OPTIMAL DESIGN OF VARIABLE STRUCTURE LOAD FREQUENCY CONTROLLER WITH NONLINEARITIES USING TABU SEARCH ALGORITHM

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Abstract: This paper discusses the optimal design of Variable Structure Controller (VSC) applied to the Load Frequency Control (LFC) problem. The controller was designed by an optimal method that utilizes Tabu Search (TS) algorithm. The proposed method has been applied to a single nonreheat area model that includes nonlinearities in the form of Generation Rate Constraint (GRC) and governor deadband backlash. The proposed optimal design was compared with other design methods reported in the literature and showed improved robust dynamical behavior.

1 INTRODUCTION

The Load Frequency Control (LFC) or Automatic Generation Control (AGC) has been one of the most important subjects concerning power system engineers in the last two decades. Extensive study of the problem was reported in literature (Fosha & Elgerd 1970, Elgerd 1971, Nanda & Kaul 1978, Chan & Hsu 1981, Sivaramakrishanan et. al 1984, Kumar et. al 1985, Pan & Lian 1989, Das et. al 1991, Beufays et. al 1994, Ha 1998, Al-Hamouz & Al-Duwaish 2000, Ming-Sheng 2000, Demiroren et. al 2001, Ryu et. al 2001, Al-Musabi et. al 2003). The purpose of the LFC is to track the load variation while maintaining both system frequency and tie-line power interchanges close to specified values. Various techniques were utilized in designing the secondary control loops of LFC. These techniques include PI and PID methods (Elgerd 1971, Nanda & Kaul 1978, Moon et. Al 1999, Ryu et. al 2001), Optimal control (Fosha & Elgerd 1970), Adaptive control (Pan & Lian 1989), and Neural network methods (Beufays et. al 1994, Demiroren et. al 2001) . Furthermore, the application of Variable Structure Control (VSC) to the LFC problem was investigated by a number of authors (Chan & Hsu 1981, Sivaramakrishanan et. al 1984, Kumar et. al 1985, Das et. al 1991, Ming-Sheng 2000, Ha 1998, Al-Hamouz & Al-Duwaish 2000, Al-Musabi et. al 2003). Chan and Hsu (1981) designed a VSC controller and compared it with conventional and optimal control methods for two equal-area nonreheat and reheat thermal systems. There study confirmed the superior performance of VSC over conventional and optimal control methods. However, a systematic method for obtaining the switching vectors and optimum feedback gain settings were not discussed. Moreover, Sivaramakrishanan et. al (1984) utilized pole placement in designing the VSC for a single nonreheat LFC system. However, optimum gain settings were not suggested by the authors. Two area nonreheat and reheat thermal systems were studied by Kumar et. al (1985) and Das et. al (1991). The former utilized simple control logic to switch between proportional and integral controllers excluding sliding modes. Das et. al (1991) used the same control logic to switch between VSC and simple Integral controller. Parameters of the controllers were optimized using Integral Squared Error (ISE) technique. Improvement in the dynamical response of the LFC system was achieved in comparison to conventional Integral controller. Using an approximating control law and a new switching function with integral action, a robust load frequency controller was designed by Ming-Sheng (2000). Ming-Sheng method was claimed to reduce chattering effect of VSC and ensure existence of sliding mode. However, the author did not show the behaviour of the control effort. Also, the frequency response of the designed controller showed questionable response with the presence of Generation Rate Constraint (GRC). Applying stricter GRC was shown to give better dynamic response, although it is known that a harsher GRC on rate of

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generation will cause more degradation in the performance of the controller. Furthermore, Ha (1998) proposed a combination of fuzzy, equivalent, and switching control in designing a robust sliding mode LFC. Simulations of the system showed both improved dynamic performance and reduced chattering.

This paper explores the optimal design of VSC for the LFC problem using the TS algorithm. It is considered an extension of the work by Al-Hamouz and Al-Duwaish (2000) and Al-Musabi et. al (2003), where the parameters of the VSC controller were optimized using GA and PSO methods respectively. However, previously only the feedback gains were optimized. The switching vector of the controller was obtained from other design methods. In this paper, both the switching vector and switching feedback gains of the VSC are designed optimally using TS. Moreover, the proposed design of VSC is applied to LFC models that incorporate the effect of nonlinearities. The organization of the paper will be as follows: First, an explanation of the LFC model will be presented followed by a brief theory of VSC. Tabu Search algorithm will then be overviewed followed by a description of the proposed optimal design procedure. Finally, comparison with other design methods reported in the literature will be investigated in the Simulation section.

2 LFC MODEL

The model of a single nonreheat LFC area is shown in Figure 1(a) (Sivaramakrishanan et. al 1984, Ha 1998). The dynamic model in state variable form can be obtained from the transfer function model and is given as

$$\dot{X} = AX(t) + Bu(t) + Fd(t) \tag{1}$$

Where X is a 4-dimensional state vector, u is 1-dimensional control force vector, d is 1-dimensional disturbance vector, A is 4x4 input matrix, and F is 4x1 disturbance matrix.

$$A = \begin{bmatrix} -\frac{1}{T_p} & \frac{K_p}{T_p} & 0 & 0 \\ 0 & -\frac{1}{T_t} & \frac{1}{T_t} & 0 \\ -\frac{1}{RT_g} & 0 & -\frac{1}{T_g} & -\frac{1}{T_g} \\ K & 0 & 0 & 0 \end{bmatrix}$$

$$B^T = \begin{bmatrix} 0 & 0 & \frac{1}{T_g} & 0 \end{bmatrix}$$

$$F^T = [K_p/T_p \; 0 \; 0 \; 0]$$

T_p is the plant model time constant, T_t is the turbine time constant, T_g is the governor time constant, K_p is the plant gain, K is the integral control gain, and R is the speed regulation due to governor action. x_2 , x_3, and x_4 are respectively the incremental changes in generator output (p.u. MW) , governor valve position (p.u. MW) and integral control. The control objective in the LFC problem is to keep the change in frequency (Hz) $\Delta\omega = x_1$ as close to zero as possible when the system is subjected to a load disturbance d by manipulating the input u.

In this study, nonlinearities will be included in the LFC models. Figure 1(a) shows these nonlinearities in the form of limits to the position of governor valve and the rate of its change. It also includes the governor deadband backlash. The dead band of the speed governor is defined as "the magnitude of the change in steady-state speed within which there is no resulting change in the position of the governor-controlled valves or gates" (IEEE Standard, 1992).

3 VSC THEORY

The fundamental theory of variable structure systems may be found in (Itkis, 1976). A block diagram of the VSC is shown in Figure 1(b), where the control law is a linear state feedback whose coefficients are piecewise constant functions. Consider the linear time-invariant controllable system given by

$$\dot{X} = AX + BU \tag{2}$$

Where X is n-dimensional state vector, U is m-dimensional control force vector, A is a n x n system matrix, and B is n x m input matrix. The VSC control laws for the system of (2) are given by

$$u_i = -\psi_i^T X = -\sum_{j=1}^{n} \psi_{ij} x_j; \; i = 1,2,\ldots, m \tag{3}$$

where the feedback gains are given as

$$\psi_{ij} = \begin{cases} \alpha_{ij}, if \; x_i\sigma_j \rangle 0; i = 1,\ldots, m \\ -\alpha_{ij}, if \; x_i\sigma_j \langle 0; j = 1,\ldots, n \end{cases}$$

and

$$\sigma_i(X) = C_i^T X = 0, \qquad i = 1,\ldots,m$$

where C_i are the switching vectors which are determined usually via a pole placement technique. The design procedure for selecting the constant switching vector C_i may be found in (Sivaramakrishanan, 1984).

4 TABU SEARCH ALGORITHM

Tabu Search Algorithm was proposed a few years ago by Fred Glover (Glover, 1989) as a general iterative heuristic method for solving combinatorial optimization problems. TS is conceptually simple and elegant heuristic method.

The basic elements of TS are defined as follows:

- Current Solution: $x_{current}$: it is a set of solutions from which new trial values are generated.

- Moves: the process of generating trial solutions from $x_{current}$.

- Candidate Moves: it is a set of trial solutions, x_{trial}, generated from neighbourhood of $x_{current}$.

- Tabu list: a list of forbidden moves that exceeded conditions imposed on moves in general.

- Aspiration Criterion: a device that override the tabu status of a move. There are different types of aspiration criteria used in literature (Glover, 1989, Glover, 1990, Glover & Laguna 1997). The criteria used here is to override the tabu status of a move if it produces a better solution than the best solution, x_{best}, seen so far.

- Stopping Criteria: these are the conditions that terminate the search process. In this study, the search process will stop when the number of iterations reaches the maximum limit or if there is no more improvement for the last 50 iterations. The Tabu Search algorithm can be described as follows:

Step 1: Generate Random initial solution, $x_{initial}$. Set $x_{best} = x_{initial} = x_{current}$.

Step 2: Trial solutions are generated randomly in the neighborhood of the current solution.

Step 3: The objective function for trial solutions is computed and compared to best solution objective function value. If better solution is obtained then $x_{best} = x_{trial}$ and then Step 4 follows. Otherwise, go to Step 4 directly.

Step 4: Tabu Status of x_{trial} is tested. If it is not in the Tabu list, then add it to the list and set $x_{current} = x_{trial}$ and go to Step 7. If x_{trial} is in the Tabu list, go to Step 5.

Step 5: The Aspiration criterion is checked. If the criterion is satisfied, then the tabu status is overridden, aspiration is updated, $x_{current} = x_{trial}$ and step 7 follows. Otherwise, Step 6 follows.

Step 6: Check all the trial solutions by going back to Step 4. If all trial solutions are assessed, go to Step 7.

Step 7: Check the Stopping criterion. If satisfied, then stop. Otherwise, go to Step 2 for the next iteration.

5 OPTIMAL DESIGN PROCEDURE

The VSC for the LFC will be designed optimally as follows:

1) Generate random values for feedback gains and switching vector values.

2) Evaluate a performance index that reflects the objective of the design. In this study the following objective functions were used:

$$J_1 = \int_0^\infty \Delta\omega^2 dt \tag{4}$$

$$J_2 = \int_0^\infty q_1\Delta\omega^2 + q_2\Delta u^2 dt \tag{5}$$

J_1 minimizes the deviation in fequency. J_2 includes a scaled value of the deviation in the control effort to reduce the chattering. The effect of inclusion of this value and a comparison of different objective functions for different scaling factors q_1 and q_2 may be found in (Al-Musabi et. al, 2004).

3) Use TS to generate new feedback gains and switching vector values as described in section 4.

4) Evaluate the performance index in step 2 for the new feedback gains and switching vector. Stop if there is no more improvement in the value of the performance index for the last 50 iterations or if the maximum number of iterations is reached; otherwise go to step 3.

6 SIMULATION RESULTS

CASE I: In this case comparison with a robust controller design (Wang et. al, 1993) is investigated. The following are the parameters of the system:

$1/T_p = 0.0665$	$1/RT_g = 6.86$
$1/T_t = 3.663$	$K_p/T_p = 8$
$1/T_g = 13.736$	$K = 0.6$

A GRC of 0.1 p.u. MW per minute = 0.0017 p.u. MW/sec was included in the model. The limits were also applied to integral control signal. The system was simulated for a 0.01 p.u. load disturbance.

The design procedure described in section 5 was applied to the system with performance index of equation (5) applied with $q_1 = q_2=1$. The optimal setting for VSC in this case is obtained as follows:

$\boldsymbol{C}$ = [1.6384 28.9077 9.3736 6.8697]

$\boldsymbol{\alpha}$ = [0.2616 0.3022 0.8951 0.0335]

The convergence of the performance index and the dynamical behaviour of the system is shown in Figure 2.

CASE II: In this case, the design method of Ha (1998) was compared with the new proposed design method. The parameters of the studied system are given below (Ha, 1998) :

$T_p = 20$ s $\qquad K_p = 120$ Hz p.u.MW^{-1}

$T_t = 0.3$ s $\qquad K = 0.6$ p.u. MW rad^{-1}

$T_g = 0.08$ s $\qquad R = 2.4$ Hz p.u. MW^{-1}

A backlash of $2D = 0.001$ and generation limits $\dot{P}_{max} =$ 0.1 p.u.MW/min and $\Delta P_{max} =$ 0.03 p.u.MW are applied. The system was simulated for a load disturbance of 0.005 p.u.MW

The design procedure described in section 5 was again applied to the system with the performance index of equation (4) applied. The optimal settings of the VSC are given below. The system response is shown in Figure 3.

$\boldsymbol{C} = [14.8804 \quad 37.3156 \quad 47.5501 \quad 2.9652]$

$\boldsymbol{\alpha} = [3.3792 \quad 4.7826 \quad 4.4277 \quad 0.5580]$

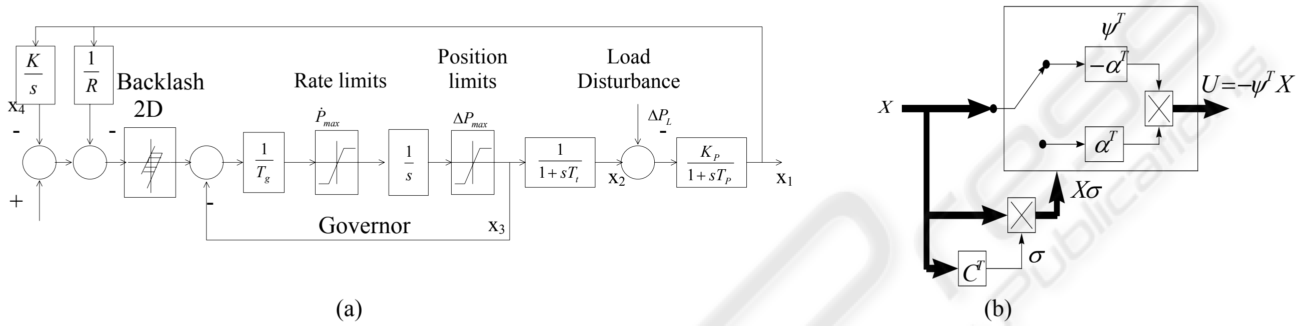


Figure 1: (a) Single area LFC with nonlinearities (b) Block diagram of Variable Structure controller

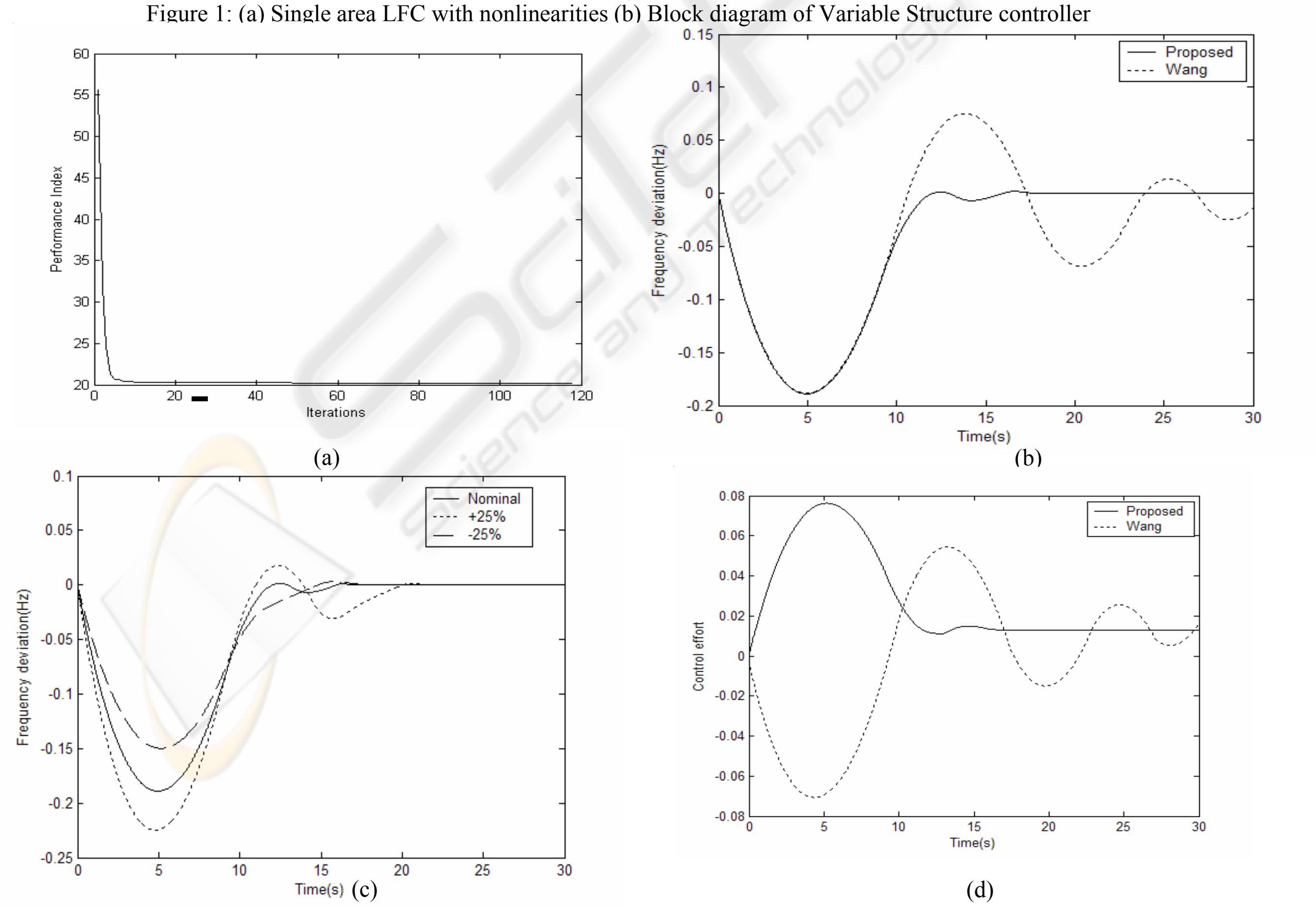
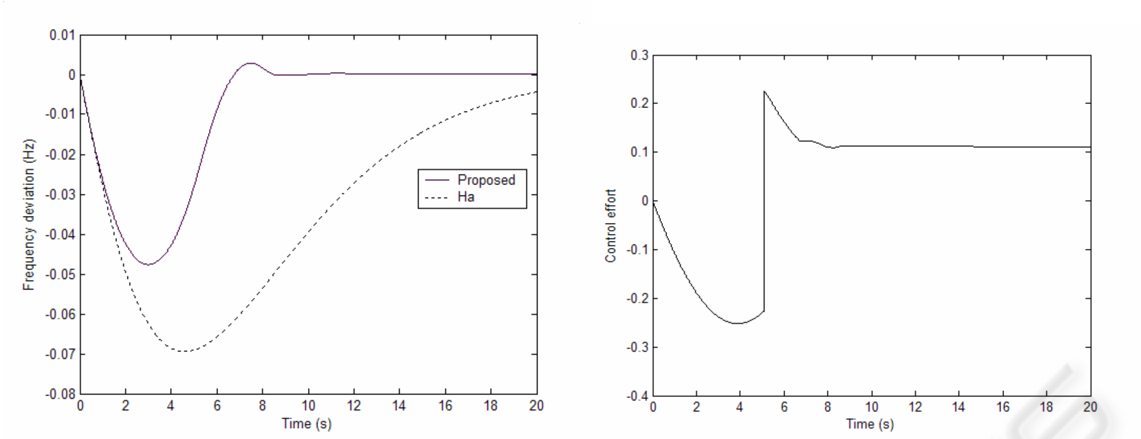


Figure 2: Case I: (a) Convergence of performance index (b) Frequency deviation (c) Frequency deviation: for a 25% change in parameters (d) Control effort



(a) (b)

Figure 3: Case II: (a) Frequency deviation (b) Control effort

The following can be concluded from the above results:

1) The new optimal design of VSC using TS algorithm improves the dynamical behavior of the LFC system when compared with other design methods reported in literature. This is depicted in Figures 2(b) and 3(a).
2) A smooth control effort is obtained. This is shown in Figures 2(d) and 3(b). Inclusion of the deviation in the control effort into the objective function, equation (5), reduced the chattering in the VSC.
3) The proposed VSC showed a robust behavior, Figure 2(c).
4) Nonlinearities can be easily included into the studied model. In this paper, the proposed VSC was applied to LFC models with governor deadband and GRC nonlinearities.

7 CONCLUSION

In this paper, Tabu Search algorithm was used in the optimal design of VSC applied to the load frequency control problem. A robust controller with smooth control signal was designed efficiently for a single area LFC system that incorporates nonlinearities. Comparison with other reported design methods showed promising results and an improvement in the dynamical behaviour of the LFC system.

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