Design of Optimal Fuzzy Logic based PI Controller using Multiple Tabu Search Algorithm for Load Frequency Control

Saravuth Pothiya, Issarachai Ngamroo, Suwan Runggeratigul, and Prinya Tantaswadi

Abstract: This paper focuses on a new optimization technique of a fuzzy logic based proportional integral (FLPI) load frequency controller by the multiple tabu search (MTS) algorithm. Conventionally, the membership functions and control rules of fuzzy logic control are obtained by trial and error method or experiences of designers. To overcome this problem, the MTS algorithm is proposed to simultaneously tune proportional integral gains, the membership functions and control rules of a FLPI load frequency controller in order to minimize the frequency deviations of the interconnected power system against load disturbances. The MTS algorithm introduces additional techniques for improvement of the search process such as initialization, adaptive search, multiple searches, crossover and restart process. Simulation results explicitly show that the performance of the proposed FLPI controller is superior to conventional PI and FLPI controllers in terms of overshoot and settling time. Furthermore, the robustness of the proposed FLPI controller under variation of system parameters and load change are higher than that of conventional PI and FLPI controllers.

Keywords: Fuzzy logic, load frequency control, power system control, tabu search.

1. INTRODUCTION

For large scale electrical power systems that normally consist of interconnected control areas or regions representing coherent groups of generators, load frequency control (LFC) is very important in power system operation and control for supplying sufficient and reliable electric power with good quality. In cases of area load changes and abnormal conditions, such as outages of generation and varying system parameters, mismatches in frequency and scheduled tie-line power flows between areas can be caused. These mismatches are corrected by controlling the frequency, which is defined as the regulation of the power output of generators within a prescribed area [1]. The objective of the LFC is to satisfy the following requirements [2,3]: (i) Zero steady state errors in tie-line exchanges and frequency deviations. (ii) Optimal transient behaviors. (iii) In steady state, the power generation levels should satisfy the optimal dispatch conditions.

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Saravuth Pothiya, Issarachai Ngamroo, and Suwan Runggeratigul are with the School of Communication, Instrumentation & Control, Sirindhorn International Institute of Technology, Thammasat University, 12121, Thailand (e-mails: p_saravuth@hotmail.com, {ngamroo, suwan)@siit.tu.ac.th).

Prinya Tantaswadi is with the School of Information and Communication Technology, Shinnawatra University, 12160, Thailand (e-mail: ptoh2509@yahoo.com).

In the past, several control designs of LFC in interconnected power systems has been studied. The conventional control strategy for the LFC problem is to take the integral of the control error as the control signal. An integral (I) controller provides zero steady state frequency deviation but it exhibits poor dynamic performance. Over the past decades, many control strategies for load frequency control of power systems such as linear feedback [4], optimal control [5] and variable structure control [6,7] have been proposed in order to improve the transient response.

Adaptive controllers with self adjusting gain settling have also been proposed for the LFC problem [8]. Artificial neural networks have been successfully applied to the LFC problem with rather promising results [9,10]. Moreover, fuzzy logic control techniques for the LFC problem are mostly based on fuzzy gain scheduling of proportional integral (PI) controller parameters [11-13].

Recently, applications of fuzzy logic theory to the engineering issues have drawn tremendous attention from researchers [14]. The fuzzy logic controller has a number of distinguished advantages over the conventional controllers. It is not so sensitive to the variation of system structure, parameters and operation points and can be easily implemented in a large scale nonlinear system. Furthermore, the fuzzy logic controller is a sophisticated technique that is easy to design and implement. Nevertheless, the determination of membership functions and control rules is an inevitable problem in a design. To achieve satisfactory membership functions and control rules, designer's experiences are necessary.

The most straightforward approaches are to define the membership functions and control rules by studying an operating system or an existing controller. Therefore, the effective methods for tuning the membership function and control rules in order to minimize the output error or maximize the performance index without a trial and error method are significantly required.

In the past, the idea of employing the tabu search (TS) algorithm to solve the combinatorial optimization problems has been proposed [15-17]. The application of the TS algorithm has been used for learning the control rules of the fuzzy logic controller [18], and applied to optimize membership functions and control rules [19].

The contribution of this paper is to propose a new approach based on the TS algorithm for optimal design of a fuzzy logic based proportional integral (FLPI) load-frequency controller in a two-area interconnected power system. This proposed approach, called the multiple tabu search (MTS) algorithm, is used to obtain optimal or nearly optimal solutions very quickly, moreover, the efficiency of the proposed algorithm will be demonstrated in this paper.

The paper is organized as follows: Section 2, a comprehensive mathematical model of a load frequency control problem for a two-area interconnected power system is presented. The proposed fuzzy logic based proportional integral controller is described in Section 3. An application of the proposed MTS algorithm to optimize PI gains, membership functions and control rules of a FLPI load frequency controller are presented in Section 4. The simulation results in a two-area interconnected power system are offered in Section 5. Finally, the conclusion is provided in Section 6.

2. PROBLEM FORMULATION

An interconnected power system is divided into control areas connected by a tie line. In each control area, all generators are supposed to constitute a coherent group. A two-area interconnected power system of a non-reheat thermal plant shown in Fig. 1 is used to explain the motivation of the proposed method. It is assumed that large loads with sudden changes, such as large steel mills, arc furnace factories, magnetic levitation transporters and testing plants for nuclear fusions etc., have been placed in both areas. The frequency deviation in both areas severely affect the production quality of frequency sensitive industries such as the spinning and weaving industry, petrochemical industry, pulp and paper industry, semiconductor industry, etc. Furthermore, the lifetime of machine apparatuses on the load side will be

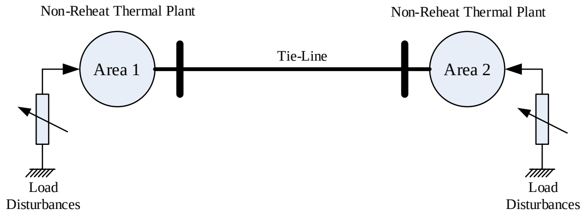


Fig. 1. Two-area interconnected power system.

reduced.

The tie-line power flow and frequency of the area are affected by the load changes. Therefore, it can be considered that each area needs its system frequency and tie-line power flow to be controlled.

A controlled two-area interconnected power system of a non-reheat thermal plant is shown in Fig. 2, where f is the system frequency (Hz), R_i is regulation constant (Hz/unit), T_g is speed governor time constant (s), T_t is turbine time constant (s) and T_p is power system time constant (s). The overall system can be modeled as a multi-variable system in the following form

$$\dot{x} = Ax(t) + Bu(t) + Ld(t), \quad (1)$$

where A is the system matrix, B and L the input and disturbance distribution matrices, and $x(t)$, $u(t)$ and $d(t)$ are state, control signal and load change disturbance vectors, respectively.

$$x(t) = \begin{bmatrix} \Delta f_1 & \Delta P_{g1} & \Delta P_{t1} & \Delta P_{tie} & \Delta f_2 & \Delta P_{g2} & \Delta P_{t2} \end{bmatrix}^T,$$
$$u(t) = \begin{bmatrix} u_1 & u_2 \end{bmatrix}^T,$$
$$d(t) = \begin{bmatrix} \Delta P_{d1} & \Delta P_{d2} \end{bmatrix}^T,$$

where Δ denotes deviation from the nominal values and u_1 and u_2 are the control signals in area 1 and 2, respectively.

The system output, which depends on area control error (ACE) is given as

$$y(t) = \begin{bmatrix} y_1(t) \\ y_2(t) \end{bmatrix} = \begin{bmatrix} ACE_1 \\ ACE_2 \end{bmatrix} = C\,x(t), \quad (2)$$

$$ACE_i = \Delta P_{tie} + b_i \Delta f_i, \quad i = 1,2, \quad (3)$$

where b_i is the frequency bias constant, Δf_i is the frequency deviation, ΔP_{tie} is the change in tie-line power for area i and C is the output matrix.

The system parameters are provided in the Appendix. The control signal for the conventional PI controller can be given in the following equation.

$$\begin{aligned} u_i(t) &= -k_P ACE_i - \int k_I (ACE)\, dt \\ &= -k_P (\Delta P_{tie} + b_i \Delta f_i) - \int k_I (\Delta P_{tie} + b_i \Delta f_i)\, dt \end{aligned} \quad (4)$$

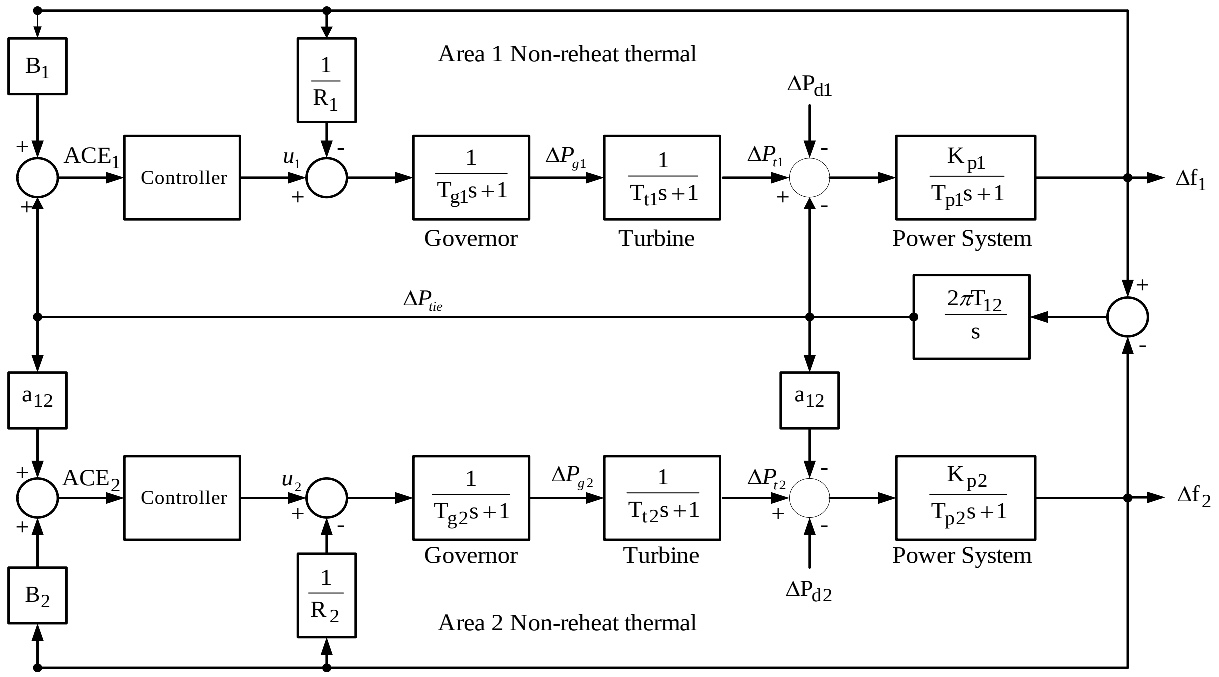


Fig. 2. Two-area interconnected power system with controller.

3. THE FUZZY LOGIC BASE ROPORTIONAL INTEGRAL CONTROLLER

Fuzzy set theory and fuzzy logic establish the rules of a non-linear mapping. The use of fuzzy sets provides a basis for a systematic way for the application of uncertain and indefinite models. Fuzzy set is based on a logical system called fuzzy logic controller. It is much closer in spirit to human thinking and natural language than classical logical systems. Nowadays, fuzzy logic is used in almost all sectors of industry and science. One of them is the LFC problem. Because of the complexity and multi-variable conditions of the power system, conventional control methods may not give satisfactory solutions. On the other hand, robustness and reliability make the fuzzy logic controller useful in solving a wide range of control problems.

The FLPI controller to solve the problem, as presented in Fig. 3, consists of a fuzzy logic controller and a conventional PI controller, connecting in series. The fuzzy logic controller has two input signals, namely, ACE and $ACE^{\bullet}$, and then the output signal (y) of the fuzzy logic controller is the input signal of the conventional PI controller. Finally, the output signal from the conventional PI controller called the control signal (u) is used for controlling the LFC in the interconnected power system.

The fuzzy logic controller is comprised of four main components: the *fuzzifier*, the *inference engine*, the *rule base*, and the *defuzzifier*, as shown in Fig. 4. The fuzzifier transforms the numeric into fuzzy sets, so that, this operation is called *fuzzification*. The main purpose of the fuzzy logic controller is the inference engine, which performs all logic manipulations in a fuzzy logic controller. The rule base consists of membership functions and control rules. Last, the results of the inference process is an output represented by a fuzzy set, however, the output of the fuzzy logic controller should be a numeric value. Therefore, fuzzy set is transformed into a numeric value by using the defuzzifier, so that, this operation is called *defuzzification*.

By taking the system output, the control signal for the FLPI controller is given by

$$u(t) = -(k_p y + \int k_i y dt)\,. \tag{5}$$

In designing the FLPI controller, important procedures are how to obtain the PI gains, membership functions and control rules. The PI gains

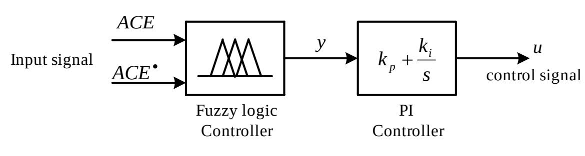


Fig. 3. Structure of fuzzy logic base proportional integral controller.

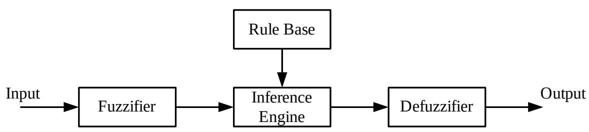
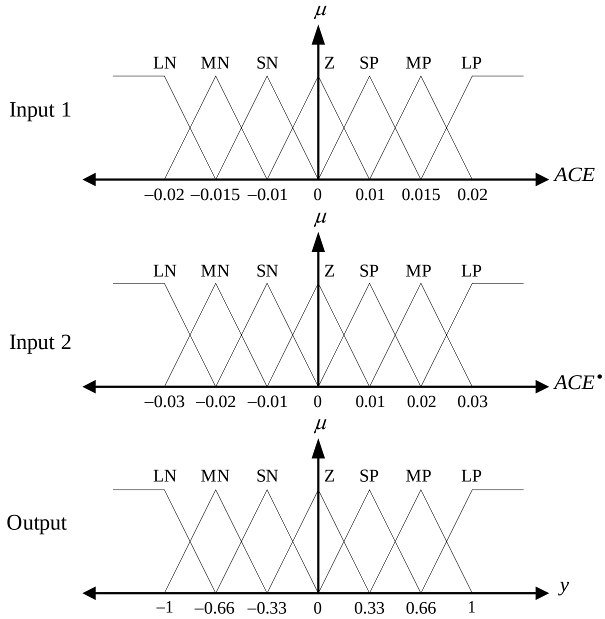


Fig. 4. Components of a fuzzy logic controller.



LN: large negative; MN: medium negative; SN: small negative; Z: zero; SP: small positive; MP: medium positive; LP: large positive.

Fig. 5. Membership function for non-optimal FLPI controller.

have been determined easily, but the membership functions and the control rules are difficult. Thus, to simplify solving this problem, this paper presents a new approach to determine the PI gains, membership functions and control rules based on the TS algorithm.

The membership functions of the fuzzy logic controller presented in Fig. 5 consist of three memberships functions (two-inputs and one-output). Each membership function has seven memberships, comprising two trapezoidal and five triangular memberships. All memberships are selected to describe all linguistic variables.

For the determination of the control rules, it can be more complicated than membership functions, which depend on the designer experiences and actual physical system. For the case of two-input and one-output, the control rules can be shown graphically in a table when every cell shows the output membership functions of a control rule with the relationship between input 1 and 2. The control rules build from

Table 1. The control rules for non-optimal FLPI controller.

		$ACE^{\bullet}$						
		LN	MN	SN	Z	SP	MP	LP
ACE	LN	*LP*	*LP*	*LP*	*MP*	*MP*	*SP*	*Z*
	MN	*LP*	*MP*	*MP*	*MP*	*SP*	*Z*	*SN*
	SN	*LP*	*MP*	*SP*	*SP*	*Z*	*SN*	*MN*
	Z	*MP*	*MP*	*SP*	*Z*	*SN*	*MN*	*MN*
	SP	*MP*	*SP*	*Z*	*SN*	*SN*	*MN*	*LN*
	MP	*SP*	*Z*	*SN*	*MN*	*MN*	*MN*	*LN*
	LP	*Z*	*SN*	*MN*	*MN*	*LN*	*LN*	*LN*

the ***if-then*** statement (if *input 1* and *input 2* then *output 1*). Table 1 indicates the appropriate rule bases in this study. Let us consider the third row and fourth column in Table 1, that means, if *ACE* is SN and $ACE^{\bullet}$ is Z then *y* is SP.

The FLPI controller uses the membership functions and the control rules as shown in Fig. 5 and Table 1 [12,13], respectively, called "***non-optimal FLPI controller***". The proposed FLPI controller is called "***Optimal FLPI controller***", where the PI gains, membership functions and control rules are tuned by the multiple tabu search algorithm.

For design of the FLPI controller, the PI gain has only two parameters to tuning, which are the proportional and integral gains. The membership functions and control rules have many parameters to tune. Consider the two shapes of a membership function; triangular and trapezoidal memberships, which are revealed in Fig. 6. A triangular membership is defined by its three parameters; left base (*L*), center (*C*), and right base (*R*). And for others, a trapezoidal membership is defined by its four parameters; left base (*L*), center 1 (C_1), center 2 (C_2), and right base (*R*). A membership function has 2 trapezoidal and 5 triangular memberships, so that, there are 23 (4+3+3+3+3+3+4=23) parameters to tuning. The fuzzy logic controller has two-inputs and one-output, with a total of 69 ($3\times 23=69$) parameters to tuning.

In the case of the control rules for two-inputs and one-output fuzzy logic controller, the control rule list

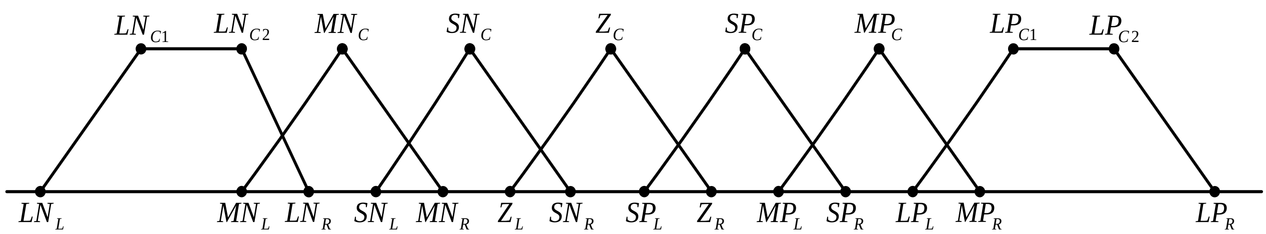


Fig. 6. The shape of membership functions.

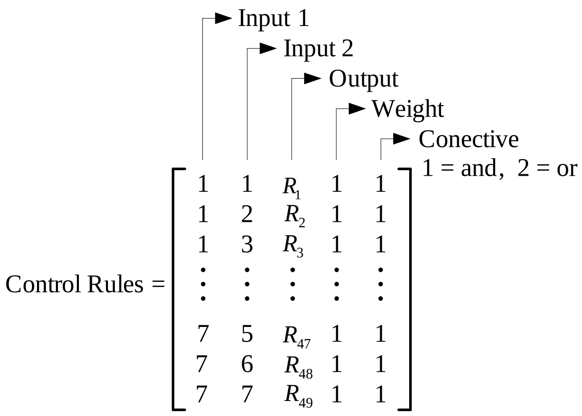


Fig. 7. Structure of control rules for fuzzy logic controller.

must be represented by a n row and 5 column matrix as shown in Fig. 7 when applying this idea in the fuzzy logic toolbox, where n is total number of relationships between all possible input pairs (for 7 membership functions, $n = 7^2 = 49$). The third column in the control rule table is the linguistic variable outputs. Generally, it is represented by a numeric symbol. The universe of discourse in this study contains seven memberships; consequently, the control rules must be represented by seven numbers (1-7), 1: LN, 2: MN, 3: SN, 4: Z, 5: SP, 6: MP, and 7: LP. Consequently, there are 49 parameters to tuning.

Therefore, the total parameters for two-inputs and one-output FLPI controller to tuning are 120 (2+69+49=120) parameters.

4. MULTIPLE TABU SEARCH ALGORITHM

4.1. Tabu search algorithm

4.1.1 Overview

In general terms, 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. 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). Discussions of these terms are presented in the following Sections.

4.1.2 Tabu list restrictions

In order to prevent cycling, a TL is introduced. The TL stores all the tabu moves that cannot be applied to the current solution. The moves stored in the TL are those carried out most frequently and recently according to some criteria called tabu restrictions and they are used to decrease the possibility of cycling because doing so prevents returning in a certain number of iterations to a solution visited recently. In this paper, the size of TL is $n \times 3$ (row $\times$ column), where n is a number of neighborhoods around the current solution. In the TL, the first column is used for storing the moves, the second column is used for frequency of a move direction, and the last column is used for recency of a move.

4.1.3 Aspiration criterion

Another key issue of the TS arises when the move under consideration has been found to be tabu. The tabu status of a move is not absolute, but can be overruled if certain conditions are met, expressed in the form of AC. If appropriate aspiration criterion is satisfied, the move will be accepted in spite of the tabu classification. Roughly speaking, AC is designed to override tabu status if a move is 'good enough' [15].

4.1.4 Stopping criterion

There may be several possible stopping conditions for the search. This implementation uses the stopping search if any of the following two conditions is satisfied: first, the accuracy of the best solution is lower than the expected value, and second, the maximum allowable number of iterations is reached.

4.1.5 General tabu search algorithm

In applying the TS 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.

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

- X : the set of feasible solutions.
- x : the current solution, $x \in X$
- x_b : the best solution reached.
- x_{nb} : 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 TS 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 $x_b = x$.

Step 2: Generate a set of trial solutions in the neighborhood of x. Let x_{nb} be the best trial solution.

Step 3: If $E(x_{nb}) > E(x_b)$, go to Step 4, otherwise set the best solution $x_b = x_{nb}$ and go to Step 4.

Step 4: Perform the tabu test. If x_{nb} is NOT in the *TL*, then accept it as a current solution, set $x = x_{nb}$, 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 $x = x_{nb}$, and update the *AC*.

Step 6: Perform the termination test. If the stopping criterion is satisfied then stop, otherwise set $k = k + 1$ and go to Step 2.

4.2. Multiple tabu search algorithm

The proposed approach is called Multiple Tabu Search (MTS) algorithm based on the TS algorithm as shown in Fig. 8, which has several TS algorithms independently. This algorithm consists of five mechanisms; namely, *initialization*, *adaptive search*, *multiple searches*, *crossover* and *restarting process* as follows:

4.2.1 Initialization

The MTS algorithm uses random feasible solutions in the determination of the several initial solutions, which contrast with the TS algorithm. Because the probability for reaching the optimal solution is higher than in the case of the single initial solution of the TS algorithm, the MTS can quickly be converged to the global optimum solution.

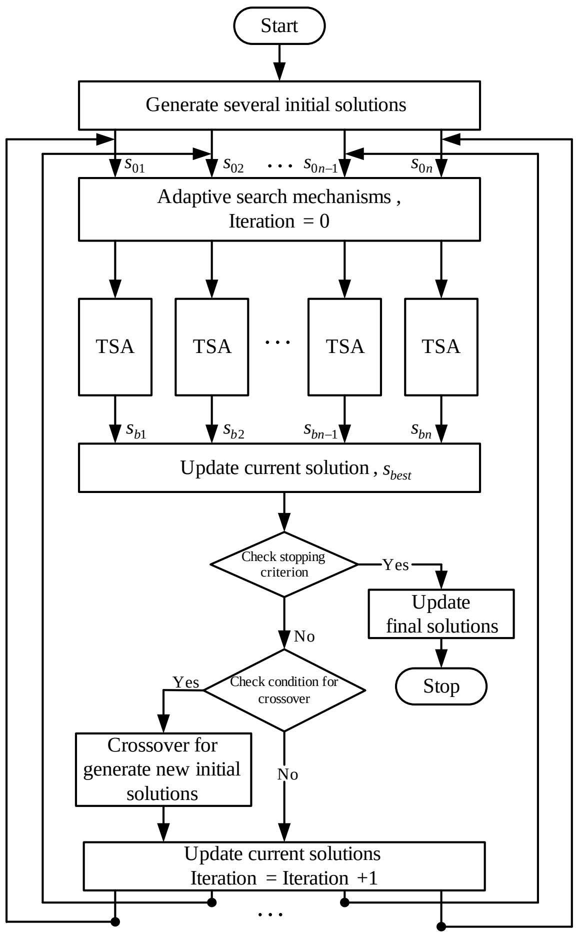


Fig. 8. Procedure of multiple tabu search algorithm.

4.2.2 Adaptive search

The step size is a range of current solutions, which is the importance factor in the searching process, so that should be appropriately chosen. Low values use long computational time. On the other hand, high values may not be obtaining the global optimum. Consequently, the adaptive search mechanism has been developed to suitably adjust the step size during the searching process. This earlier process helps to speed up the move to the vicinity of the global solution. Once the searching process approaches the near global solution, the small step size is then employed in order to move to the solution in a high resolution.

4.2.3 Multiple search

Recently, personal computers have acquired high speed for computational purposes. When solving the large scale problems, several computers run in parallel, a process known as ***parallel search***. ***Multiple-search*** is also executed by a personal computer. This process helps the TS algorithm find the promising region of the search very rapidly.

4.2.4 Crossover

Once the iteration of the searching process is satisfied, all independent TS algorithms are stopped. The crossover process is used for comparison, exchange of the solutions found by these TS algorithms, and to generate the best initial solutions for the next iteration.

4.2.5 Restarting process

When the searching is stuck on the local solution for an extended time and the procedure of the TS algorithm cannot escape from the local solution, then the restarting process is applied for assistance to continue searching to find a new solution.

5. IMPLEMENTATION AND RESULTS

Simulations were performed using the conventional PI, Non-optimal FLPI and the proposed optimal FLPI controllers applied to a two-area interconnected power system as shown in Fig. 1 by applying 0.01 p.u MW step load disturbance to both areas. The same system parameters [12,13], given in the Appendix, were used in all controllers for a comparison. The implementation worked with Matlab 7.0-Simulink software and Fuzzy Logic Toolbox. The simulation was run on a personal computer Pentium 4, 1.5 GHz, 256 Mbytes RAM, under Windows XP.

In the optimization, the integral absolute error

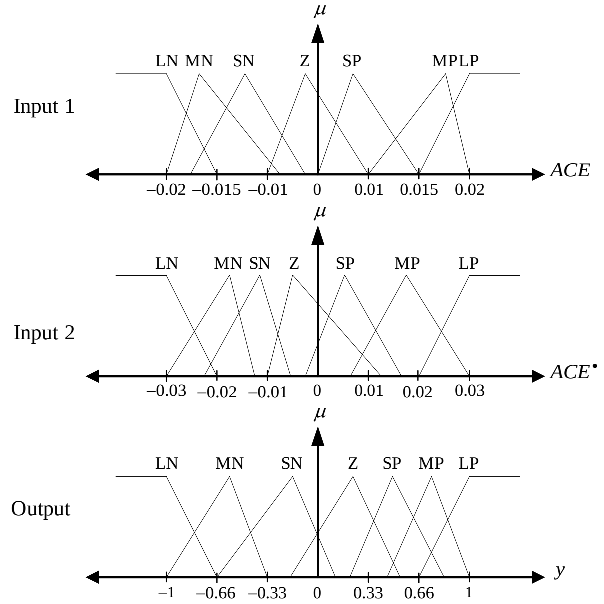


Fig. 9. Optimized membership functions for optimal FLPI controller.

Table 2. Optimized control rule for optimal FLPI controller.

		ACE•						
		LN	MN	SN	Z	SP	MP	LP
	LN	*LP*	*LP*	*LP*	*MP*	*MP*	*SP*	*Z*
	MN	*LP*	*LP*	*LP*	*LP*	*MP*	*SP*	*SN*
	SN	*LP*	*LP*	*LP*	*MP*	*Z*	*SN*	*MN*
ACE	Z	*LP*	*LP*	*LP*	*Z*	*SN*	*MN*	*LN*
	SP	*MP*	*SP*	*Z*	*SN*	*SN*	*MN*	*LN*
	MP	*SP*	*Z*	*SN*	*MN*	*MN*	*MN*	*LN*
	LP	*Z*	*SN*	*MN*	*MN*	*LN*	*LN*	*LN*

(IAE) of the frequency deviation of the first area is selected as the performance index. Accordingly, the objective function J is set by

$$\text{Minimize} \quad J = \int_0^\infty \left|\Delta f_1\right| dt . \qquad (6)$$

After tuning, the optimal FLPI controller has optimized PI gains, which are $k_p = 0.0113$ and $k_i = 0.0353$. The optimized membership functions of inputs 1 and 2 and the output are depicted in Fig. 9, and the optimized control rule is given in Table 2.

The frequency deviations of the first area after a sudden load change are shown in Fig. 10 and Fig. 11. The non-optimal FLPI controller highly improves the system performance comparison to the conventional PI controller. Moreover, the optimal FLPI controller is significantly superior to the conventional PI controller. It gives a better performance than the non-optimal

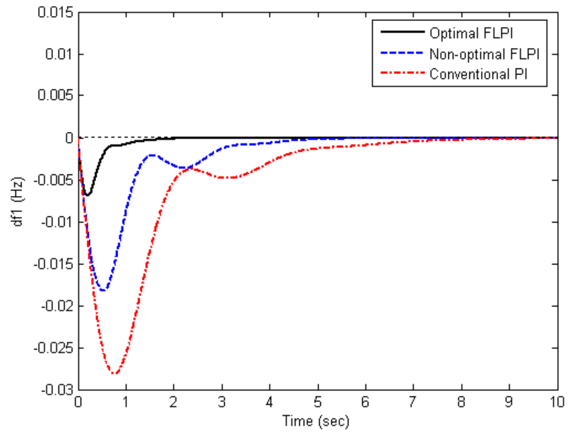


Fig. 10. The frequency deviation of the first area for different controller types.

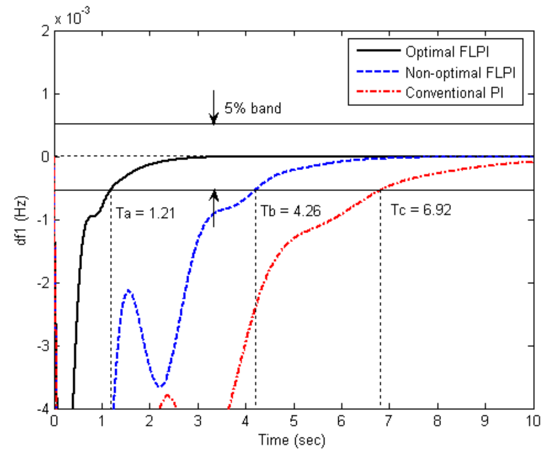


Fig. 11. The frequency deviation of the first area in a larger scale and settling time for optimal FLPI (T_a), Non-optimal FLPI (T_b), and conventional PI (T_c).

FLPI controller. The settling time and overshoot are reduced considerably.

Next, the robustness of each controller against system parameters variations are evaluated by the settling time, overshoot, and IAE. These values are calculated under an occurrence of load disturbances while the system parameters are varied from −30% to 30% of the nominal values. The comparison results are indicated in Figs. 12, 13, and 14 and show the values of settling time, overshoot, and IAE of Δf_1, respectively.

Considering Figs. 12-14, in case of the conventional PI and FLPI controllers, the values of the settling time, overshoot, and IAE change as system parameters are varied. In contrast, the values of the settling time, overshoot, and IAE in case of the optimal FLPI controller are lower and rarely change. This clarifies that the robustness of the optimal FLPI controller against parameters variations is superior to that of the conventional PI and FLPI controller.

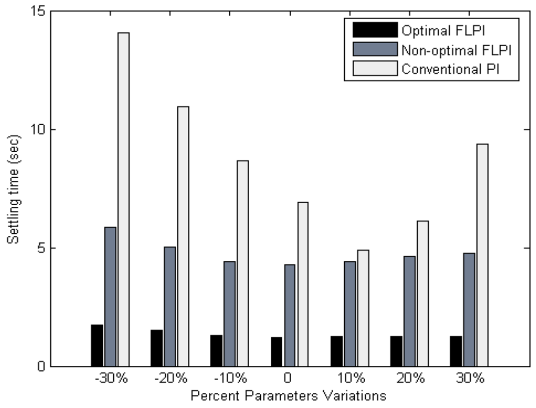


Fig. 12. Comparison results of settling time Δf_1 under parameter variations.

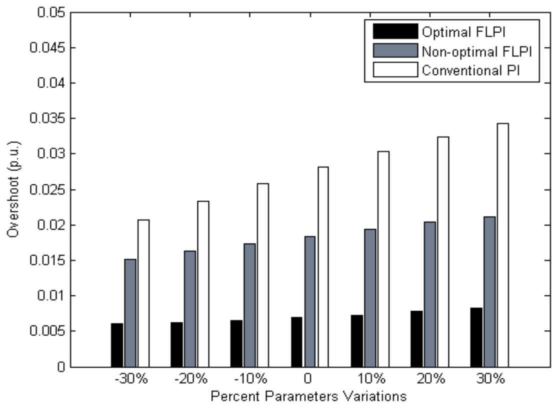


Fig. 13. Comparison results of overshoot Δf_1 under parameter variations.

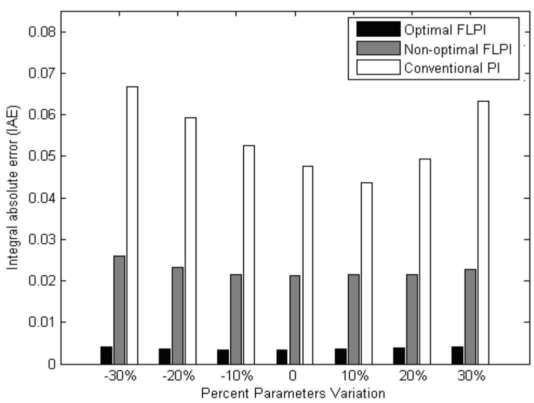


Fig. 14. comparison results of Δf_1 under parameter variations by IAE.

Finally, the frequency control effects of conventional PI, non-optimal FLPI, and optimal FLPI controllers are evaluated under different random step load variations that are applied to both areas as indicated in Fig. 15. The result of the frequency deviations of the first area is shown in Fig. 16. Furthermore, Fig. 17 presents the results of the change in tie-line power for the first area. The frequency

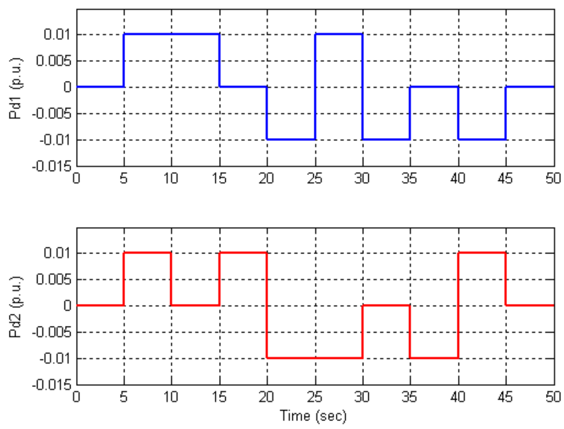


Fig. 15. Step load change in areas 1 and 2.

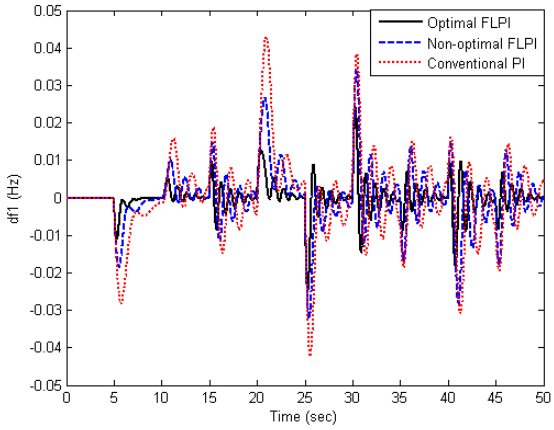


Fig. 16. Time response of Δf_1 under load change.

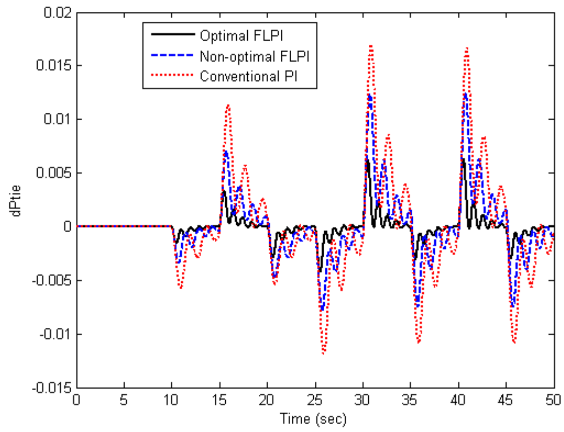


Fig. 17. Time response of ΔP_{tie} under load change.

deviations and the change in tie-line power for the first area are improved considerably by the optimal FLPI controller in comparison with the case of the conventional PI, non-optimal FLPI controller.

6. CONCLUSION

In this paper, a new approach, called the MTS algorithm has been used for developing an optimal

FLPI controller for the LFC of a two-area interconnected power system. The proposed technique for designing a FLPI controller helps us save time when compared to those from conventional trial and error design procedures. Another benefit of this approach is that it does not require experts for the design of the fuzzy logic controller. A number of studies have been performed with the proposed FLPI controller to test for effectiveness and robustness. Finally, the simulation results indicate that the proposed FLPI controller performs significantly better than other controllers in the areas of settling time, overshoot, and absolute error integral. Therefore, this proposed FLPI controller is effective, efficient and robust over a wide range of operating conditions.

APPENDIX A

In the following, most of the parameters of the two-area interconnected power system in Fig. 1 are from Refs [12,13] and some parameters have been modified:

$R_1 = R_2 = 2.4$ Hz/p.u., $T_{p1} = T_{p2} = 20$ s,

$K_{p1} = K_{p2} = 120$ Hz/p.u., $a_{12} = -1$,

$B_1 = B_2 = 0.425$, $T_{12} = 0.086$,

$T_{t1} = T_{t2} = 0.3$ s.

REFERENCES

[1] N. Jaleeli, L. S. VanSlyck, D. N. Ewart, L. H. Fink, and A. G. Hoffmann, “Understanding automatic generation control,” *IEEE Trans. on Power Systems*, vol. 7, no. 3, pp. 1106-1112, 1992.

[2] C. S. Chang and F. Weihui, “Area load-frequency control using fuzzy gain scheduling of PI controllers,” *Electr. Power Syst. Res.*, vol. 42, pp. 145-152, 1997.

[3] J. Talaq and F. AL-Basri, “Adaptive fuzzy gain scheduling for load frequency control,” *IEEE Trans. on Power Systems*, vol. 14, no. 1, pp. 145-150, 1999.

[4] O. P. Malik, A. Kumar, and G. S. Hope, “A load frequency control algorithm based on a generalized approach,” *IEEE Trans. Power Systems.*, vol. 3, no. 2, pp. 375-382, 1988.

[5] N. Saha and S. P. Ghoshal, “State adaptive optimal generation control of energy systems,” *JIEEE*, vol. 67, Part EL-2, 1986.

[6] A. Kumar, O. P. Malik, and G. S. Hope, “Variable structure-system control applied to AGC of an interconnected power system,” *IEE Proc. 132*, Part C, no. 1, pp. 23-29, 1985.

[7] Z. M. Ai-Hamouz and Y. L. Abdel-Magid, “Variable-structure load-frequency controllers for multi area power systems,” *Int. J. Electr. Power Energ. Syst.*, vol. 15, no. 5, pp. 23-29, 1993.

[8] C. T. Pan and C. M. Liaw, “An adaptive control using fuzzy logic,” *IEEE Trans. on Power Systems*, vol. 4, no. 1, pp. 122-128, 1989.

[9] C. S. Indulkar and B. Raj, “Application of fuzzy controller to automatic generation control,” *Electric Mach. Power Systems*, vol. 23, no. 2, pp. 209-220, 1995.

[10] D. K. Chaturvedi, P. S. Satsangi, and P. K. Kalra, “Load frequency control: A generalized neural network approach,” *Electrical Power and Energy Systems*, vol. 21, pp. 405-415, 1999.

[11] A. Hariri and O. P. Malik, “Fuzzy logic power system stabilizer based on genetically optimized adaptive network,” *Fuzzy Sets Systems*, vol. 102, pp. 31-40, 1999.

[12] C. Ertugrul and I. Kocaarslan, “A fuzzy gain scheduling PI controller application for an interconnected electrical power system,” *Electr. Power Syst. Res.*, vol. 73, pp. 267-274, 2005.

[13] C. Ertugrul and I. Kocaarslan, “Load frequency control in two area power systems using fuzzy logic controller,” *Energy Conversion and Management*, vol. 46, pp. 233-243, 2005.

[14] M. E. El-Hawary, *Electric Power Applications of Fuzzy Systems*, IEEE Press, New York, 1998.

[15] F. Glover, “Tabu search part I,” ORSA *J. Comput*., vol. 1, no. 3, pp. 190-206, 1989.

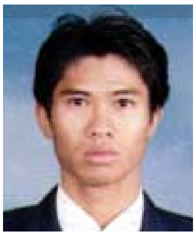
[16] F. Glover, “Tabu search part II,” *ORSA J. Comput*., vol. 2, no. 1, pp. 4-32, 1990.

[17] J. A. Bland and G. P. Dawson, “Tabu search and design optimization” *Computer-Aided Design*, vol. 23, no. 3, pp. 195-201, 1991.

[18] M. Denna, G. Mauri, and A. M. Zanaboni, “Learning fuzzy rules with tabu search-an application to control,” *IEEE Trans. on Fuzzy Systems*, vol. 7, pp. 295-318, 1999.

[19] D. Karaboga, “Design of fuzzy logic controllers using tabu search algorithm,” *Fuzzy Information Processing Society, NAFIPS, 1996 Biennial Conference of the North American*, pp. 489-491, 1996.

[20] C. C. Lee, “Fuzzy logic in control systems: Fuzzy logic controller, parts I-II.,” *IEEE Trans. Syst. Man Cyber*, vol. 20, no. 2, pp. 404-418, 1990.



Saravuth Pothiya received the B.Eng. and M.Eng. degrees in Electrical Engineering from North Eastern University and Khon Kaen University, Thailand in 1992 and 1997, respectively. He is now working towards his Ph.D. in Electrical Engineering at Sirindhorn Internatio-nal Institute of Technology, Thammasat University, Thailand. His research interests include intelligent control, adaptive control, computational intelligence and system identification.

Issarachai Ngamroo received the B.Eng. degree in Electrical Engineering from King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand in 1992 and the M.Eng. and Ph.D. degrees in Electrical Engineering from Osaka University, Japan in 1997 and 2000, respectively. His research interests include power system stability, dynamics and control, FACTS applications and robust control application to power system stabilization

Suwan Runggeratigul received the B.Eng. (1st Class Honors) degree in Electrical Engineering from Chulalong korn University, Thailand in 1989, and the M.Eng and D.Eng. degrees in Electronic Engineering from the University of Tokyo, Japan in 1992 and 1995, respectively. He was a Visiting Researcher at the National Center for Science Information Systems, and Nippon Telegraph and Telephone Multimedia Networks Laboratory, Japan from 1995 to 1997. He is now with the Sirindhorn International Institute of Technology, Thammasat University, Thailand. His research interests include analysis of communications systems and network design.

Prinya Tantaswadi received the B.Eng. degree in Electrical Engineering from Chulalongkorn University, Thailand in 1988, the M.S. degree in Electrical Engineering from the University of Texas at Arlington, USA in 1990 and the Ph.D. in Electrical Engineering from Texas A&M University in 1995. From 1996 to 2005, he worked for the Sirindhorn International Institute of Technology, Thammasat University. In 2005, he joined the School of ICT, Shinawatra University. His research interests include fiber optic current sensors, signal processing using LabVIEW for optical current sensors, optical fiber and wireless communications, image processing using neural networks and colorimetry.