Application of Adaptive Tabu Search for Optimum PID Controller tuning AVR System

ANANT OONSIVILAI and PADEJ PAO-LA-OR
Alternative and Sustainable Energy Research Unit (ASER-U), Power and Control Research Group
School of Electrical Engineering,
Institute of Engineering, Suranaree University of Technology
111 University Street, Muang District, Nakhon Ratchasima, 30000
THAILAND
anant@sut.ac.th, padej@sut.ac.th, http://www.sut.ac.th

Abstract: - This paper postulates the ascertainment of offline, optimal proportional-integral-derivative (PID) controller parameters of an automatic voltage regulator (AVR) system using Adaptive Tabu Search (ATS) algorithm. By minimizing the performance index such as integrated absolute error (IAE), the integral of squared error (ISE), and the integral time absolute error (ITAE) employed method, the parameters of this PID controller is acquired. For significant contrast, the classical tuning proposed by Ziegler and Nichols is applying compared with demostrated method. The performance of the proposed tuning mechanism had been demonstrated and analysed in efficient and robust in improving the step response of an AVR system with application to control of synchronous generator excitation system by selecting the suitable performance index.

Key-Words: - Optimal control, AVR, Excitation system, PID controller, Adaptive Tabu Search

1 Introduction

In Hydro and Thermal power plants the generator excitation system preserves generator voltage and controls the reactive power flow using an automatic voltage regulator (AVR) [1]-[2]. The stability of a synchronous generator which connects to power system would critically affect the security of the power system which depends on the role of AVR.

In process plants, several control theories techniques have been developed. Many control methods such as adaptive control have been developed [3]-[5].

The widely popular use of PID controllers in the process control and instrumentation of industry because of its straight forward structure which can be simply implemented and established in a wide range of operating condition with robust performance. Although it has simple structure but it also has been hardly setup to PID controller parameters properly. The classical tuning rules proposed by Ziegler and Nichols are often difficult to find optimal PID parameters.

Many artificial intelligence (AI) techniques have been vitalized to re-association basic characteristics of controller to improve the controller performance by adding new feature or new criterion. Proper tuning PID controller parameters is using AI techniques for instance fuzzy logic system, neural network, and neural-fuzzy logic system [3][4]. Not only proper tuning PID but also optimum tuning PID has been applied by many random search methods such as genetic algorithm (GA), simulated annealing (SA) and evolutionary computational techniques (EC).

This paper focuses on optimal tuning of PID controller for the AVR system using adaptive tabu search (ATS). Tabu search (TS) is one of the modern heuristic algorithms while introduced by [6]-[8]. Many performance estimation schemes are performed by ATS method to obtain the optimum PID controller parameters of an AVR system. The proposed method has better performance than classical Ziegler and Nichols method in working out the optimal PID controller parameters.

2. Representative of synchronous machine excitation systems in power system studies

Excitation control elements include both excitation regulating and stabilizing functions. The terms “ excitation system stabilizer” and “transient gain reduction” are used to describe circuits inseveral of the models emcompassed by the excitation control elements that afect the stability and response of those systems [25].

2.1 Type DC-Direct current commutator exciter

Few new synchronous machines are being equipped with Type DC exciters, which have been superseded by Type AC and ST systems. However many such systems are still in service. Considering the dwindling percentage and importance of units equipped with these exciters, the previously developed concept of accounting for loading effects on the exciter by using the loaded saturation curve is considered adequate.

2.1.1 Type DC 1A excitation system model

This model, described by the block diagram of Figure 1, is used to represent field-controlled dc commutator exciters with continuously acting voltage regulators (especially the direct-acting rheostatic, rotating amplifier, and magnetic amplifier types). Because this model has been widely implemented by the industry, it is sometimes used to represent other types of systems when detailed data for them are not available or when a simplified model is required.

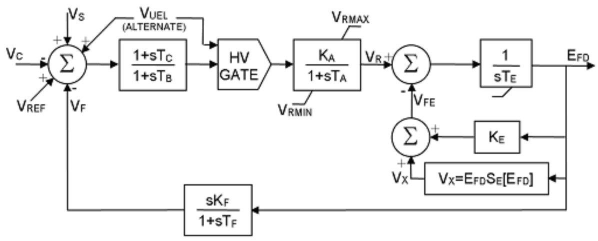

Figure 1 Type DC1A-DC commutator exciter[25].

2.1.2 Type DC2A excitation system model

The model shown in Figure 2 is used to represent field-controlled dc commutator exciters with continuously acting voltage regulators having supplies obtained from the generator or auxiliary bus. It differs from the Type DC1A model only in the voltage regulator output limits, which are now proportional to terminal voltage V_T .

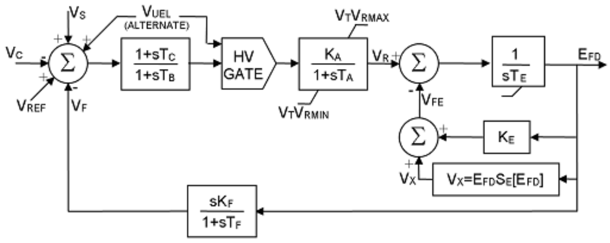

Figure 2 Type DC2A-DC commutator exciter with bus-fed reulator[25].

2.1.3 Type DC3A excitation system model

The Type DC3A model is used to represent older systems, in particular those dc commutator exciters with non-continuously acting regulators that were commonly used before the development of the continuously acting varieties.

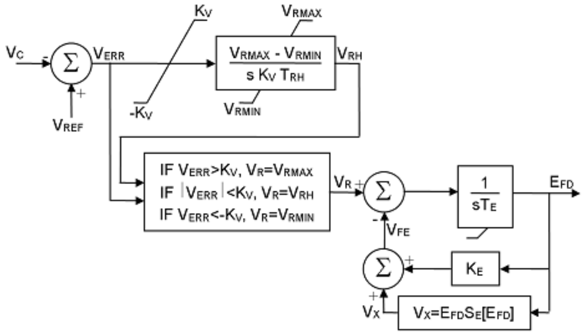

Figure 3 Type DC3A-DC commutator exciter with non-continuously acting regulators[25].

2.1.4 Type DC4B excitation system model

These excitation systems utilize a field-controlled dc commutator exciter with a continuously acting voltage regulator having supplies obtained from the generator or auxiliary bus. The replacement of the controls only as an upgrade (retaining the dc commutator exciter) has resulted in a new model. The block diagram of this model is shown in Figure 4. This excitation system typically includes a proportional, integral, and differential (PID) generator voltage regulator (AVR). An alternative rate feedback loop (K_F , T_F) for stabilization is also shown in the model if the AVR does not include a derivative term. If a PSS control is supplied, the appropriate model is the Type PSS2B model.

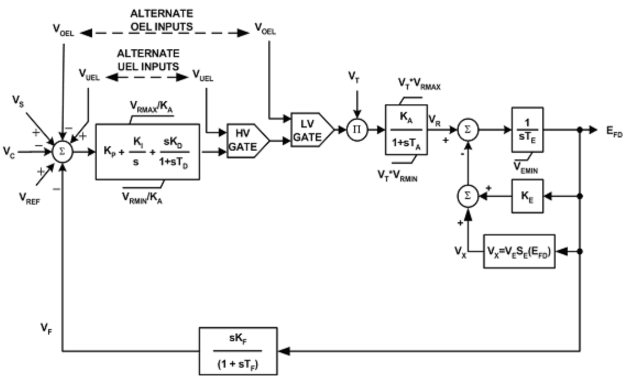

Figure 4 Type DC4B-DC commutator exciter with PID style regulator [25].

2.2 Type AC-Alternator-supplied rectifier excitation systems

These excitation systems use an ac alternator and either stationary or rotating rectifiers to produce the dc field requirements. Loading effects on such exciters are significant, and the use of generator field current as an input to the models allows these effects to be represented accurately. These systems do not allow the supply of negative field current, and only the Type AC4A model allows negative field voltage forcing.

Modeling considerations for induced negative field currents are discussed in Annex G. If these models are being used to design phase lead networks for PSSs, and the local mode is close to 3 Hz or higher, a more detailed treatment of the ac machine may be needed. However, the models will be satisfactory for large scale simulations.

2.2.1 Type AC1A excitation system model

The model shown in Figure 6-1 represents the field-controlled alternator-rectifi er excitation systems designated Type AC1A. These excitation systems consist of an alternator main exciter with non-controlled rectifiers. The exciter does not employ self-excitation, and the voltage regulator power is taken from a source that is not affected by external transients. The diode characteristic in the exciter output imposes a lower limit of zero on the exciter output voltage, as shown in Figure 5.

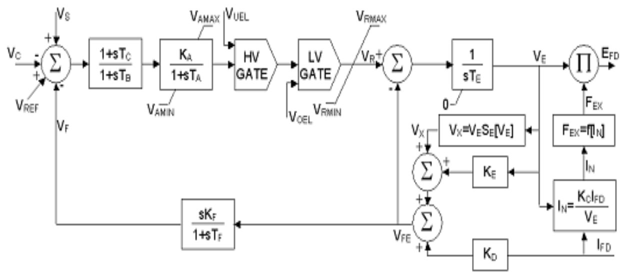

Figure 5 Type AC1A—Alternator-rectifier xcitation system with non-controlled rectifiers and feedback from exciter field current [25].

2.2.2. Type AC2A excitation system model

The model shown in Figure 6, designated as Type AC2A, represents a high initial response field-controlled alternator-rectifier excitation system. The alternator main exciter is used with non-controlled rectifiers. The Type AC2A model is similar to that of Type AC1A except for the inclusion of exciter time constant compensation and exciter field current limiting elements.

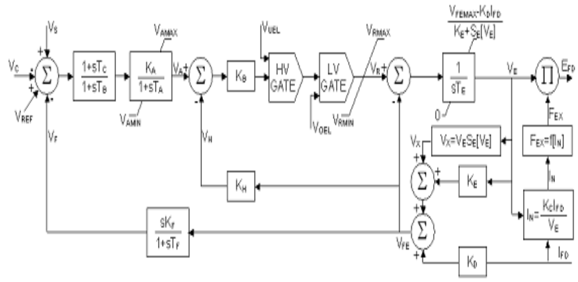

Figure 6 Type AC2A—High initial response alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current [25].

2.2.3 Type AC3A excitation system model

The model shown in Figure 7, represents the field-controlled alternator-rectifier excitation systems designated Type AC3A. These excitation systems include an alternator main exciter with non-controlled rectifiers. The exciter employs self-excitation, and the voltage regulator power is derived from the exciter output voltage. Therefore, this system has an additional nonlinearity, simulated by the use of a multiplier whose inputs are the voltage regulator command signal, V_A, and the exciter output voltage, E_{FD}, time K_R . This model is applicable to excitation systems employing static voltage regulators.

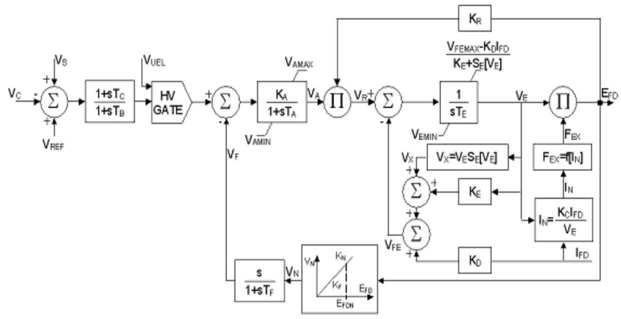

Figure 7 Type AC3A—Alternator-rectifier exciter with alternator field current limiter[25].

2.2.4 Type AC4A excitation system model

The Type AC4A alternator-supplied controlled-rectifier excitation system illustrated in Figure 8 is quite different from the other type ac systems. This high initial response excitation system utilizes a full thyristor bridge in the exciter output circuit.

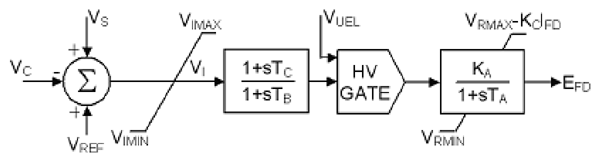

Figure 8 Type AC4A alternator-supplied controlled-rectifier exciter[25].

2.2.5 Type AC5A excitation system model

The model shown in Figure 10, designated as Type AC5A, is a simplified model for brushless excitation systems. The regulator is supplied from a source, such as a permanent magnet generator, which is not affected by system disturbances.

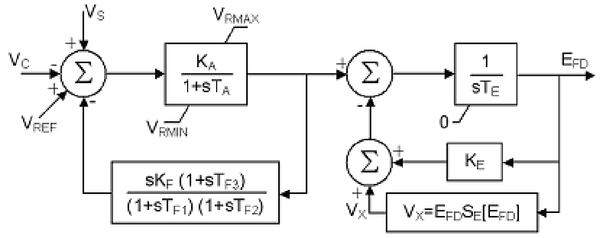

Figure 9 Type AC5A—Simplified rotating rectifier excitation system representative [25].

2.2.6 Type AC6A excitation system model

The model shown in Figure 10 is used to represent field-controlled alternator-rectifier excitation systems with system-supplied electronic voltage regulators. The maximum output of the regulator, V is a function R, of terminal voltage, V .

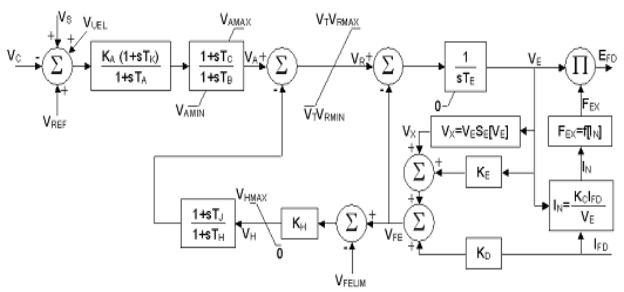

Figure 10 Type AC6A—Alternator-rectifier excitation system with non-controlled rectifiers and system-supplied electronic voltage regulator [25].

2.2.7 Type AC7B excitation system model

These excitation systems consist of an ac alternator with either stationary or rotating rectifiers to produce the dc field requirements. Upgrades to earlier ac excitation systems, which replace only the controls but retain the ac alternator and diode rectifier bridge, have resulted in this new model, as shown in Figure 11. Some of the features of this excitation system include a high bandwidth inner loop regulating generator field voltage or exciter current (K_{F2} , K_{F1}), a fast exciter current limit, V_{FEMAX} , to protect the field of the ac alternator, and the PID generator voltage regulator (AVR). An alternative rate feedback loop (K_F , T_F) is provided for stabilization if the AVR does not include a derivative term. If a PSS control is supplied, the Type PSS2B or PSS3B models are appropriate.

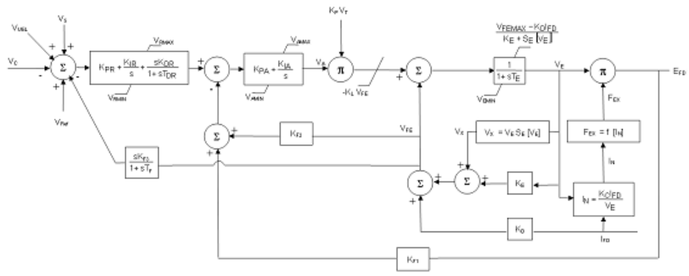

Figure 11 Type AC7B—Alternator-rectifier excitation system [25].

2.2.8 Type AC8B excitation system model

The block diagram of the AC8B model is shown in Figure 12. The AVR in this model consists of PID control, with separate constants for the proportional (K_{PR}), integral (K_{IR}), and derivative (K_{DR}) gains. The values for the constants are chosen for best performance for each particular generator excitation system. The representation of the brushless exciter (T_E , K_E , S_E K_C , K_D) is similar to the model Type AC2A. Sample data for this model is shown in Annex H. The Type AC8B model can be used to represent static voltage regulators applied to brushless excitation systems. Digitally based voltage regulators feeding dc rotating

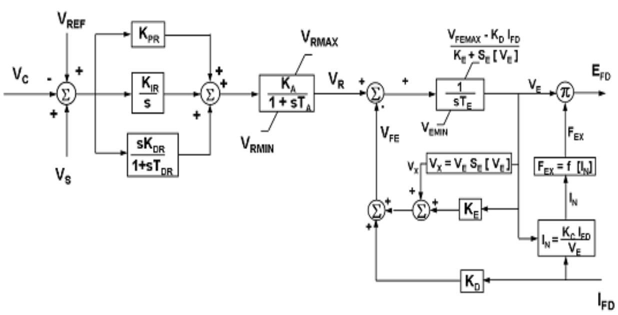

Figure 12 Type AC8B—Alternator-rectifier excitation system [25].

2.3 Type ST—Static excitation systems

In these excitation systems, voltage (and also current in compounded systems) is transformed to an appropriate level. Rectifiers, either controlled or non-controlled, provide the necessary direct current for the generator field.

2.3.1 Type ST1A excitation system model

The computer model of the Type ST1A potential-source controlled-rectifier excitation system shown in Figure 13 is intended to represent systems in which excitation power is supplied through a transformer from the generator terminals (or the unit's auxiliary bus) and is regulated by a controlled rectifier. The maximum exciter voltage available from such systems is directly related to the generator terminal voltage.

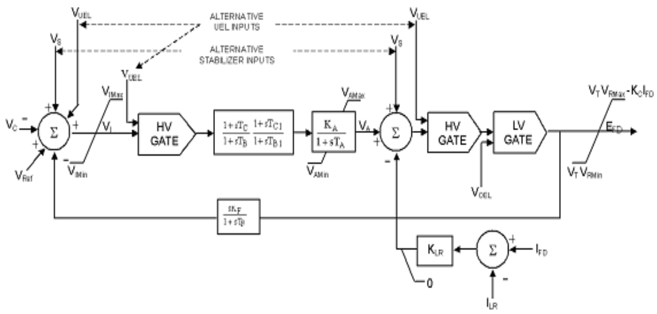

Figure 13 Type ST1A—Potential-source, controlled-rectifier exciter [25].

2.3.2 Type ST2A excitation system model

Some static systems utilize both current and voltage sources (generator terminal quantities) to comprise the power source. These compound-source rectifier excitation systems are designated Type ST2A and are modeled as shown in Figure 14. It is necessary to form a model of the exciter power source utilizing a phasor combination of terminal voltage, V_T , and terminal current, I_T . Rectifier loading and commutation effects are accounted. E_{FDMAX} represents the limit on the exciter voltage due to saturation of the magnetic components. The regulator controls the exciter output through controlled saturation of the power transformer components. T_E is a time constant associated with the inductance of the control windings.

2.3.3 Type ST3A excitation system model

Some static systems utilize a field voltage control loop to linearize the exciter control characteristic as shown in Figure 15. This also makes the output independent of supply source variations until supply limitations are reached. These systems utilize a variety of controlled-rectifier designs: full thyristor complements or hybrid bridges in either series or shunt configurations. The power source may consist of only a potential source, either fed from the machine terminals or from internal windings. Some

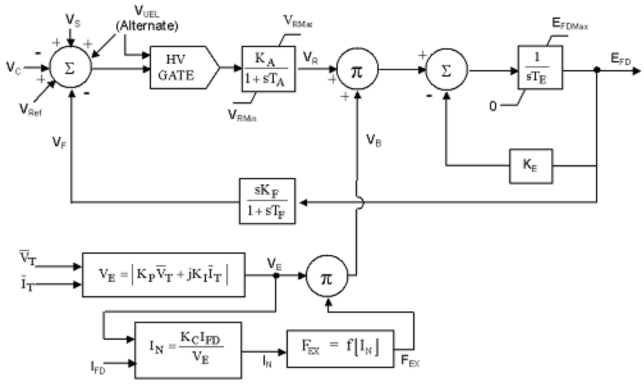

Figure 14 Type ST2A—Compound-source rectifier exciter [25].

designs may have compound power sources utilizing both machine potential and current. These power sources are represented as phasor combinations of machine terminal current and voltage and are accommodated by suitable parameters in the model shown.

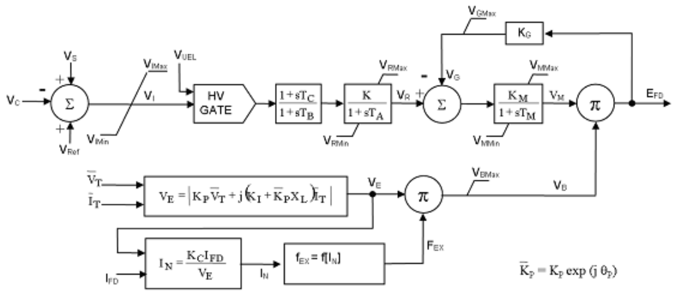

Figure 15 Type ST3A—Potential- or compound-source controlled-rectifier exciter with field voltage control loop [**25**].

2.3.4 Type ST4B excitation system model

This model is a variation of the Type ST3A model, with a proportional plus integral (PI) regulator block replacing the lag-lead regulator characteristic that was in the ST3A model. Both potential- and compound-source rectifier excitation systems are modeled as shown in Figure 16. The PI regulator blocks have non-windup limits that are represented. The voltage regulator of this model is typically implemented digitally.

2.3.5 Type ST5B excitation system model

The Type ST5B excitation system shown in Figure 17 is a variation of the Type ST1A model, with alternative overexcitation and underexcitation inputs and additional limits. The corresponding stabilizer models that can be used with these models are the Type PSS2B, PSS3B, or PSS4B.

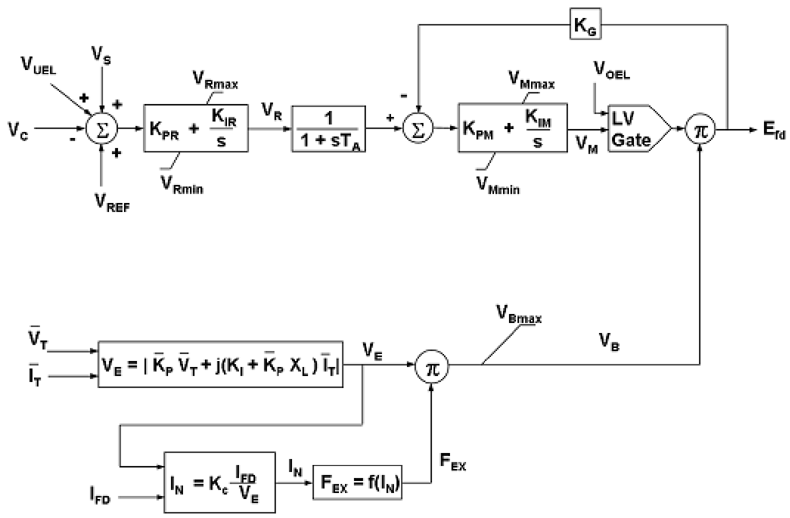

Figure 16 Type ST4B—Potential- or compound source controlled-rectifier exciter[25].

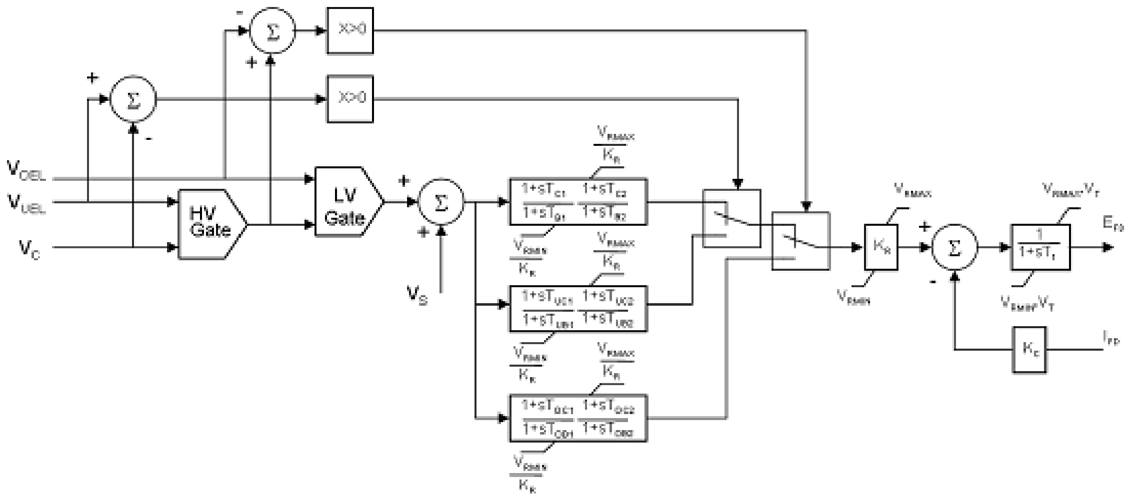

Figure 17 Type ST5B—Static Potential- source excitation system [25].

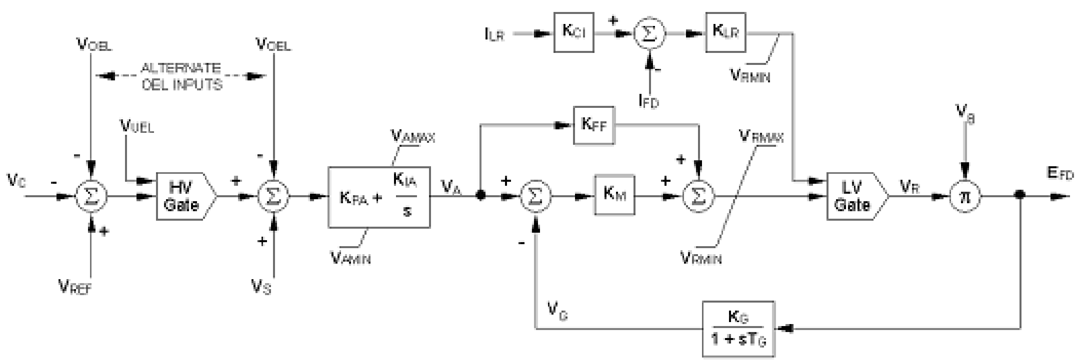

Figure 18 Type ST6B—Static Potential- source excitation system with field current limiter [25].

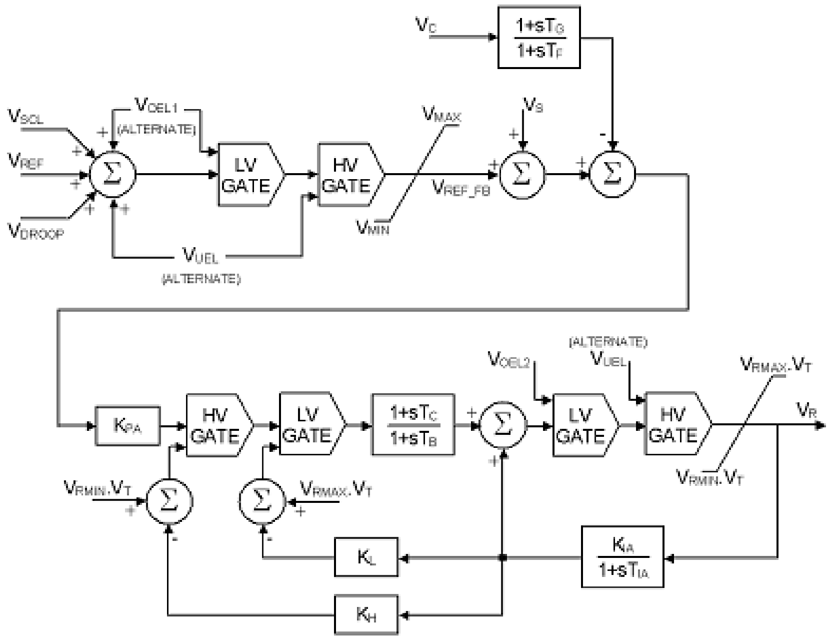

Figure 19 Type ST7B—Static Potential- source excitation system [25].

2.3.6 Type ST6B excitation system model

The AVR shown in Figure 18 consists of a PI voltage regulator with an inner loop field voltage regulator and pre-control. The field voltage regulator implements a proportional control. The pre-control and the delay in the feedback circuit increase the dynamic response. If the field voltage regulator is not implemented, the corresponding parameters K_{FF} and K_G are set to 0. V_R represents the limits of the power rectifier. The ceiling current I_{FD} limitation is included in this model. The power for the rectifier, V_B , may be supplied from the generator terminals or from an independent source. Inputs are provided for external models of the overexcitation limiter (V_{OEL}), underexcitation limiter (V_{UEL}), and PSS (V_S).

2.3.7 Type ST7B excitation system model

The model ST7B in Figure 19 is representative of static potential-source excitation systems. In this system, the AVR consists of a PI voltage regulator. A phase lead-lag filter in series allows introduction of a derivative function, typically used with brushless excitation systems. In that case, the regulator is of the PID type. In addition, the terminal voltage channel includes a phase lead-lag filter.

3 Simplified Excitation Control Systems

A simple excitation control system comprises basic AVR function and four main components, namely amplifier, exciter, generator, and sensor. The terminal voltage magnitude of a synchronous generator is hold by an AVR at specified rated point. For mathematical modeling and transfer function of the four components, these components are required to linear, which takes into relation the major time constant and ignores the saturation or other nonlinearities. The practical transfer function of these components may be shown as follows [9], [26-27]

3.1 Amplifier model

The amplifier model can be described by a gain K_A and a time constant T_A ; the transfer function is

$$\frac{v_R(s)}{v_e(s)} = \frac{K_A}{1+T_A s} \tag{1}$$

Usual values of K_A are in the range of 10 to 400. The amplifier time constant T_A is very small ranging from 0.02 to 0.1 s.

3.2 Exciter model

A modern exciter transfer function is modeled by a gain K_E and a single time constant T_E

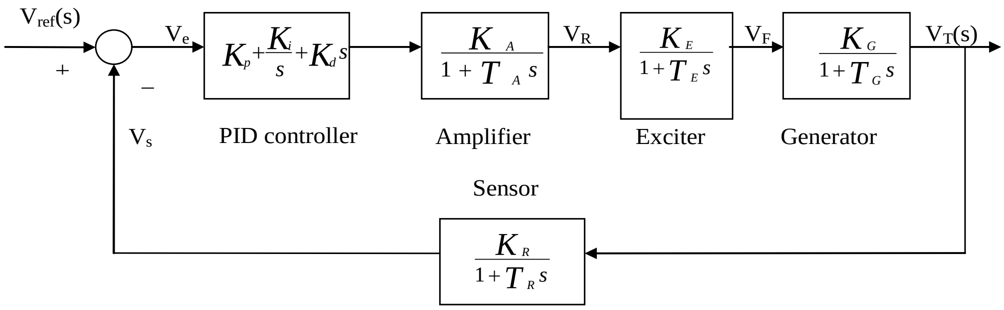

Fig. 20. Block diagram of an excitation control system with PID controller.

$$\frac{v_F(s)}{v_R(s)} = \frac{K_E}{1+T_E s} \quad (2)$$

Typical values of K_E are in the range of 1 to 400. The time constant T_E is in the range of 0.1 to 1.0 s.

3.3 Generator model

In the linearized model, the transfer function relating the generator terminal voltage to its field voltage can be represented by a gain and a time constant T_G

$$\frac{v_t(s)}{v_F(s)} = \frac{K_G}{1+T_G s} \quad (3)$$

These constants are load dependent, may vary between 0.7 to 1.0, and between 1.0 and 2.0 s from full load to no load.

3.4 Sensor model

A sensor may be represented by a simple first-order transfer function, given by

$$\frac{v_s(s)}{v_t(s)} = \frac{K_R}{1+T_R s} \quad (4)$$

Normal T_R is very small, ranging from of 0.001 to 0.06 s.

3.5 PID Controller

The PID controller is accustomed to improve the dynamic response in addition to reduce or eliminate the steady-state error. The transient response is improved by the derivative controller in PID adds a finite zero to the open-loop plant transfer function. The steady-state error due to a step function to zero is reduced by the integral controller in PID adds a pole at the origin, thus increasing system type by one. The PID controller transfer function is shown

$$C(s) = k_p + \frac{k_i}{s} + k_d s \quad (5)$$

3.6 Performance Evaluation of PID Controller

In most cases, the PID controller performance evaluation technique using the integrated absolute error (IAE), the integral of squared error (ISE), or the integrated of time weighted absolute error (ITAE) is frequently engaged in control system design because it can be appraised methodically in the frequency domain [10]–[13]. In the frequency domain, an integral performance criterion's had advantages and disadvantages. For instance, disadvantage of IAE and ISE criteria is its minimization could result in a response with small overshoot but long settling time de to ISE performance criterion weights all errors time independently. Although ITAE performance criterion could overcome this disadvantage, the derivation processes of analytical formula are complex and time-consuming [13]. The IAE, ISE, and ITAE performance criterion formulas are represented as follows:

$$\text{IAE} = \int_0^\infty |r(t) - y(t)|\, dt = \int_0^\infty |e(t)|\, dt \quad (6)$$

$$\text{ISE} = \int_0^\infty e^2(t)\,dt \quad (7)$$

$$\text{ITAE} = \int_0^\infty t\left|e(t)\right|dt \quad (8)$$

4. Adaptive Tabu Search Algorithm

The tabu search (TS) algorithm is an iterative search that starts from some initial feasible solution and attempts to determine a better solution in the manner of a hill-climbing algorithm. TS is commonly developed for solving local optimization problem. The algorithm keeps historical local optima for leading to the near-global optimum fast and efficiently. The local optima are kept in Tabu List (TL) for making sure that there will be no same local optimum happening again in the process. Another powerful tool in TS is called backtracking. Backtracking process starts from stepping back to some local optimum in TL and then searching a new optimum in different directions. Backtracking is performed when the backtracking criterion (BC) is encountered.

The TS algorithm has a flexible memory in which to maintain the information about the past step of the search and uses it to create and exploit the better solutions. The main two components of the TS algorithm are the tabu list (TL) restrictions and the aspiration criterion (AC). Well description and detail of adaptive tabu search (ATS) can be found in [14]-[16].

In applying the ATS algorithm, to solve a combinatorial optimization problem, the basic idea is to choose a feasible solution at random and then obtain a neighbor to this solution. A move to this neighbor is performed if either it does not belong to the TL or, in case of being in the TL it passes the AC test. During these search procedures the best solution is always updated and stored aside until the stopping criterion is satisfied [17].

The following notations are used through the description of the ATS algorithm for a general combinatorial optimization problem:

X : the set of feasible solutions.
x : the current solution, $x \in X$
xb : the best solution reached.
xnb : the best solution among trial solutions.
E(x) : the objective function of solution x
N(x) : the set of neighborhood of $x \in X$
TL : tabu list.
AL : aspiration level.

The procedure of the ATS algorithm is as follow:
Step 0: Set TL as empty and AC as zero.
Step 1: Set iteration counter k = 0 . Select an initial solution $x \in X$, and set xb = x .
Step 2: Generate a set of trial solutions in the neighborhood of x. Let xnb be the best trial solution.
Step 3: If E(xnb) > E(xb) , go to Step 4, otherwise set the best solution xb = xnb and go to Step 4.
Step 4: Perform the tabu test. If xnb is NOT in the TL, then accept it as a current solution, set x = xnb , and update the TL and AC and go to Step 6, otherwise go to Step 5.
Step 5: Perform the AC test. If satisfied, then override the tabu state, set x = xnb , and update the AC.
Step 6: Perform the termination test. If the stopping criterion is satisfied then stop, otherwise - Activate the AR (adaptive search redius) mechanism to speed up the searching process. - Activate the BT mechanism if a local minimum trap occurs. Reset Iteration and repeat step 2.

Based on ATS algorithm, PID controller can be identified using the flow chart show in Fig.21.

Although in this paper, the PID controller parameters were obtained using adaptive tabu search technique. For comparison, however, the PID controller parameters were also obtained using the conventional Zeeigler-Nichols tunning technique [1-3, 23-24].

5. Results and Discussions

By using ATS techniques conjunction with the equation of performance criterion (6-8),[1-3],[18-21], optimal controller parameters were obtained as shown in Table 1.

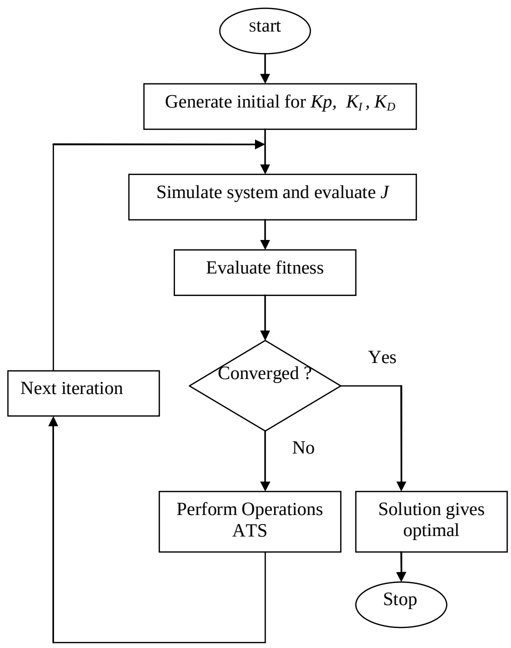

Figure 21 Flow chart for the ATS process.

Table 1 Optimal Controller Parameter after using ATS technique.

Performance index	K_P	K_I	K_D
IAE	99.8181	99.9908	11.7996
ISE	99.7361	99.8021	99.5959
ITAE	99.3463	99.9443	0.7531

Performance of the ATS based PID controller was compared with conventionally tuned PID controller. Bound values of PID Controller parameters in ATS algorithm are depicted in Table 2.

Table 2 Bound of the PID parameters.

PID parameters	Range	
	Min	Max
K_P	0	100
K_I	0	100
K_D	0	100

Fig. 22, Fig. 23, Fig. 24 and Fig.25 show the time domain performance of the AVR system with ATS turned controller. System was simulated for 30 seconds with step response in reference voltage of AVR summing. Disturbance was given at starting time. Time response with the conventional PID controller is also plot.

The ATS tuned controller IAE result in Fig 22 gave long setting time, while the ATS tuned controller ISE result in Fig 23 gave high overshoot and more swing. As seen in the time response, the ATS tuned controller ITAE performance index gave better performance in terms of overshoot and setting time the ATS based controller oscillations are damped out within 4 seconds this shows the efficacy of the ATS tuned PID controller over the performance of the conventionally tuned PID controller (Ziegler-Nichols method).

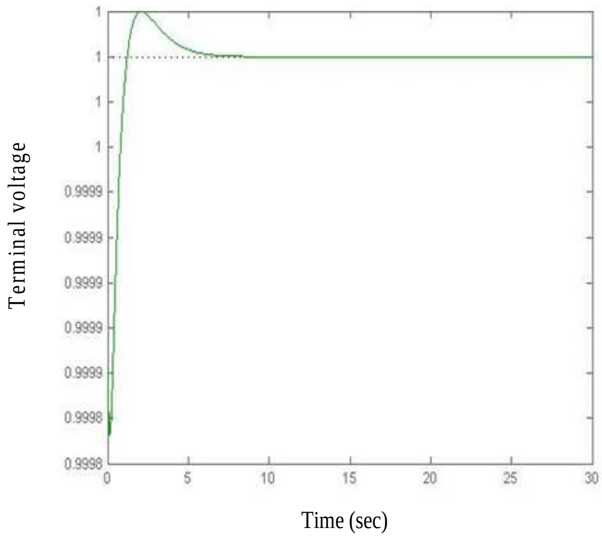

Figure 22 Terminal voltage step response of an AVR (Excitation) system with ATS using IAE performance index.

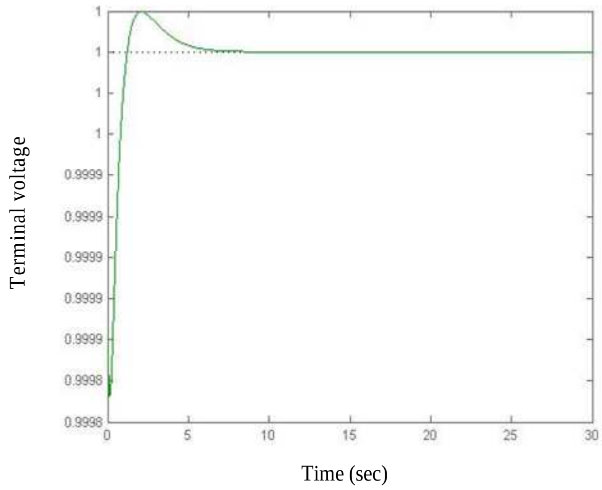

Figure 23 Terminal voltage step response of an AVR (Excitation) system with ATS using ISE condition.

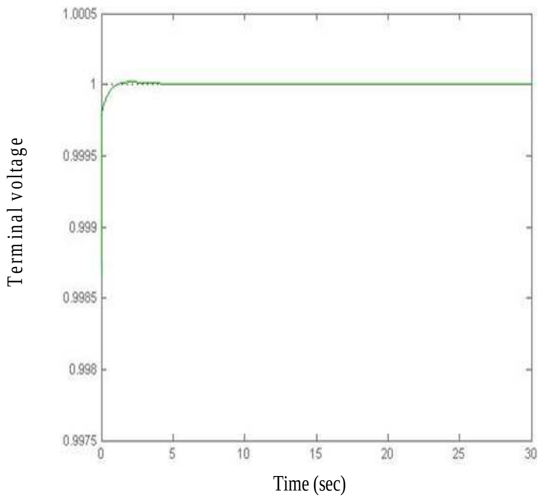

Figure 24 Terminal voltage step response of an AVR (Excitation) system with ATS using ITAE performance index.

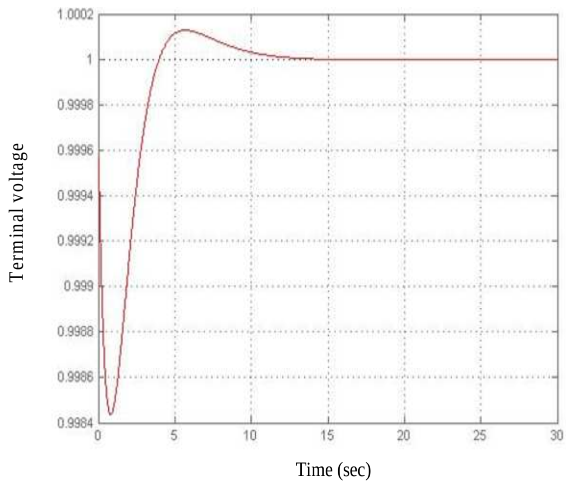

Figure 25 Terminal voltage step response of an AVR (Excitation) system with ATS using Ziegler-Nichols performance index.

5. Conclusion

The outcomes illustrated in this paper show that adaptive tabu search technique could be used for tuning and designing more proficient AVR controllers. Performance evaluation of ATS based controller of synchronous generator excitation system shows that its performance is superior than that could be obtained by conventionally tuned controller. The advantage of ATS technique is independent of the complexity of performance index considered. From the result, ATS method perform depend on the performance index, user should choose the proper performance index which responding the system condition. In addition, the design method is straightforward much prospective for realistic implementation.

References:

[1] G. Cheng, Genetic Algorithms & Engineering Design. New York: Wiley, 1997.
[2] H. Saadat, Power System Analysis. New York: McGraw-Hill, 1999.
[3] A. Visioli, “Tuning of PID controllers with fuzzy logic,” Proc. Inst. Elect. Eng. Contr. Theory Applicat., vol. 148, no. 1, pp. 1–8, Jan. 2001.
[4] T. L. Seng, M. B. Khalid, and R. Yusof, “Tuning of a neuro-fuzzy controller by genetic algorithm,” IEEE Trans. Syst., Man, Cybern. B, vol. 29, pp. 226–236, Apr. 1999.
[5] R. A. Krohling and J. P. Rey, “Design of optimal disturbance rejection PID controllers using genetic algorithm,” IEEE Trans. Evol. Comput., vol. 5, pp. 78–82, Feb. 2001.
[6]A. Oonsivilai and M. E. El-Hawary, “Power System Dynamic Load Modeling using Adaptive-Network-Based Fuzzy Inference System”, IEEE Canadian Conference on Electrical and Computer Engineering, Vol. 3, 1999, pp. 1217 – 1222.
[7]A. Oonsivilai and M. E. El-Hawary, “A self-organizing fuzzy power stabilizer”, IEEE Canadian Conference on Electrical and Computer Engineering, Vol. 1, 1998, pp. 197 – 200.
[8]A. Oonsivilai and M. E. El-Hawary, “Wavelet Neural Network based Short Term Load Forecasting of Electric Power System Commercial Load”, IEEE Canadian Conference on Electrical and Computer Engineering, Vol. 3, 1999, pp. 1223 – 1228.
[9] H. Yoshida, K. Kawata, and Y. Fukuyama, “A particle swarm optimization for reactive power and voltage control considering voltage security assessment,” IEEE Trans. Power Syst., vol. 15, pp. 1232–1239, Nov. 2000.
[10] R. A. Krohling and J. P. Rey, “Design of optimal disturbance rejection PID controllers using genetic algorithm,” IEEE Trans. Evol. Comput., vol. 5, pp. 78–82, Feb. 2001.
[11] Y. Mitsukura, T. Yamamoto, and M. Kaneda, “A design of self-tuning PID controllers using a genetic algorithm,” in Proc. Amer. Contr. Conf., San Diego, CA, June 1999, pp. 1361–1365.
[12] T. Kawabe and T. Tagami, “A real coded genetic algorithm for matrix inequality design approach of robust PID controller with two degrees

of freedom," in Proc. 12th IEEE Int. Symp. Intell. Contr., Istanbul, Turkey, July 1997, pp. 119–124.

[13] R. A. Krohling, H. Jaschek, and J. P. Rey, "Designing PI/PID controller for a motion control system based on genetic algorithm," in Proc. 12th IEEE Int. Symp. Intell. Contr., Istanbul, Turkey, July 1997, pp. 125–130.

[14]D. Puangdownreong, S. Sujitjorn and T. Kulworawanichpong, "Convergence Analysis of Adaptive Tabu Search", International Journal of ScienceAsia, Vol. 38, No.2, 2004, pp. 183-190.

[15]C. Chaiyaratana and A.M.S. Zalzala, "Recent Developments in Evolutionary and Genetic Algorithms: Theory and Applications", 2nd Int. Conf. on Genetic Algorithms in Engineering System: Innovations and Applications, 2-4 September 1997, pp. 270 – 277.

[16]D. Puangdownreong, K.-N. Areerak, A. Srikaew, S. Sujitjorn and P. Totarong, "System Identification via Adaptive Tabu Search", IEEE Int. Conf. on Industrial Technology, Vol. 2, 11-14 December 2002, pp. 915 – 920.

[17]B. Marungsri, N. Meeboon and A. Oonsivilai, "Dynamic Model Identification of Induction Motors using Intelligent Search Techniques with taking Core Loss into Account" , WSEAS Trans. on Power Systems, Vol. 1, No. 8, August 2006, pp. 1438 – 1445.

[18] Y. Mitsukura, T. Yamamoto, and M. Kaneda, "A design of self-tuning PID controllers using a genetic algorithm," in Proc. Amer. Contr. Conf., San Diego, CA, June 1999, pp. 1361–1365.

[19] T. Kawabe and T. Tagami, "A real coded genetic algorithm for matrix inequality design approach of robust PID controller with two degrees of freedom," in Proc. 12th IEEE Int. Symp. Intell. Contr., Istanbul, Turkey, July 1997, pp. 119–124.

[20] R. A. Krohling, H. Jaschek, and J. P. Rey, "Designing PI/PID controller for a motion control system based on genetic algorithm," in Proc. 12th IEEE Int. Symp. Intell. Contr., Istanbul, Turkey, July 1997, pp. 125–130.

[21] D. P. Kwok and F. Sheng, "Genetic algorithm and simulated annealing for optimal robot arm PID control," in Proc IEEE Conf. Evol. Comput., Orlando, FL, 1994, pp. 707–713.

[22] T. Ota and S. Omatu, "Tuning of the PID control gains by GA," in Proc. IEEE Conf. Emerging Technol. Factory Automation, Kauai, HI, Nov. 1996, pp. 272–274.

[23] Oonsivilai, A. and Boonruang, M. Optimal PID Tuning for AGC system using Adaptive Tabu Search. Proc. Of the 7th WSEAS Int. Conf. on Power Systems, pp. 42-47, Beijing, China, September 2007.

[24] Pao-La-Or, P., Kulworawanichpong, T., and Oonsivilai, A. 2007. Frequency domain parameter estimation of a synchronous generator using bi-objective genetic algorithms. Proc. Of the 7th WSEAS Int. Conf. on Simulation, Modelling and Optimization, pp. 429-433, Beijing, China, September 2007.

[25] Energy Development and Power Generation Committee. 2006. IEEE Recommended Practice for Excitation System Models for Power System Stability Studies. IEEE Std 421.5TM-2005.

[26] K.Benatchba,, M. Kondil., H. Drias., and R. Belkacem. 2003. An adapted genetic algorithms for solving Max-Sat problems. WSEAS TRANSACTIONS on SYSEMS. Issue 4, Volume 2, October, ISSN: 1109 – 2777.

[27] Pao-La-Or, P., Kulworawanichpong, T., and Oonsivilai, A. 2007. Bi-objective Intelligent Optimization for Frequency Domain Parameter Identification of a Synchronous Generator. WSEAS TRANSACTIONS on Ppower SYSTEM, Issue 3, Volume 3, March 2008, pp. 56-62.