện có chất lượng với giá thành rẻ, chúng thường được nối với lưới điện bằng các bộ nghịch lưu nối lưới. Khi đó, chất lượng bộ điều khiển dòng trong nghịch lưu sẽ ảnh hưởng đến sóng hài ngõ ra của nghịch lưu. Vì hàm truyền vòng kín của các bộ nghịch lưu nối lưới có dạng vô định, nên sẽ có nhiều giá trị của các hệ số bộ điều khiển thỏa mãn hàm truyền để ổn định hệ thống nghịch lưu. Tuy nhiên, các phương pháp xác định các hệ số dựa vào hàm truyền như giản đồ Bode có thể cho kết quả rơi vào cực trị địa phương. Bài báo này đề xuất một phương pháp để xác định các hệ số tối ưu cho bộ điều khiển dòng điện sử dụng giải thuật tối ưu bầy đàn (PSO). Phương pháp đề xuất không đòi hỏi nhiều thời gian, công sức và kinh nghiệm của người thiết kế. Các kết quả mô phỏng của kỹ thuật đề xuất được so sánh với kết quả của phương pháp dựa vào hàm truyền để khẳng định tính hiệu quả của phương pháp đề xuất.

***Từ khóa**: bộ điều khiển dòng; nguồn điện phân tán (DG); nghịch lưu nối lưới; tối ưu bầy đàn (PSO); độ méo hài toàn phần (THD).*

1. INTRODUCTION

The penetration of Distributed Generation (DG) system using renewable energy sources like solar and wind power in power grid network is rapidly increasing worldwide. To limit harmonics of inverter in DGs, the increasingly stringent grid standards [1] are imposed by utility companies to maintain grid stability.

The structure of a three-phase grid-connected inverter system in Fig. 1 shows that the current controllers affect the modulaltion waveforms. As a result, they also affect output harmonics of inverter. There are many control techniques published recently. However, the Proportional Resonant (PR) controller offers the best performance for the grid-connected inverter system [2].

Since the closed-loop transfer function of grid-connected inverter is infinite. Thus, there are numerous values of the coefficients that can satisfy the transfer function to stabilize system. However, the methods for determining manually the coefficients basing on the transfer functions like Bode diagram are difficult to offer the optimum or global result [2]–[4].

Currently, with the development of computer engineering, the parameters of the controllers can be determined by the methods of artificial intelligence such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Cuckoo Search, Harmony search, etc.

PSO is a method basing on the collective knowledge [5] introduced by James Kennedy and Russell C. Eberhart. The optimal techniques using PSO have been researched in [6], [7]. But the PSO algorithm has not applied specifically for the grid-connected inverter [8].

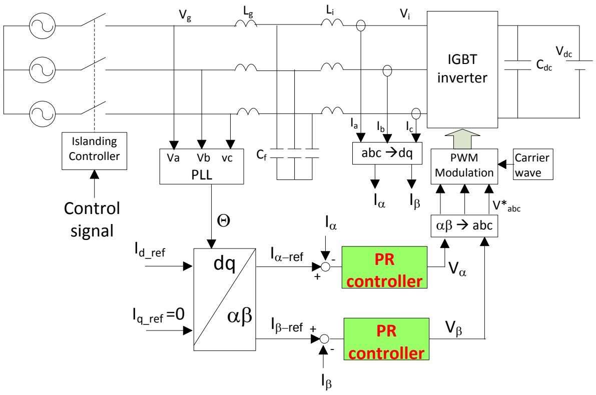


***Fig.1** Structure of the three-phase LCL filter-based grid-connected inverter*

This paper proposes a method for determining the coefficients of the current controller in grid-connected inverter using the PSO algorithm. The simulation results of the proposed technique have been compared to those of the method basing on Bode diagram to confirm the performance of the proposed.

2. METHOD BASING ON BODE DIAGRAM

The PR controller is widely used in grid-connected inverters due to its advantages [2]–[4] such as controlling sinusoidal signals, eliminating well steady-state errors, lowering overshoot, and offering good dynamics.

2.1 Transfer function of grid-connected inverter

The quantities in the three-phase coordinates are converted to the stationary α-β frame [1] as follows:

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix}\begin{bmatrix} p_a \\ p_b \\ p_c \end{bmatrix} \quad (1)$$

Ignoring the influences of L_g and C_f, voltage balanced equation can be written in the stationary $\alpha\beta$ frame as follows:

$$\left.\begin{aligned} \frac{di_\alpha}{dt} &= \frac{1}{L}\left[-Ri_\alpha - V_{g\alpha} + V_{i\alpha}\right] \\ \frac{di_\beta}{dt} &= \frac{1}{L}\left[-Ri_\beta - V_{g\beta} + V_{i\beta}\right] \end{aligned}\right\} \quad (2)$$

The active and reactive powers can be calculated as:

$$\left.\begin{aligned} P_{ref} &= \left[V_{g\alpha} i_{\alpha\_ref} - V_{g\beta} i_{\beta\_ref}\right] \\ Q_{ref} &= \left[V_{g\alpha} i_{\beta\_ref} + V_{i\beta} i_{\alpha\_ref}\right] \end{aligned}\right\} \quad (3)$$

Basing on (3), the reference currents can be determined as follows:

$$\begin{bmatrix} i_{\alpha\_ref} \\ i_{\beta\_ref} \end{bmatrix} = \frac{1}{V_{g\alpha}^2 + V_{g\beta}^2} \begin{bmatrix} V_{g\alpha} & V_{g\beta} \\ -V_{g\beta} & V_{g\alpha} \end{bmatrix} \begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix} \quad (4)$$

2.2 Determining coefficients of controller

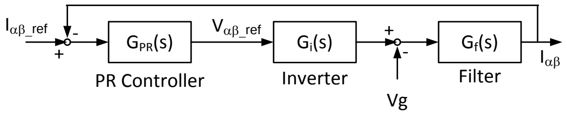


Fig.2 Control block diagram of grid-connected inverter system

Block diagram of control principle for grid-connected inverter is shown in Fig. 2. The open-loop transfer function of the system with the ideal PR controller is yielded as follows:

$$G_{OL}(s) = \left(K_p + \frac{K_i s}{s^2 + \omega_{res}^2}\right)\left(\frac{1}{1 + 1.5\tau_{sw} s}\right)\left(\frac{K}{1 + \tau_c s}\right) \quad (5)$$

Table 1. *System parameters*

Parameter	Symbol	Value
Inductance of filter	L_i	5 mH
Resistance of L_i	R_i	0.3 Ω
Inductance of grid source	L_g	0.01 mH
Resistance of L_g	R_g	0.01 Ω
DC voltage value	V_{dc}	600 V
Capacitor of filter	C_f	0.22 µF
Grid source phase voltage	V_{ac}	220V
Resonant frequency	ω_{res}	100π rad/s
Bandwidth	ω_c	2 rad/s

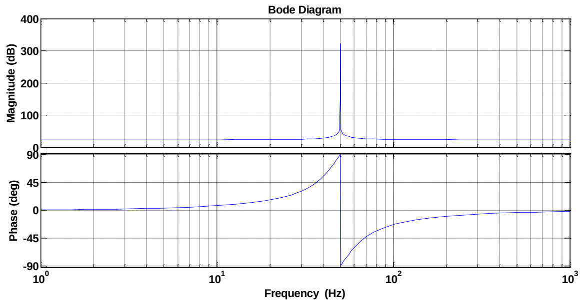


Fig.3 Bode diagram of PR controller (K_p=15; K_i=3000; f_{res}=50Hz)

The parameters of grid-connected inverter system are also listed in Table 1. The ideal PR controller offers a gain very high at resonant frequency in Fig. 3 with K_p and K_i proposed in [2]–[4]. But this controller gives the gain very low at frequencies near the resonant one. This leads to instability in the system when the actual grid frequency fluctuates.

Therefore, the actual PR controller requires a bandwidth ω_c to guarantee the stability as follows:

$$G_{PR}(s) = K_p + \frac{2K_i\omega_c s}{s^2 + 2\omega_c s + \omega_{res}^2} \quad (6)$$

Then, the resonant frequency can be regulated adaptively by the grid one. Bode diagram response of PR controller with different values of K_i is shown in Fig. 4.

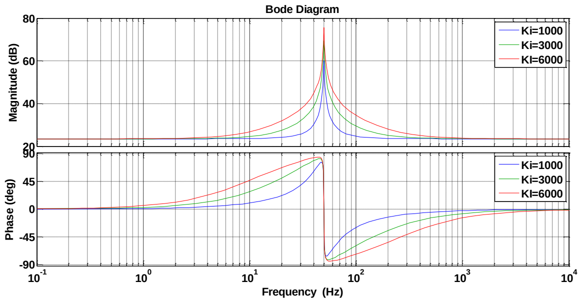


Fig.4 Bode diagram with f_{res}=50 Hz (K_p=15; K_i=1000÷6000; ω_c=2rad/s)

Then, the open-loop transfer function of the system with the actual PR controller will be as:

$$G_{OL}(s) = \left(K_p + \frac{2K_i\omega_c s}{s^2 + 2\omega_c s + \omega_{res}^2}\right)\left(\frac{1}{1 + 1.5\tau_{sw} s}\right)\left(\frac{K}{1 + \tau_c s}\right) \quad (7)$$

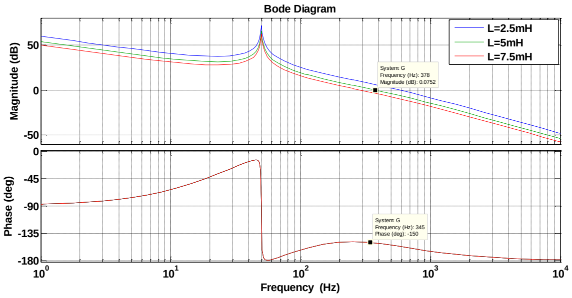


Fig.5 *Response of open-loop transfer function at 378 Hz*

Responses in Fig. 5 with different values of inductance L_i (2.5mH÷7.5mH) show the stability of the system. The response of closed-loop transfer function is also shown in Fig. 6.

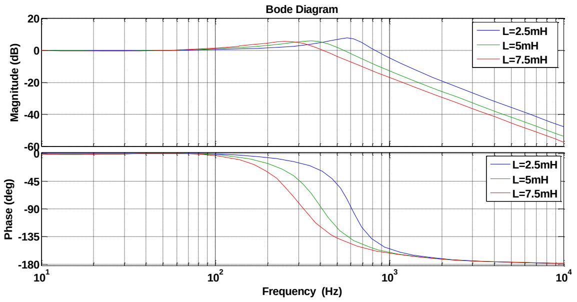


Fig.6 *Response of the closed-loop transfer function*

3. THE PROPOSED METHOD

PSO method is used simply basing on velocity and position updates as follows:

$$\begin{aligned} V_i^k &= w.V_i^{k-1} + \alpha.R_1(P_{local\_besti} - P_i^{k-1}) \\ &+ \beta.R_2(P_{global\_best} - P_i^{k-1}) \end{aligned} \tag{8}$$

$$P_i^k = P_i^{k-1} + \gamma.V_i^k \tag{9}$$

where V_i^{k-1} is velocity of ith particle at (k-1)th iteration, P_i^{k-1} is position of ith particle at (k-1)th iteration, w is inertia weight, α, β, and γ are acceleration factors, R_1 and R_2 are search radii, P_{local_besti} is the local best value, and P_{global_best} is the global best value.

The flowchart of the proposed PSO algorithm is also shown in Fig. 7. The results offer the coefficients K_p= 199.537 and K_i= 4794.3 after 25 iterations.

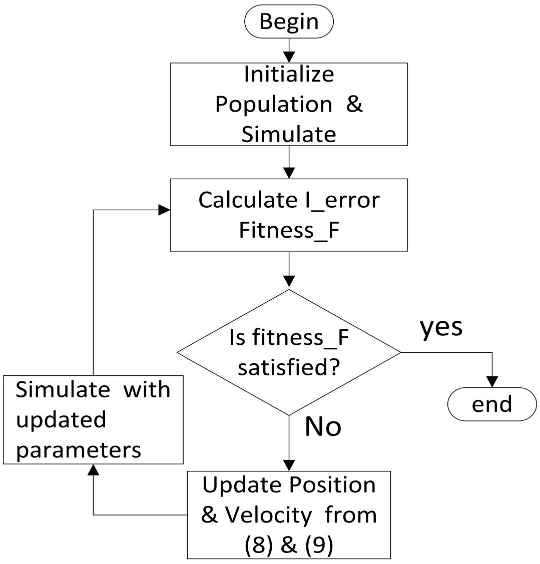


Fig.7 *The proposed PSO algorithm*

4. SIMULATION RESULTS

The active and reactive powers injecting into the grid are characterized by setting reference currents I_{d_ref} and I_{q_ref}.

The current I_{d_ref} is 20 A and 10 A for the intervals 0-0.2s and 0.2-0.6s, respectively. The current I_{q_ref} is 0.0 A and 10 A for the intervals 0-0.4s and 0.4-0.6s. Thus, there are three surveyed intervals with period of 0.6 s.

4.1 Method basing on Bode diagram

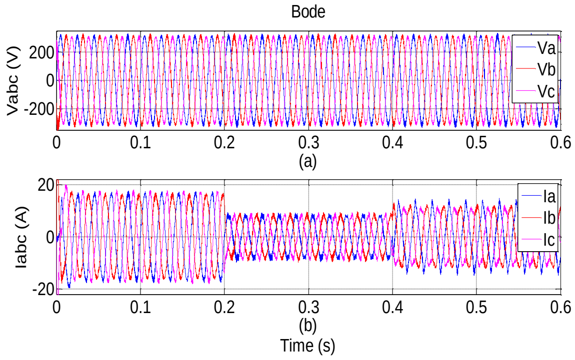


Fig.8 *Three-phase voltage and current*

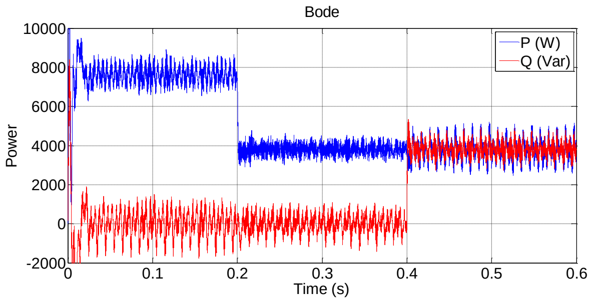


Fig.9 *Active and reactive powers*

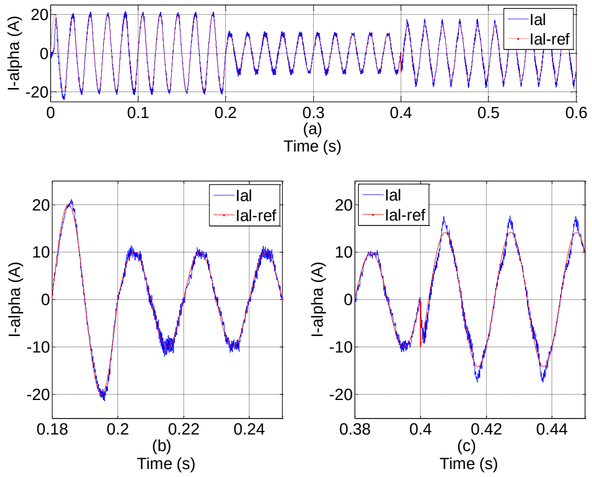


Fig.10 *Reference and response of* I_α

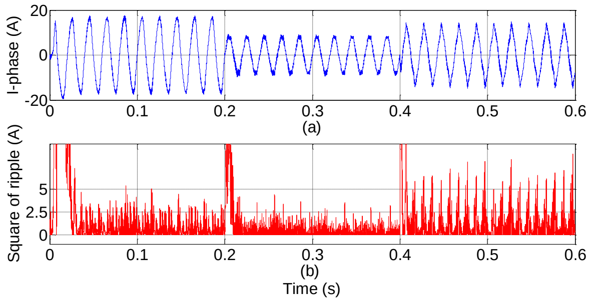
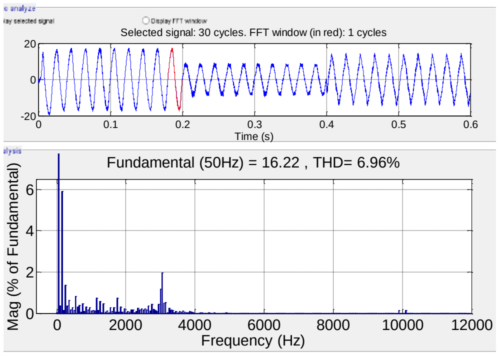
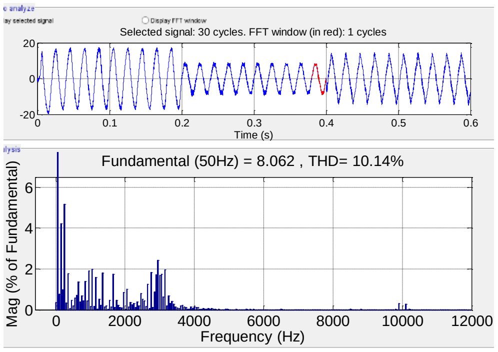


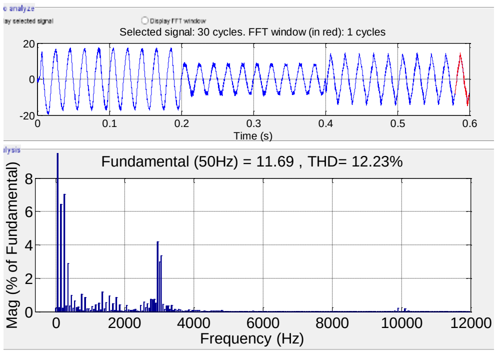
Fig.11 *Phase current and square of ripple*



(a)



(b)



(c)

Fig.12 *THD of the Bode method*

4.2 The proposed method

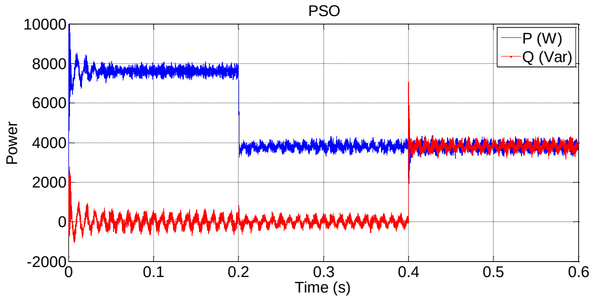


Fig.13 *Response of powers*

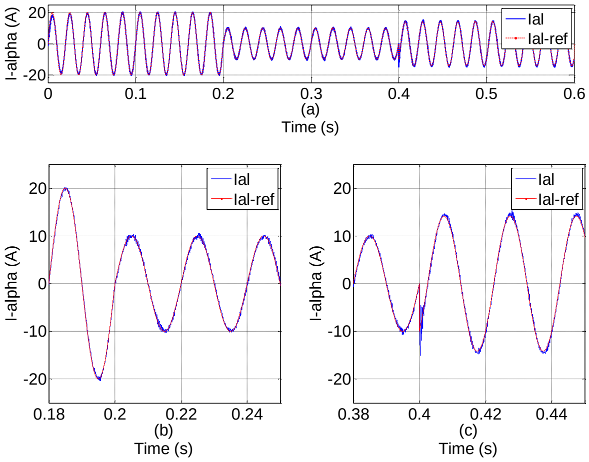


Fig.14 *Current* I_α *of the proposed method*

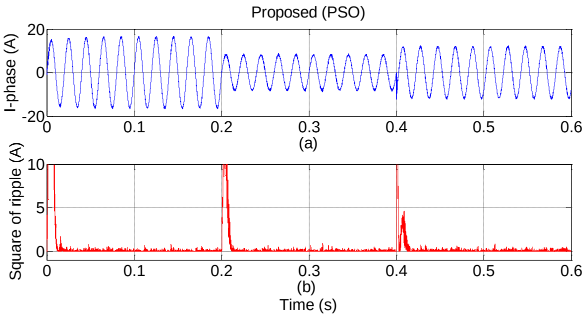
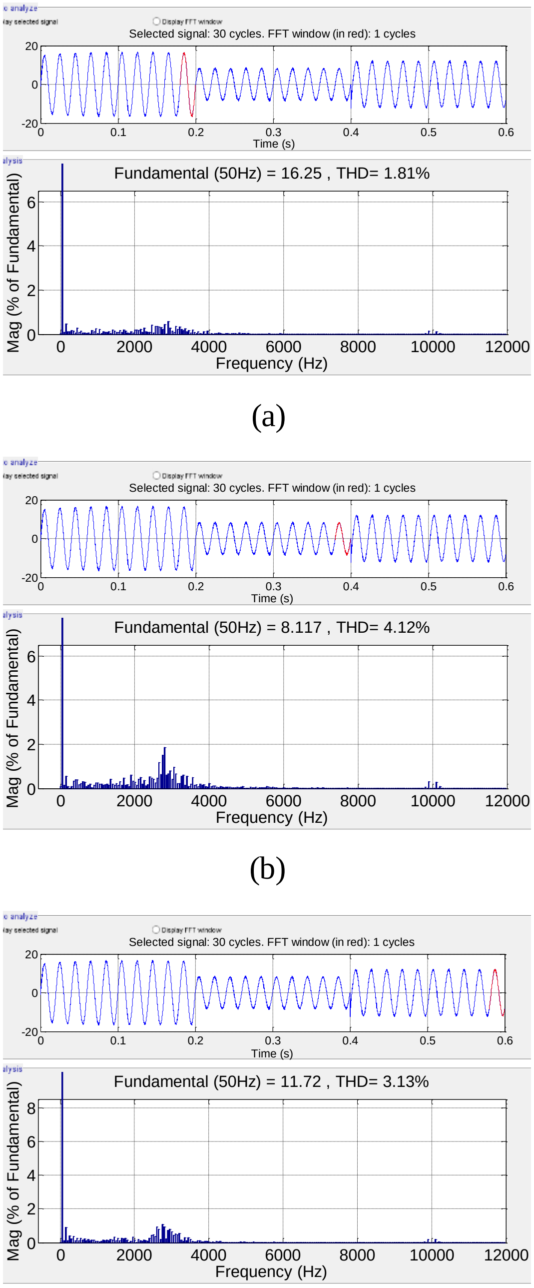


***Fig.15** Phase current and ripple of the proposed method*



(a)

(b)

(c)

***Fig.16** THD of the proposed method*

***Table 2.** Current THD results*

	Bode	PSO	P (W)	Q (Var)
K_p	15	199.537		
K_i	3000	4794.3		
ω_c	2 rad/s	2 rad/s		
THD (%)	6.96	**1.81**	7584	0
	10.14	**4.12**	3792	0
	12.23	**3.13**	3792	3792

5. DISCUSSIONS

The simulation results are shown in Figs. 8-16 and Table 2. The THD values are measured at the last fundamental cycle of each interval to guarantee the steady-state of current.

The active and reactive powers are obtained in Fig. 9 and Fig. 13 for the Bode method and the proposed one, respectively. The three-phase currents in Fig. 8 also showed a compatibility with the obtained powers.

Steady-state error of zoomed current in Figs. 10(b)-(c) of the Bode method is also higher than that of the proposed in Figs. 14(b)-(c).

The currents of the Bode method in Fig. 11 contain more ripples than those of the proposed in Fig. 15. These make the powers of the Bode method in Fig. 9 contain more ripples than those of the proposed in Fig. 13.

In the first interval, 0-0.2 s, the active power P is 7584 W and the reactive power Q is zero. The current THD of the proposed method is 1.81% in Fig. 16(a) while that of the Bode method is 6.96% in Fig. 12(a).

In the second interval, 0.2-0.4 s, the power P is lowered to 3792 W and the power Q is still zero. The THD of the proposed method is 4.12% in Fig. 16(b) whereas that of the Bode method is 10.14% in Fig. 12(b).

In the last, 0.4-0.6 s, the power P is still 3792 W and the power Q is 3792 Var to compensate for the grid. This leads to increasing of current and makes the current THD of the proposed in Fig. 16(c) lower to 3.13%, whilst that of the Bode method is 12.23% in Fig. 12(c), because the coefficients of controller are not optimal values.

The peak current values in Fig. 16 of the proposed method as 16.25 A, 8.117 A, and 11.72 A are a little higher than those of the Bode method in Fig. 12 as 16.22 A, 8.062 A, and 11.69 A, respectively. These lead to power factor of the proposed higher than that of the Bode method [9].

The current THD results in Table 2 also showed that THD values of the proposed method are always lower than the limit [1]. On the contrary, those of the method basing on Bode diagram are higher than the limit.

6. CONCLUSION

The accuracy of coefficients in current controllers affects significantly power quality of grid-connected inverters.

In the conventional methods basing on Bode diagram, the coefficients of current controller determined manually are difficult to offer the optimal values due to the infinite of the transfer function.

This paper proposed a method for offering the optimal coefficients of current controller relying on the PSO algorithm. The simplicity of the proposed helps determine the coefficients more easily.

The simulation results of the proposed method have been compared to those of the method basing on Bode diagram to validate the performance of the proposed.

The approach of the proposed can also extend to other applications such as automation, electric motor control, etc.

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