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An Intelligent Voltage Controller for a PV Inverter System Using Simulated Annealing Algorithm-Based PI Tuning Approach

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Abstract: This study associates an intelligent voltage controller based PI approach for PV electrical inverter by employing a meta-heuristic optimization algorithmic called a Simulated Annealing (SA) algorithm. It's outlined as a physical process of minimization which is a kind of optimization problems. During this methodology, the procedure of trial and error in getting k_p and k_i parameters utilized in a conventional PI controller is avoided. Besides, it is then used to optimize the PI parameters in order to get the desired output voltage of the PV electrical inverter along with the PWM method. The proposed design of the overall PV electrical inverter is modelled using simulink/code of matlab environment. As a result, firstly; to evaluate the proposed controller (SA-PI) of the PV inverter. Its performance is investigated by connecting three different loads to the system. Noted that, it is robust in terms of voltage amplitude, Total Harmonic Distortion (THD) and a minimum value of Mean Absolute Error (MAE). Secondly, the SA algorithm based PI controller generally provides a better desired output and fast response with a high convergence rate as compared with the PSO algorithm.

Key words: PV inverter, simulated annealing algorithm, mean absolute error, total harmonic, distortion and matlab code

INTRODUCTION

In the past years, the demand electricity sector has attracted much attention to the power production using the natural resources such as fossil fuel, coal and natural gas which considered as the main source of negative impacts for environmental issues (Monfared and Golestan, 2012; Akorede *et al*., 2012). In order to overcome these issues, the concept of Renewable Energy Sources (RES) has increased more and more as a clean sustainable energy based on its development and utilization (Figueiredo and Martins, 2010; Ozgener, 2006; Najeeb *et al*., 2006).

Among RES, PV systems have played most important role in the electricity generation because of the technology improvement, zero pollution generated, clean and cost is decreased (Khatib *et al*., 2012; Chel *et al*., 2009; Ali *et al*., 2015). However, there are two modes for implementing the PV generators either grid connected or stand-alone. For both of them, there is a power electronic device; it is called a Voltage Source Inverter (VSI) located between the PV generator and the loads to achieve the desired output (Blaabjerg *et al*., 2004). In the stand-alone mode operation, the PV inverter should be able to provide the required power to the connected loads (Daud *et al*., 2013; Kaundinya *et al*., 2009). In addition, the output current and voltage waveforms of a VSI should be controlled based on a control technique by using its reference values as a feedback. Thus, the main objective of a good PV inverter regardless of the external disturbances is to provide a constant frequency and amplitude voltage as mentioned in the international standard IEEE-929-2000.

To meet the robust output performance in the PV inverter systems, there are different controller's techniques have been suggested such as PI, Fuzzy Logic (FL) deadbeat and so on along with using different types of Pulse Width Modulation (PWM) methods (Kumar and

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Sivakumar, 2015; Rajkumar and Manoharan, 2013; Messenger and Ventre, 2010; Awadallah *et al*., 2009). The Proportional-Integral (PI) controller is one of the most commonly controllers used to regulate the voltage response for the PV grid system as in (Tsengenes and Adamidis, 2011) because of the simplicity of its structure and design. In a related research of advantages, the PI controller is carried out for solving the problems in the PV inverter controls by controlling the current waveform as well as to inject the sinusoidal wave form from a single-phase inverter topology as explained by Heng .

Selvaraj and Rahim (2009) a digital algorithm of PI current control is implemented in the PV inverter to maintain the current as a sinusoidal waveform using DSP TMS320F2812. The researcher by Sanchis *et al*. (2005) also has been proposed a traditional PI controller which requires differential equations to obtain a better performance by controlling the DC-AC inverter. Moreover, the Fuzzy Logic Controller (FLC) has been utilized for the PV inerter systems in the literature by the researchers due to it is a non-mathematical model, simplicity and its performance is described as a convenient under load disturbances (Altin and Sefa, 2012; Messai *et al*., 2011; Spiegel *et al*., 2003; Lalouni *et al*., 2009). On the other hand, it is difficult to tune the PI parameters (k_p and k_i) because of its mathematical model (Calais *et al*., 2001). Therefore, the utilization of optimization techniques in tuning the PI controller has been widely investigated to improve the PV inverter systems performance (Daud *et al*., 2014). For example, Genetic Algorithm (GA) based PI controller has been suggested by Jin *et al*. (2010) to help in attaining optimized PI controller parameters. In addition, Particle Swarm Optimization (PSO) has been utilized in tuning the PI parameters along with connected loads for different types of applications (Mushtaq *et al*., 2015; Mohammed *et al*., 2015; Liserre *et al*., 2004; Li *et al*., 2008; Sundareswaran *et al*., 2007). But when the load is varying in a stand-alone PV inverter system, Simulated Annealing (SA) algorithm has the ability to support in finding the optimal values of the PI controller.

In this study, a PI optimization controller for the PV inverter systems using the Simulated Annealing (SA) algorithm is proposed to find its optimal values in order to get the desired output voltage. Furthermore, the manual procedure of trial and error in getting (k_p and k_i) parameters used in the traditional method of Ziegler-Nichols is also avoided. To evaluate the response performance and the robustness of the proposed controller under different connected loads, the SA algorithm and the design of the overall PV inverter system are implemented by using (m-file) code and simulink of matlab environment, respectively along with the conventional PWM method. Based on this, the Mean Absolute Error (MAE) is used as an objective function to minimize its error value depending on the inverter output voltage and then compared with the PSO algorithm.

MATERIALS AND METHODS

Simulated annealing algorithm concept: The simulated annealing is one of the most popular meta-heuristics techniques inspired by natural phenomena which has been established by Kirkpatrick *et al*. (1983) to convert the state space search problems to optimization problems. In other words, it is an exploration algorithm used to explore the global optima for an objective function based on the observation of local search optima. The principle research of the simulated annealing algorithm can be described as shown down in Algorithm1 (Talbi, 2009). Firstly, the algorithm generates an initial solution "E" depending on a high starting value of temperature "T". Then, it moves to the next solution if a random neighbour generated "E^'" is better than the current solution "E" (i.e., the difference between them is less than zero). Otherwise, a certain amount of probability "P" is accepted along with the moving to the next solution (i.e., local optima is escaped by accepting worse solutions). After that, a certain number of iterations is repeated for this procedure by updating the temperature (i.e., temperature is decreased) for the next level until the termination criteria is satisfied. Finally, the optimal solution is found.

Algorithm 1: Control flow of simulated annealing:

Input: Set starting temperature (T); Create initial solution E;
While: Termination criteria, if not satisfied do, Generate a random neighbourE'; $\Delta f = f(E')-f(E)$: Calculate difference of Δf
if $\Delta f < 0$ then
E = E' Accept: current solution E is replaced by E';
else
Accept E' with some probability $\{p = \exp(-\Delta f/T)\}$;
end
T = Update temperature for next level;
end
Return: Optimal solution found;

In a related literature, the SA algorithm has also been applied in power system engineering to solve various problems such as the sizing cost minimization of the hybrid PV/wind energy system but it is less popular used as compared to PSO and GA algorithms. In the optimal controller combination of automatic voltage regulation and load frequency control for multi-source multi-area system is proposed using simulated annealing technique to regulate the frequency deviation and keep tie-line power exchange through connected to load disturbance. In addition, some optimization methods have been used in this review study to justify the investment cost of a microgrid system by enabling new economic ways and reliable utilization of renewable energy sources such as Differential Evolution algorithm (DE) Simulated Annealing (SA) and Ant Colony Algorithm (ACS). On the other hand, the Simulated Annealing (SA) is compared to another meta-heuristic method which called tabu-search algorithm in hybrid renewable sources to minimize the sizing problem of the energy cost and it was faster to converge (Katsigiannis *et al*., 2012).

Overall proposed system description: The block Fig. 1 of the overall proposed PV inverter system is shown in Fig. 1. It consists of a PV source, DC-DC converter, single-phase inverter (DC-AC) LC filter and an Intelligent PI controller connected through three different loads. The ability of a good power inverter for PV systems is one of the main features to generate the AC output voltage.

The PI controller is one of the popular feedback controller used with the PV inverter system for providing an excellent control performance and higher stability. The transfer function of the PI controller consists of two basic parameters; Proportional (P) and Integral (I). The advantages of each parameter are (Ali *et al*., 2016) proportional is used to reduce the system peak overshoot, an integral is employed to eliminate the effect of the steady state error to be zero. According to Mushtaq *et al*. (2015) the typical transfer function of the classical PI controller in terms of Laplace domain is described:

$$G_{pi}(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} \quad (1)$$

Where:

K_p = The proportional gain

K_i = The integration gain

U(s) and E(s) = The control signal and the error signal which computes the difference between the measured output voltage V_0 and the reference voltage V_0^* correspondingly at each sampling time to find the missing components values of V_0

After that the output u(t) of the PI optimization controller (SA-PI) is given Eq. 2 which can be used to control the PV inverter system by generating the IGBT switching signals (S_1-S_4) through the PWM technique:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \quad (2)$$

where, u(t) and e(t) are in the form of time domain. Based on the researcher's survey, it usually refers to Ziegler-Nichols PI approach for tuning its parameters. In this research, the initial parameters of the PI optimization controller (SA-PI) are generated randomly and then the optimal values (K_p and K_i) can be tuned using an optimization technique such as simulated annealing algorithm which can lead the controller to meet the desired control requirement.

Proposed SA-PI optimization controller: Figure 2 shows the proposed intelligent voltage controller for a PV

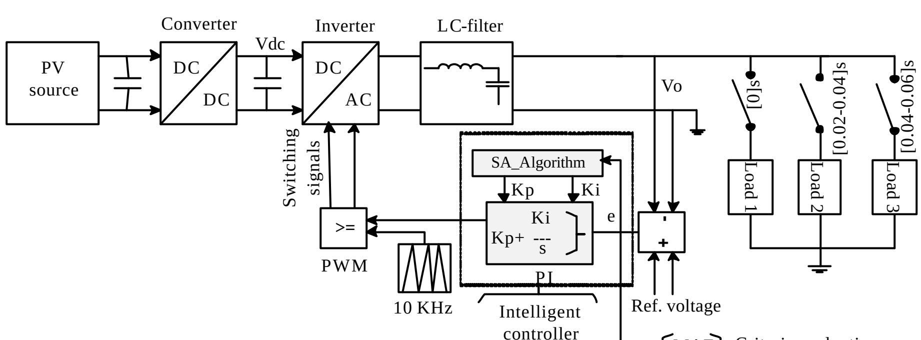

Fig. 1: Overall proposed PV inverter system

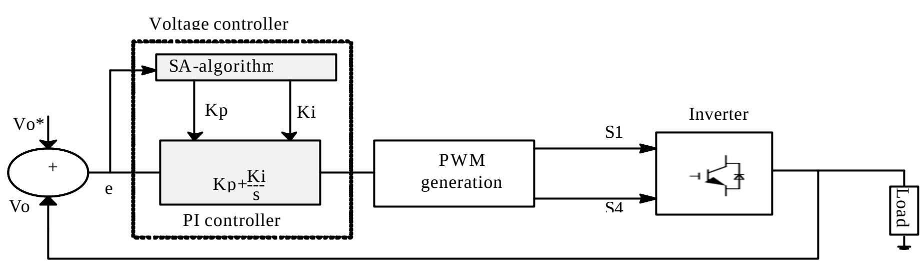

Fig. 2: Closed loop of the proposed SA-PI optimization controller

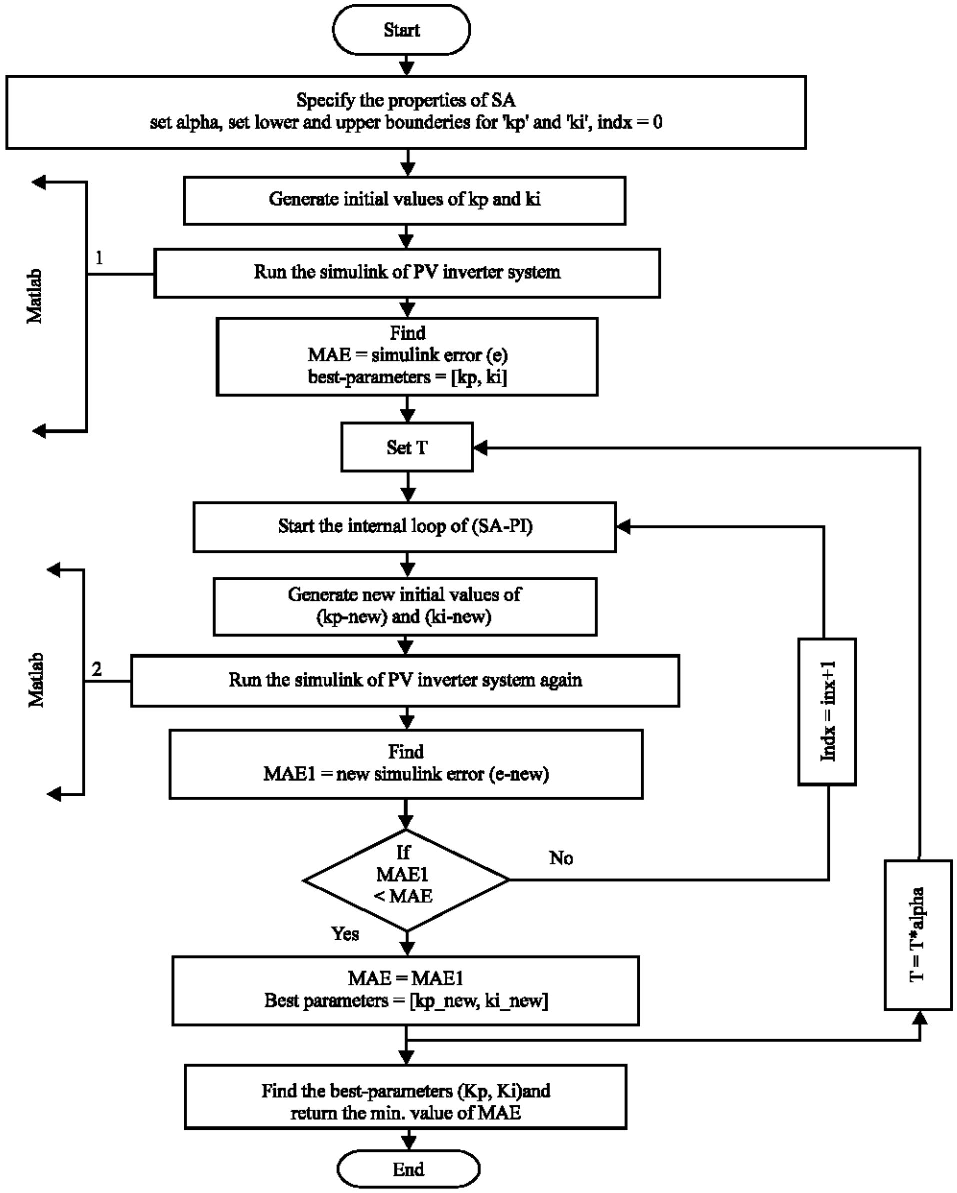

Fig. 3: Flowchart of proposed SA-based PI optimization controller

Table 1:Proposed PV inverter system parameters

Parameters	Values
Input DC voltage (V_{dc})	400 V
Filter inductance (L)	4.7 mH
Filter capacitance (C)	20 μF
Resistive load (R)	100, 75, 50 Ω
frequency Switching (f_s)	10 Khz

inverter system which called the simulated annealing based PI optimization controller (SA-PI). For the investigation purpose, the proposed system parameters are shown in Table 1 with characteristics of solar radiation and ambient temperature are 1 kW/m^2 and 25°C, respectively. The success robustness of PV inverter systems depends highly on the proposed controllers. The basic flow chart of the proposed control algorithm is shown in Fig. 3 which can be summarized the steps of applying the simulated annealing technique. In this process, the most important part is the probability which depends on the temperature parameter that starts with a high value and decreased in each iteration. At the end, the probability will decrease over long iterations as well as converge to get the optimum value.

To demonstrate the proposed SA-PI optimization controller, set the lower and upper boundaries of (K_p and K_i) which are recommended by the literature review.

Firstly, the output voltage V_0 of the system is measured at each sampling time (t_s = 1 μs) based on the random initial values of (K_p and K_i). Then, the Simulink model of the proposed system shown in Fig. 1 is running to find the error value (MAE) using the Eq. (3) and considered the obtained values of the K_p and K_i are the best parameters. Secondly, the optimization process is started by specify the initializing properties of the simulated annealing; the high temperature value (T) as (50°C) the alpha value as 0.3, the number of iterations (Index) as 100 and start the internal loop. After that, it generates the new initial values of [$K_{p\text{-}new}$, $K_{i\text{-}new}$] and calculates the new value of the objective function (MAE1) for the optimization loop. If the MAE1 is less than MAE, then the new values of [$K_{p\text{-}new}$, $K_{i\text{-}new}$] replace by the previous values of [K_p, K_i].Otherwise, updates and initiates a new iteration (Index). Next, if the maximum iteration of the SA is reached, the proposed SA algorithm based PI optimization controller with the minimum MAE is obtained. This is to say that, the proposed method indicates an easy way to find the best PI parameters for a PV inverter system as shown in the results study.

RESULTS AND DISCUSSION

In this study, the overall proposed PV inverter system shown in Fig. 1 was modelled and investigated using the environment of matlab simulink/code. In this study, simulation has been carried out for 0.08s and the sampling Time (Ts) is 1 μs to assess the proposed controller for the PV inverter system in order to supply 340 V as a peak voltage and 50 Hz as a frequency with different loads. As shown in Fig. 4, the loads has been rapidly increased in the periods [(0.02-0.04) s, (0.04-0.06) s] form 0.5-0.75 KW and from 0.75-1KW, respectively and it has been decreased in the period (0.06-0.08) s to the initial status (0.5 KW). The waveform of AC output voltage for the proposed PV inverter is presented in Fig. 5, its rms voltage is 238.9 V which equivalent to 338.9 V as a peak voltage without any effect of oscillation. This is to say that the proposed controller has succeeded to track the load steps change which demonstrate the effectiveness of using the simulated annealing optimization algorithm.

Figure 6 shows the AC waveform of the output current for the proposed PV inverter. The stability of the sinusoidal waveform is clearly noted with 50 Hz through three different loads connected among different periods of time. Meanwhile, the response of transient and steady-state values is achieved quickly similar to

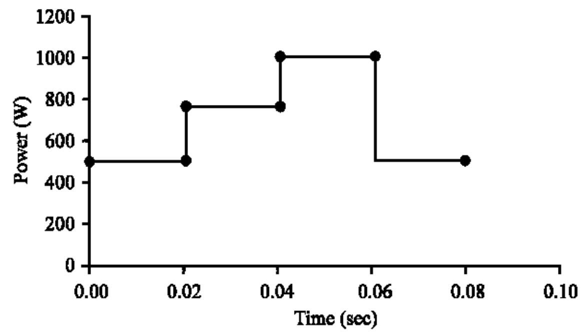

Fig. 4: Load steps change

the output voltage waveform. Figure 7 shows the waveform relationship between the current and the voltage where the load current is scaled up to 25 times to show the phase difference with each other. It is observed that the phase shift is zero as expected and the power factor is not affected by changing the 3 loads. According to the standard IEEE-929-2000 (Chel *et al*., 2009) the Total Harmonic Distortion (THD) is one of the important standards that used to describe the quality signal of the inverter output waveforms.

Therefore, Fast Fourier Transform (FFT) has been conducted to the current and the voltage waveforms in order to calculate the total harmonic distortion for both of them which must be <5%. The THD for the output current waveform of the proposed inverter system is found to be 2.835 % shown in Fig. 8 which meets with the international standard along with 200th harmonic order (10 KHz) as a frequency spectrum. While, the THD for the output voltage wave form is 0.20% as presented in Fig. 9 which conforms to the standards as well.

Furthermore, the performance evaluation of the convergence characteristics in finding the optimal solution (K_p and K_i) for the PV inverter test system is shown in Fig. 10 to demonstrate the effectiveness of the proposed PI-SA optimization controller as compared to the PI-PSO optimization controller. This is to indicate that the proposed PI-SA converges faster than PI-PSO by using the Mean Absolute Error as an objective function (MAE) which is given by Eq. 3 with the same number of iterations for both algorithms:

$$\text{MAE} = \frac{\sum_{i=1}^{n} |e|}{n} \quad (3)$$

Where:

$e = V_0\text{-}V_0^*$ = The measured output voltage
V_0 = The reference voltage V_0^*
n = The number of samples

which can be defined as:

t_r(Running time of simulation/t_s(Sampling time)

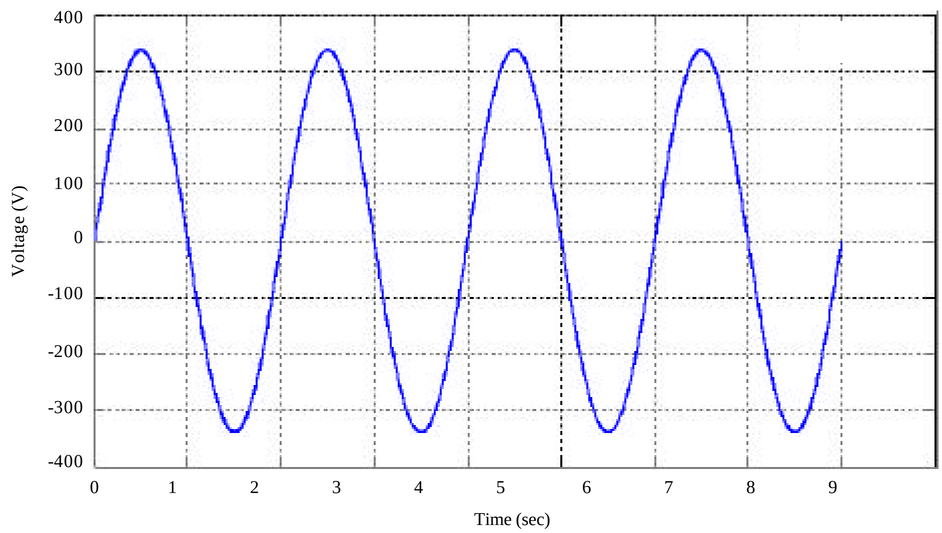

Fig. 5: Output voltage waveform of VSI

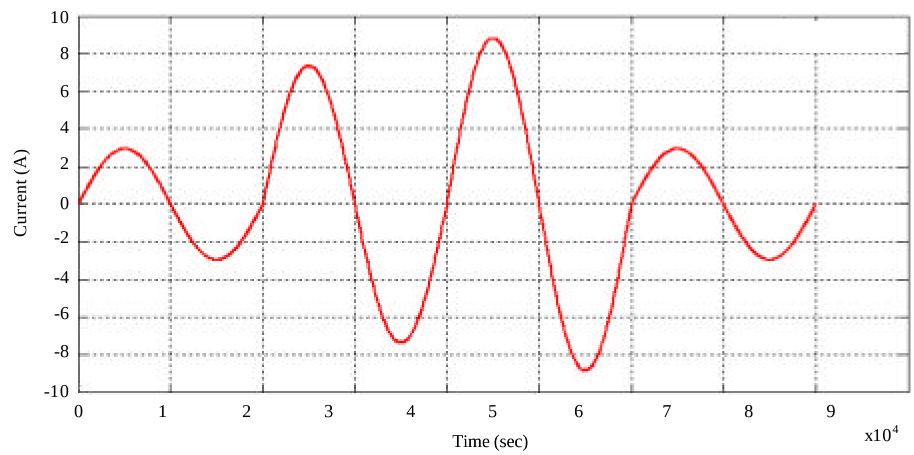

Fig. 6: Output current waveform of VSI during load steps change

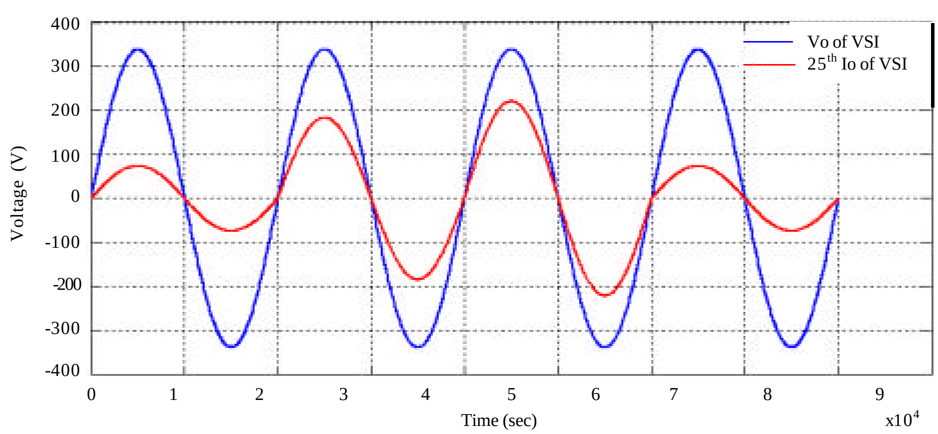

Fig. 7: Output waveforms for voltage and current of VSI

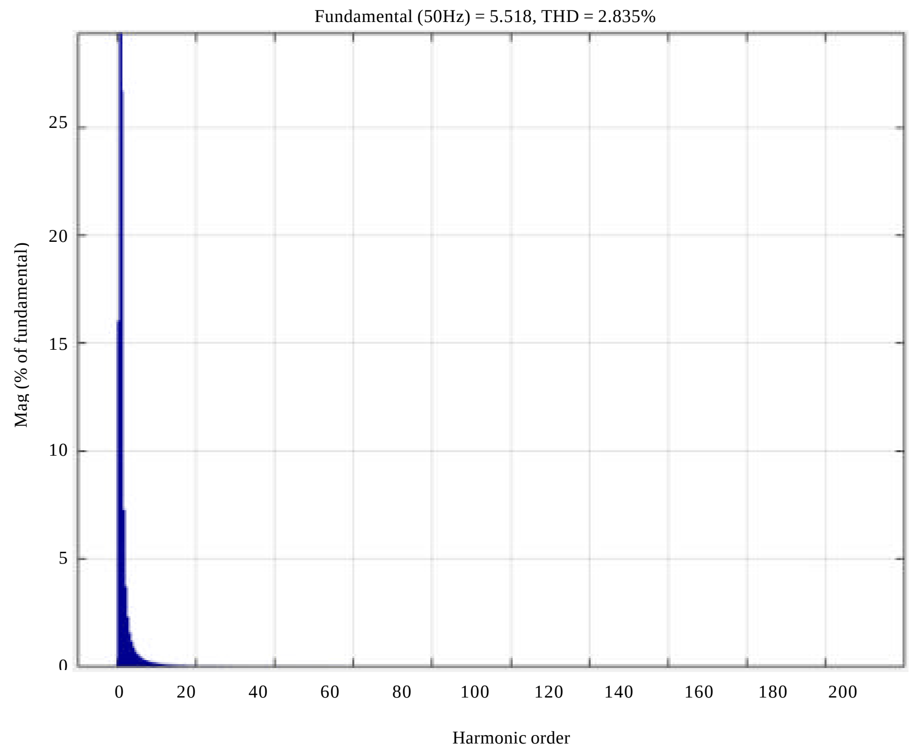

Fig. 8: THD for the output current of VSI

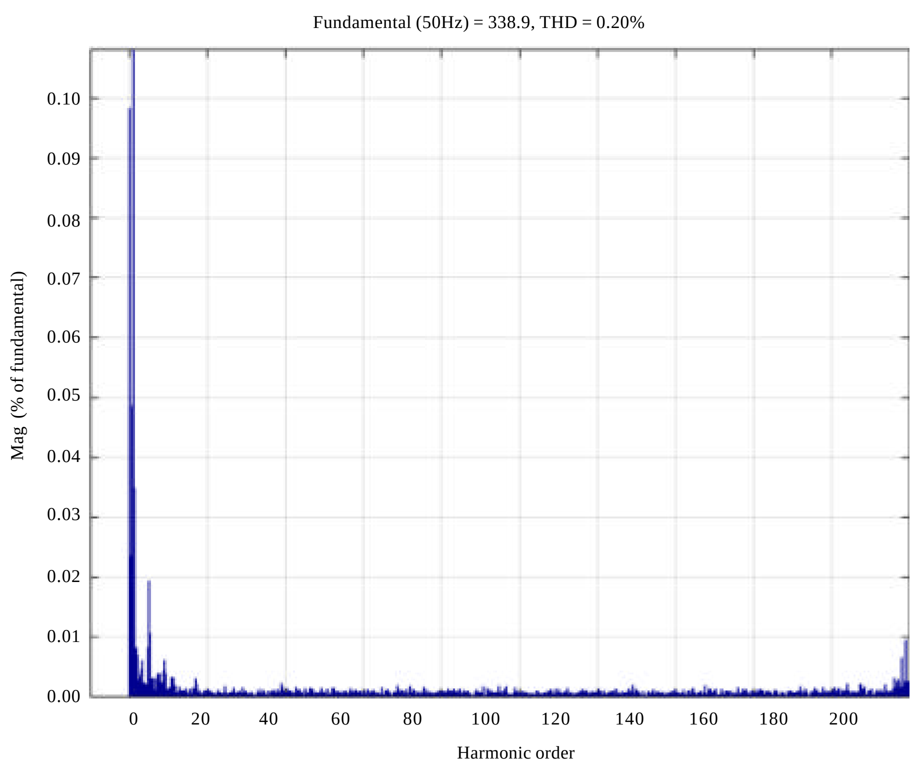

Fig. 9: THD for the output voltage of VSI

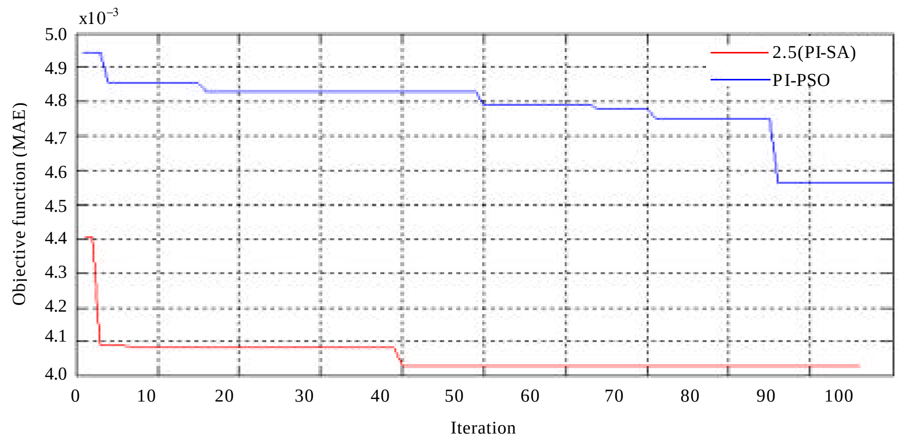

Fig. 10: Performance comparison based on PI-SA and PI-PSO

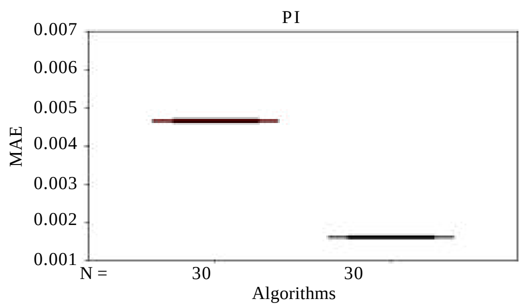

Fig. 11: Box plot of solution distributions for SA and PSO algorithms

Finally, a Wilcoxon statistical test with 0.05 (p-value) critical level was conducted to verify if the results of the SA and the PSO algorithms are statistically significant. The p-value of the SA versus the PSO is <0.05 which means the SA is statistically better than PSO on all tested iterations. In addition, the box plot of solutions distribution over 30 runs for the SA and the PSO is presented in Fig. 11 to investigate the solutions distribution obtained by both of them. This figure shows that the distribution of SA results is much better than PSO results especially in the minimum value of the MAE.

CONCLUSION

In this study an intelligent voltage controller has been proposed for a PV inverter system using simulated annealing algorithm under different load change conditions. This algorithm has been incorporated to implement a self-tuning of PI approach in order to avoid the trial and error procedure in getting K_p and K_i parameters. To control the inverter output voltage, the overall PV inverter system has been simulated using matlab environment and its controller algorithm was coded using m-file technique. The simulation results showed that the SA algorithm based PI controller offers a great response and reduce the Total Harmonic Distortion (THD) in the output of current and voltage. The THD obtained is 2.835 and 0.2% respectively which meets the international standard (IEEE-929-2000). Furthermore, an efficient evaluation between the proposed simulated annealing algorithm based PI controller and the PSO-PI has been compared to ensure the accuracy. Based on this, the objective function value of Mean Absolute Error (MAE) for the proposed algorithm is 0.0016 as compared to 0.0046 for the PSO-PI algorithm. Finally, the TIC and TOC function has been used to find the execution time for both algorithms. It is found that the time of the proposed algorithm is (16 min) as compared to (4*16 min) of the PSO-PI algorithm.

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