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The Application of Adaptive Tabu Search Algorithm and Averaging Model to the Optimal Controller Design of Buck Converters

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***Abstract*—**The paper presents the applications of artificial intelligence technique called adaptive tabu search to design the controller of a buck converter. The averaging model derived from the DQ and generalized state-space averaging methods is applied to simulate the system during a searching process. The simulations using such averaging model require the faster computational time compared with that of the full topology model from the software packages. The reported model is suitable for the work in the paper in which the repeating calculation is needed for searching the best solution. The results will show that the proposed design technique can provide the better output waveforms compared with those designed from the classical method.

***Keywords*—**Buck converter, adaptive tabu search, DQ method, generalized state-space averaging method, modeling and simulation

I. INTRODUCTION

PRESENTLY, the artificial intelligence (AI) techniques are widely applied to many works of engineering such as the system identifications using adaptive tabu search (ATS) [1]-[5], the protection design in power system via ATS [6], the active power filter design using genetic algorithm (GA) [7], power loss minimization using particle swarm optimization (PSO) and artificial bee colony (ABC) [8], reactive power optimization for distribution systems based on ant colony optimization (ACO) [9], and etc.

The power system considered in the paper consists of balanced three-phase voltage source, six-pulse diode rectifier, DC-link filter feeding a controlled buck converter. The aim of the paper is to design the controller of a buck converter to achieve the best performance of the output waveform by using the ATS algorithm. However, the ATS searching process needs to simulate the power electronic system for each controller parameter until the appropriate parameters are obtained. In addition, it is well know that the transient simulations of the power electronic system consume the vast simulation time due to the switching devices in the circuit. Therefore, according to the huge simulation time of the switching devices, the application of AI techniques is not widely applied to design the controller of the power converter. To solve the simulation time problem, the averaging model is used in the paper instead of the exact topology model. There are many approaches used to eliminate the switching action of power converter to achieve the approximate model called the averaging model in the paper. From the literature reviews [10]-[13], the combination between the DQ modeling approach and the GSSA modeling method is selected to derive the mathematical model of the studied power system. According to the advantages of DQ and GSSA methods, the DQ method is selected to analyze the three-phase diode rectifier including the transmission line components on AC side, while the GSSA method is used to analyze the buck converter with its controls. The proposed model is compared with the intensive time-domain simulation via the full switching model of software package in terms of accuracy and simulation time. The comparison results show that the proposed mathematical models provide high accuracies in both transient and steady-state responses with the faster simulation time. Hence, the reported model is suitable for the optimal controller design via the ATS method. In addition, the dynamics of transmission line, diode rectifier, and DC-link filters are taken into account for the controller design of the buck converter via the proposed averaging model. Normally, these dynamics are not considered in the design process. The constant DC voltage source is used to represent these dynamics for the previous publications. The final results show that the proposed technique using the ATS algorithm with the averaging model can be used to design the controller of buck converter in which the better output response is obtained compared with the waveforms from the classical design method.

The paper is structured as follows. In Section II, considered system with deriving the dynamic model by using the DQ and GSSA modeling methods is firstly explained. Moreover, the comparison results between the reported model and the full switching model from the commercial software package in terms of accuracy and simulation time are also illustrated in Section II. In Section III, the controller designs using the ATS algorithm and the classical method are addressed. The simulation results are fully shown in Section IV. Finally, Section V concludes and discusses the advantages of the proposed technique for the optimal controller design of the power electronic systems.

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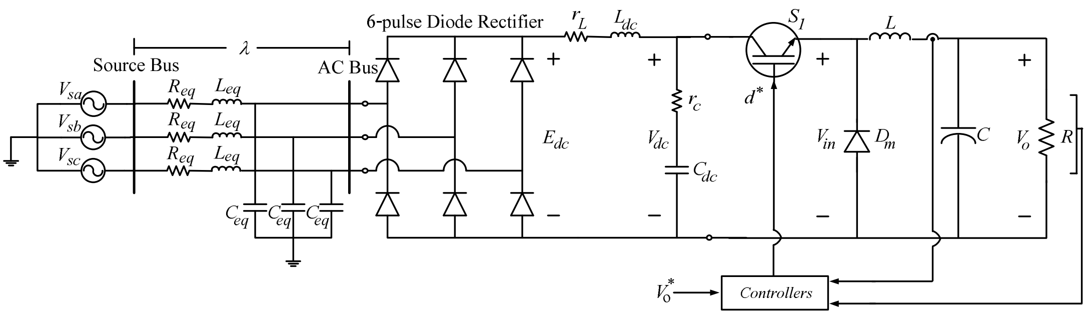

Fig. 1 The considered power system

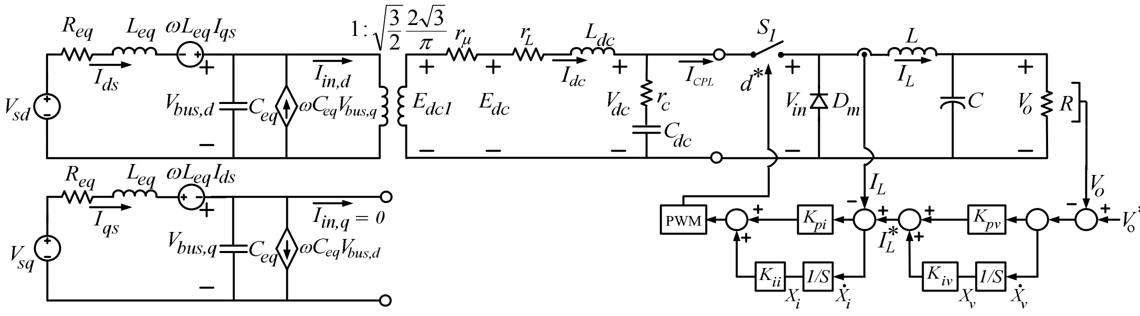

Fig. 2 The equivalent circuit of the system on DQ frame

II. Dynamic Model of Considered System

The studied power system in the paper is depicted in Fig.1. It consists of a balanced three-phase voltage source, transmission line, 6-pulse diode rectifier, DC-link filters feeding a controlled buck converter. The buck converter is controlled by the cascade PI controllers to regulate the output voltage equal to the command input V_o^*. In the paper, the diode rectifier and the buck converter are assumed to operate under the continuous conduction mode (CCM). As mentioned in Section I, the DQ method is selected to analyze the three-phase diode rectifier in which this rectifier can be modeled as the transformers on DQ frame. This results in the equivalent circuit on DQ frame with the schematic of controllers for the buck converter as shown in Fig.2.

After applying the DQ modeling method, the GSSA model is then used to eliminate the switching behavior of the buck converter. It can be seen that the PI controllers of the current loop (inner loop) and the voltage loop (outer loop) are represented by K_{pv}, K_{iv}, K_{pi}, and K_{ii}, respectively. From Fig. 2, d^* can be derived and given in (1).

$$d^* = -K_{pi} I_L - K_{pv} K_{pi} V_o + K_{iv} K_{pi} X_v + K_{ii} X_i + K_{pv} K_{pi} V_o^* \tag{1}$$

Finally, KCL, KVL, GSSA method, and the linearization technique are applied to the circuit in Fig. 2 with (1) so as to achieve the linear time-invariant (LTI) dynamic model of the studied power system. After derivation, the LTI model can be expressed as:

$$\begin{cases} \delta \dot{\mathbf{x}} = \mathbf{A}(\mathbf{x_0}, \mathbf{u_0})\delta \mathbf{x} + \mathbf{B}(\mathbf{x_0}, \mathbf{u_0})\delta \mathbf{u} \\ \delta \mathbf{y} = \mathbf{C}(\mathbf{x_0}, \mathbf{u_0})\delta \mathbf{x} + \mathbf{D}(\mathbf{x_0}, \mathbf{u_0})\delta \mathbf{u} \end{cases} \tag{2}$$

where

$$\delta \mathbf{x} = \begin{bmatrix} \delta I_{ds} & \delta I_{qs} & \delta V_{bus,d} & \delta V_{bus,q} & \delta I_{dc} & \delta V_{dc} & \delta I_L & \delta V_o & \delta X_v & \delta X_i \end{bmatrix}^T$$

$$\delta \mathbf{u} = \begin{bmatrix} \delta V_m & \delta V_o^* \end{bmatrix}^T$$

$$\delta \boldsymbol{y} = \begin{bmatrix} \delta V_{dc} & \delta V_o \end{bmatrix}^T$$

As can be seen in (2), when we consider the controlled buck converter, the PI controller parameters are included in the model. Therefore, the resulting mathematical model as given in (2) will be used with the ATS algorithm to search the appropriate PI controller parameters for both current and voltage loops. The ATS will search the solution until the best output response is achieved. However, before using this LTI dynamic model with the ATS method, we need to ensure that the proposed model in (2) can correctly describe the system dynamic. Therefore, the simulation of the full topology model from the commercial software package, here is SimPowerSystem™ (SPS™) of SIMULINK is used as the comparator in terms of accuracy and computational time. The set of system parameters is given in Table I with the voltage loop controllers $K_{pv} = 0.05$ and $K_{iv} = 20$ ($\omega_{nv} = 400$ Hz, $\zeta_v = 1.0$), and the current loop controllers $K_{pi} = 0.6819$ and

$$\mathbf{A(x_o,u_o)}=\begin{bmatrix} -\frac{R_{eq}}{L_{eq}} & \omega & -\frac{1}{L_{eq}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\omega & -\frac{R_{eq}}{L_{eq}} & 0 & -\frac{1}{L_{eq}} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C_{eq}} & 0 & 0 & \omega & \sqrt{\frac{3}{2}}\cdot\frac{2\sqrt{3}}{\pi C_{eq}} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_{eq}} & -\omega & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sqrt{\frac{3}{2}}\cdot\frac{2\sqrt{3}}{\pi L_{eq}} & 0 & -\left(\frac{r_\mu+r_L+r_c}{L_{dc}}\right) & -\frac{1}{L_{dc}} & a(5,7) & -\frac{r_cK_{pv}K_{pi}I_{L,o}}{L_{dc}} & \frac{r_cK_{iv}K_{pi}I_{L,o}}{L_{dc}} & \frac{r_cK_{ii}I_{L,o}}{L_{dc}} \\ 0 & 0 & 0 & 0 & \frac{1}{C_{dc}} & 0 & a(6,7) & \frac{K_{pv}K_{pi}I_{L,o}}{C_{dc}} & -\frac{K_{iv}K_{pi}I_{L,o}}{C_{dc}} & -\frac{K_{ii}I_{L,o}}{C_{dc}} \\ 0 & 0 & 0 & 0 & 0 & a(7,6) & -\frac{K_{pi}V_{dc,o}}{L} & -\frac{K_{pv}K_{pi}V_{dc,o}+1}{L} & \frac{K_{iv}K_{pi}V_{dc,o}}{L} & \frac{K_{ii}V_{dc,o}}{L} \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C} & -\frac{1}{RC} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & -K_{pv} & K_{iv} & 0 \end{bmatrix}_{10x10}$$

$$\mathbf{B(x_o,u_o)}=\begin{bmatrix} \sqrt{\frac{3}{2}}\cdot\frac{\cos(\lambda_o)}{L_{eq}} & 0 \\ \sqrt{\frac{3}{2}}\cdot\frac{\sin(\lambda_o)}{L_{eq}} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{r_cK_{pv}K_{pi}I_{L,o}}{L_{dc}} \\ 0 & -\frac{K_{pv}K_{pi}I_{L,o}}{C_{dc}} \\ 0 & \frac{K_{pv}K_{pi}V_{dc,o}}{L} \\ 0 & 0 \\ 0 & 1 \\ 0 & K_{pv} \end{bmatrix}_{10x2}$$

$$\mathbf{C(x_o,u_o)}=\begin{bmatrix}0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0\end{bmatrix}_{1\times10}$$

$$\mathbf{D(x_o,u_o)}=\begin{bmatrix}0 & 0\end{bmatrix}_{1\times2}$$

$$a(5,7)=-\frac{2r_cK_{pi}I_{L,o}}{L_{dc}}-\frac{r_cK_{pv}K_{pi}V_{o,o}}{L_{dc}}+\frac{r_cK_{iv}K_{pi}X_{v,o}}{L_{dc}}+\frac{r_cK_{ii}X_{i,o}}{L_{dc}}+\frac{r_cK_{pv}K_{pi}V^*_{o,o}}{L_{dc}}$$

$$a(6,7)=\frac{2K_{pi}I_{L,o}}{C_{dc}}+\frac{K_{pv}K_{pi}V_{o,o}}{C_{dc}}-\frac{K_{iv}K_{pi}X_{v,o}}{C_{dc}}-\frac{K_{ii}X_{i,o}}{C_{dc}}-\frac{K_{pv}K_{pi}V^*_{o,o}}{C_{dc}}$$

$$a(7,6)=-\frac{K_{pi}I_{L,o}}{L}-\frac{K_{pv}K_{pi}V_{o,o}}{L}+\frac{K_{iv}K_{pi}X_{v,o}}{L}+\frac{K_{ii}X_{i,o}}{L}+\frac{K_{pv}K_{pi}V^*_{o,o}}{L}$$

K_{ii} = 1948 (ω_{ni} = 4000 Hz, ζ_i = 0.7). These controller parameters are designed by using the classical method [14] that will be explained in Section III.

TABLE I
THE PARAMETERS OF THE SYSTEM IN FIG. 1

Parameter	Value
V_s	50 $V_{rms/phase}$
ω	2πx50 rad/s
R_{eq}	0.1 Ω
L_{eq}	24 µH
C_{eq}	2 nF
r_L	0.01 Ω
r_c	0.4 Ω
L_{dc} ($\Delta I_{dc} \leq$ 0.5 A)	50 mH
C_{dc} ($\Delta V_{dc} \leq$ 10 V)	500 µF
L ($\Delta I_L \leq$ 0.5 A)	14.168 mH
C ($\Delta V_o \leq$ 50 mV)	125 µF
R	20 Ω

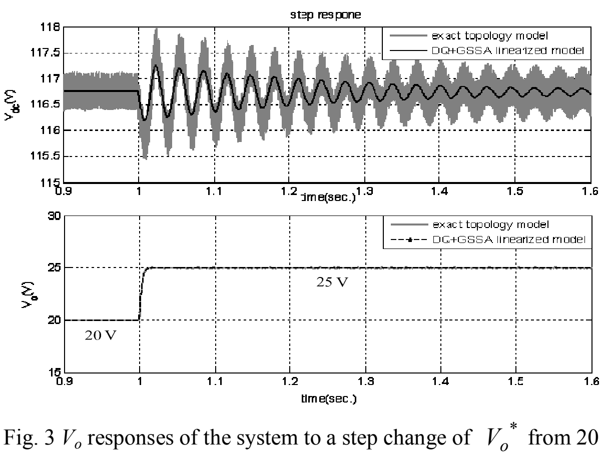

Fig. 3 V_o responses of the system to a step change of V_o^* from 20 to 25 V

Fig. 3 shows the comparison results between the mathematical model and the full topology model for *Vdc* and *Vo* responses of the system in Fig. 1 to a step change of V_o^* from 20 to 25 V that occurs at t = 1 second. From the results in Fig. 3, an excellent agreement between both models is achieved under the small-signal simulation. It confirms that the mathematical model of the power system with a controlled buck converter derived from both DQ and GSSA methods provide a good accuracy. Moreover, the simulation time when the system was simulated via the proposed model coding in MATLAB requires 0.2 second, while the full topology model of SPS[TM] consumes 90 second. The comparison of simulation time demanded from both models can be illustrated in terms of computational saving time that can be defined by:

$$\%t_{saving} = \frac{t_{fs} - t_{av}}{t_{fs}} \times 100\% \tag{3}$$

where t_{fs} and t_{av} are the simulation times of full topology model and the proposed averaging model, respectively. Therefore, according to (3), the $\%t_{saving}$ = 99.78% is obtained when the proposed model is applied to simulate the system. Hence, the proposed model is suitable for the optimal controller design of the buck converter via the ATS techniques because the very fast simulation time can be achieved.

III. Controller Design

In this section, the controller designs for the buck converter via the classical and ATS methods are illustrated.

A. Classical method

The details of classical method for PI controller design based on the work in [14] can be summarized as follows:

1. Current loop control

The schematic of the current loop control of the system in Fig. 1 is shown in Fig. 4.

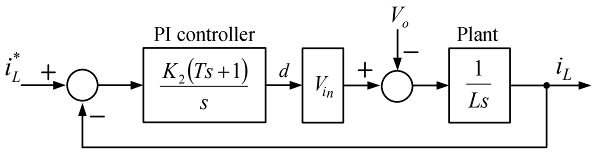

Fig. 4 Current loop control

In Fig. 4, the K_2 and T are the coefficients of current loop controller, while L is the inductor of the buck converter. Closed loop transfer function of the current loop is given by:

$$\frac{i_L}{i_L^*} = \frac{K_2 V_{in}(Ts+1)}{Ls^2 + K_2 T V_{in} s + K_2 V_{in}} \tag{4}$$

The closed loop denominator has roots with ω_n and ζ. The standard second order form is

$$s^2 + 2\zeta\omega_n s + \omega_n^2 \tag{5}$$

Hence, the current loop controller can be designed by comparing between the denominator of (4) and (5) to yield:

$$T = \frac{2\zeta_i}{\omega_{ni}} \tag{6}$$

and

$$\omega_{ni} = N\omega_{nv} = \sqrt{\frac{K_2 V_{in}}{L}}, N > 4 \tag{7}$$

From (7), K_2 can be calculated by

$$K_2 = \frac{\omega_{ni}^2 L}{V_{in}} \tag{8}$$

The PI controller in Fig. 4 can be rewritten in the form:

$$K_{pi} + \frac{K_{ii}}{s} = \frac{K_2(Ts+1)}{s} \tag{9}$$

According to (6), (8) and (9), the PI controller parameters (K_{pi} and K_{ii}) can be designed by

$$K_{pi} = K_2 T = \frac{2\zeta_i \omega_{ni} L}{V_{in}} \tag{10}$$

$$K_{ii} = K_2 = \frac{\omega_{ni}^2 L}{V_{in}} \tag{11}$$

2. Voltage loop control

The schematic of the voltage loop control of the system in Fig. 1 is shown in Fig. 5.

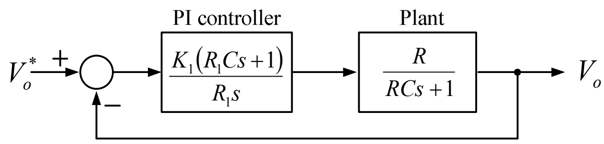

Fig. 5 Voltage loop control

In Fig. 5, the K_1 and R_1 are the coefficients of voltage loop controller, while C and R are the capacitor and resistive load of the buck converter, respectively. Closed loop transfer function of the voltage loop is given by:

$$\frac{V_o(s)}{V_o^*(s)} = \frac{K_1 R_1 RCs + K_1 R}{R_1 RCs^2 + (R_1 + K_1 R_1 RC)s + K_1 R} \tag{12}$$

Therefore, the voltage loop controller can be designed by comparing between the denominator of (5) and (12) to yield:

$$\omega_{nv} = \sqrt{\frac{K_1}{R_1 C}} \tag{13}$$

$$2\zeta_v \omega_{nv} = \frac{1}{RC} + K_1 \quad (14)$$

Setting $R = R_1$ and $\zeta_v = 1$ for the critically damped response [14] gives:

$$\omega_{nv} = \sqrt{\frac{K_1}{R_1 C}} \quad (15)$$

$$2\omega_{nv} = \frac{1}{R_1 C} + K_1 \quad (16)$$

From (15) and (16), K_1 can be calculated by:

$$K_1 = \frac{1}{R_1 C} \quad (17)$$

Under this condition, the bandwidth of voltage loop becomes

$$\omega_{nv} = \frac{1}{R_1 C} \quad (18)$$

The PI controller in Fig. 5 can be rewritten in the form:

$$K_{pv} + \frac{K_{iv}}{s} = \frac{K_1 (R_1 C s + 1)}{R_1 s} \quad (19)$$

According to (17) and (19), the PI controller parameters (K_{pv} and K_{iv}) can be designed by

$$K_{pv} = K_1 C = \frac{1}{R_1} \quad (20)$$

$$K_{iv} = \frac{K_1}{R_1} = \frac{1}{R_1^2 C} \quad (21)$$

In this paper, the PI controllers of both current and voltage control loops are designed by using (10), (11), (20), and (21). It can be seen that the controllers depend on the system parameters, damping ratio of voltage loop (ζ_v) and current loop (ζ_i), and the bandwidths of current loop ω_{ni} and voltage loop ω_{nv}. The PI parameters for the classical method in this paper are designed by selecting $\zeta_v = 1$, $\zeta_i = 0.7$, $\omega_{ni} = 2\pi\times4000$ rad/s, and $\omega_{nv} = 2\pi\times400$ rad/s. Hence, the PI controller parameters designed by the classical method are $K_{pv} = 0.05$, $K_{iv} = 20$, $K_{pi} = 0.6819$, and $K_{ii} = 1948$.

B. Adaptive Tabu Search (ATS) method

The controller design using the ATS searching methods is briefly explained in this section. The block diagram to explain how to search the PI controller parameters using ATS methods is shown in Fig. 6. The mathematical model derived from both DQ and GSSA method is used to simulate the system during the search process in which the computational time can considerably reduced.

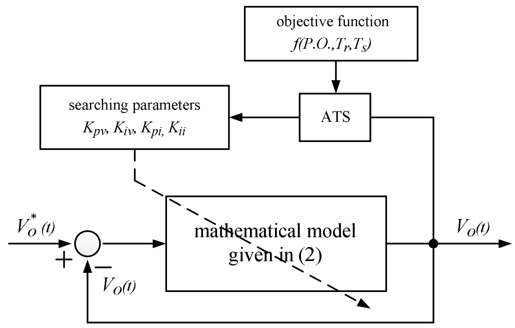

Fig. 6 The ATS methods for the PI controller design

In Fig. 6, ATS algorithm will search the controller parameters K_{pv}, K_{iv}, K_{pi}, K_{ii} in which the objective value (W) is defined by

$$W(T_r, T_s, P.O.) = \sigma T_r + \alpha T_s + \gamma P.O. \quad (22)$$

and

$$\sigma + \alpha + \gamma = 1 \quad (23)$$

where

$P.O.$ is the percent overshoot of the V_o response.
T_r is the rise time of the V_o response.
T_s is the setting time of the V_o response
σ, α, and γ are the priority coefficients of T_r, T_s, and $P.O.$, respectively.

In this paper, the values of σ, α, and γ are set to 0.33, 0.33, and 0.34, respectively. The ATS searching method will try to search the best controller parameters until the minimum W is achieved. It means that the controller parameters from the searching provide the best performance of V_o response. The ATS algorithm is developed by K-N. Areerak and S. Sujitjorn in 2002 [1]. This algorithm guarantees the optimal solution for the searching process. According to Fig. 6, the steps of searching controller parameters by using ATS are as follows:

***Step 1*:** Determine the boundary of parameters, radius value (R: the one of ATS parameters), maximum of searching iteration ($Count_{max}$). In this paper, the upper and lower limits of K_{pv}, K_{iv}, K_{pi}, K_{ii} are set to [0.05 0.1125], [20 101.25], [0.6819 3.4095], [1948 48707], respectively. These boundary values are calculated by using $\omega_{ni} = 2\pi\times2000$ to $2\pi\times20000$ rad/s and $\omega_{nv} = 2\pi\times500$ to $2\pi\times900$ rad/s with the constant ζ_i=0.8, ζ_v = 1and the system parameters as defined in Section II. Note that ω_{ni} is the bandwidth of current loop control, while ω_{nv} is the bandwidth of voltage loop control.

***Step 2*:** Random the initial value for each parameter (S_0) within the search space as defined from *Step 1* and define S_0 is the best solution in the search space (*best_neighbor*).

***Step 3*:** Random the N solutions (N neighborhood) around S_0 in the search space with radius equal to R. After that, define the set of N solutions is $S(R)$.

***Step 4*:** Evaluate the solutions in $S(R)$ with the objective function as defined in (22) and define S_1 (*best_neighbor1*) is the best solution in $S(R)$. Note that the best solution means the solution that can provide the minimum value of W. The W value can be calculated from (22) via the proposed dynamic model given in (2), The W value depends on the output voltage response of each PI controller parameter.

***Step 5*:** If $S_1 < S_0$ then define $S_0 = S_1$ and keep S_0 in the tabu list.

***Step 6*:** If $count \geq count_{max}$ then stop the ATS searching and S_0 is the best solution. However, the ATS still search the solution if $count < count_{max}$ by start the *Step 3* again. In this step, the back tracking process is used to escape the local solution.

***Step 7*:** Adjust the radius of search space with the decreasing factor (DF) by

$$radius_{new} = \left.\frac{radius_{old}}{DF}\right\} \quad (24)$$

Note that the more details of ATS algorithm can be found in [1]-[6].

IV. Simulation Results

In this section, the system as shown in Fig.1 having the controllers designed by using the ATS and the classical methods is simulated by using SPS™ in SIMULINK. The aim of the ATS approach is to minimize the W value to achieve the best output response. The comparison results of the controller parameters that are designed from the difference methods are given in Table II.

TABLE II
THE COMPARISON BETWEEN ATS AND CLASSICAL METHODS

Controller Parameters	Design Method	
	ATS Method	Classical Method
K_{pv}	0.09	0.05
K_{iv}	36.2848	20
K_{pi}	1.5667	0.6819
K_{ii}	28419	1948
W	0.003	0.072

According to Table II, the controllers designed from the ATS method provide the minimum W value compared with those of the classical method. Fig. 7 shows the V_o response to a step change of V_o^* from 20 V to 25 V that occurs at t = 1 second. The comparison result show that the output response when the controllers designed by the ATS method is better than that from the classical method in terms of percent overshoot, rise time and setting time. In addition, the convergence of W value from the ATS search is depicted in Fig. 8.

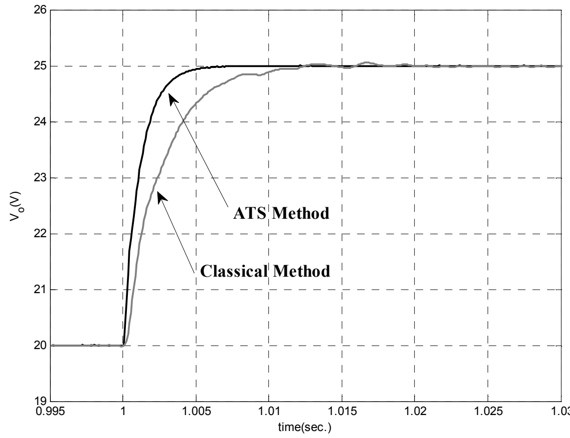

Fig. 7 Transient simulation results when the controllers designed by the classical and the ATS methods

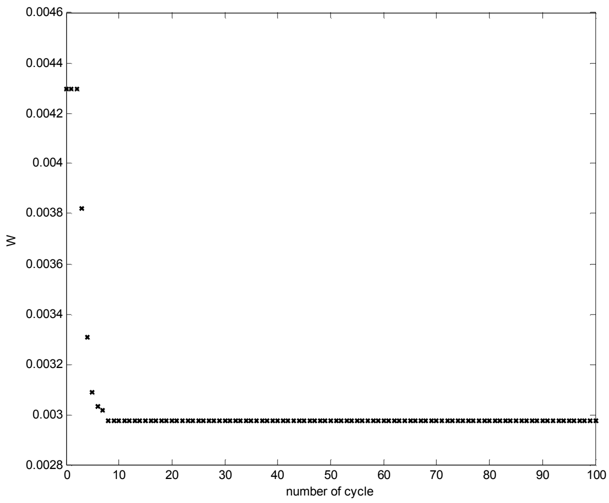

Fig. 8 The convergence of W value from ATS method

V. Conclusion

The paper presents the cooperation between the averaging model and the ATS algorithm to design the appropriate PI controller parameters of the buck converter. The resulting output response using the ATS design is better than that of the classical method. Moreover, the paper also show that the simulation of the switching converter system using the averaging model requires the fast computational time compared with the simulation time of the exact topology model from the software package. Hence, the reported dynamic model is suitable for the optimal controller design application in which the repeating calculation during the searching process is needed. The proposed design technique is very useful for engineers. For the future work, the dynamic model will be used for the stability analysis and simulations of complex power systems.

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REFERENCES

[1] D. Puangdownreong, K-N. Areerak, A. Srikaew, S. Sujijorn and P. Totarong, System Identification via Adative Tabu Search, In Proceedings *IEEE International Conference on Industrial Technology (ICIT02)*, 2002, pp.915-920.

[2] S. Sujitjorn, T. Kulworawanichpong and D. Puangdownreong and K-N Areerak, Adaptive Tabu Search and Applications in Engineering Design, *Book Chapters in Integrated Intelligent Systems for Engineering Design (ed. X. F. Zha and R..J. Howlett)*, IOS Press, The Netherlands, 2006, pp. 233-257.

[3] D. Puangdownreong, K-N. Areerak, K-L. Areerak, T. Kulworawanichpong, and S. Sujitjorn, "Application of adaptive tabu search to system identification", *IASTED International Conference on Modelling, Identification, and Control (MIC2005)*, Innsbruck, Austria: February 16-18, 2005, pp.178-183.

[4] T. Kulworawanichpong, K-L. Areerak, K-N. Areerak, P. Pao-la-or, D. Puangdownreong, and S. Sujitjorn, "Dynamic parameter identification of induction motors using intelligent search techniques", *IASTED International Conference on Modelling, Identification, and Control (MIC2005)*, Innsbruck, Austria: February 16-18, 2005, pp.328-332.

[5] T. Kulworawanichpong, K-L. Areerak, K-N. Areerak, and S. Sujitjorn, "Harmonic Identification for Active Power Filters Via Adaptive Tabu Search Method", *LNCS (Lecture Notes in Computer Science)* , Springer-Verlag Heidelberg, vol. 3215, 2004, pp. 687-694.

[6] K-N. Areerak, T. Kulworawanichpong and S. Sujitjorn, "Moving Towards a New Era of Intelligent Protection through Digital Relaying in Power Systems", *Lecture Notes in Computer Science*, Springer-Verlag Heidelberg, vol. 3213, 2004, pp. 1255-1261.

[7] T. Narongrit, K-L. Areerak, and K-N. Areerak, "Design of an Active Power Filter using Genetic Algorithm Technique", *The 9th WSEAS International Conference on Artificial Intelligent, Knowledge Engineering and Data Bases (AIKED'10),* Cambridge, United Kingdom: February 20-22, 2010, pp.46-50.

[8] U. Leeton, D. Uthitsunthorn, U. Kwannetr, N. Sinsuphun, T. Kulworawanichpong, "Power loss minimization using optimal power flow based on particle swarm optimization", *International Conference on* Electrical Engineering/Electronics Computer Telecommunications and Information Technology (ECTI-CON), Chaing Mai: May 19-21, 2010, pp. 440-444.

[9] G. Lirui, H. Limin, Z. Liguo, L. Weina, and H. Jie, "Reactive Power Optimization for sidtribution systems based on Dual Population Ant Colony Optimization," in *Proc. 27th Chinese Control Conference (CCC 2008)*., China, pp. 89-93.

[10] J. Mahdavi, A. Emadi, M.D. Bellar, and M. Ehsani, Analysis of Power Electronic Converters Using the Generalized State-Space Averaging Approach, *IEEE Trans. on Circuit and Systems.*, *Vol. 44*, August 1997, pp.767-770.

[11] A. Emadi, Modeling and Analysis of Multiconverter DC Power Electronic Systems Using the Generalized State-Space Averaging Method, *IEEE Trans. on Indus. Elect.*, *Vol. 51*, *n. 3*, June 2004, pp. 661-668.

[12] K-N. Areerak, S.V. Bozhko, G.M. Asher, and D.W.P. Thomas, 2008. "DQ-Transformation Approach for Modelling and Stability Analysis of AC-DC Power System with Controlled PWM Rectifier and Constant Power Loads," in *Proc. 13th International Power Electronics and Motion Control Conference (EPE-PEMC 2008).,* Poznan, Poland.

[13] K. Chaijarurnudomrung, K-N. Areerak, and K-L. Areerak, 2010. "Modeling of Three-phase Controlled Rectifier using a DQ method", *2010 International Conference on Advances in Energy Engineering (ICAEE 2010)*, pp.56-59.

[14] K.M. Tsang and W.L. Chan, "Cascade controller for DC/DC buck convertor," *IEE Electric Power Applications*, vol. 152, no. 4, 2005, pp. 827-831.

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