A TABU SEARCH APPROACH FOR THE DESIGN OF VARIABLE STRUCTURE LOAD FREQUENCY CONTROLLER INCORPORATING MODEL NONLINEARITIES

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This paper presents a new method of designing Variable Structure Controllers (VSC) applied to the Load Frequency Control (LFC) problem. The proposed method formulates the design of VSC as an optimization problem and utilizes Tabu Search Algorithm (TS) to find the optimal settings of the controller. The objective function used in the optimization process guarantees enhancement of the controller performance and reduces VSC chattering. The designed VSC is applied to LFC model that incorporates the nonlinearity of the Generation Rate Constraint (GRC). Furthermore, the complexity of the controller is reduced by using only the accessible states in designing the VSC. Comparison with other LFC methods reported in literature validates the significance of the proposed VSC design.

K e y w o r d s: variable structure control (VSC), load frequency control (LFC), Tabu Search Algorithm (TS)

1 INTRODUCTION

The Load Frequency Control (LFC) problem has been one of the most important issues in the operation and design of contemporary electric power systems. This importance is due to the role of the LFC in securing a satisfactory operation of power systems and ensuring constancy of the speed of induction and synchronous motors, thereby improving the performance of generating units [1]. The purpose of LFC is to track the load variation while maintaining system frequency and tie line power interchanges (for interconnected areas) close to the specified values. In this way, transient errors in frequency and tie line power should be minimized and steady error should not appear.

In the past years, many techniques were proposed for the supplementary control of LFC systems [2–20]. Conventionally, PI and PID controllers are used for LFC [2–4]. However, PI has many drawbacks, some of which are the long settling time and relatively large overshoots in the transient frequency deviations. Furthermore, utilization of the optimal control theory was examined in [5, 6]. The controller design is normally based on the parameters of the linear incremental model of the power system which, in turn, depend on the condition of the power system. Therefore, the linear optimal controller is sensitive to variations in the plant parameters or operating conditions of the power system. Moreover, the linear optimal controller yields an unsatisfactory dynamic response in the presence of Generation Rate Constraint (GRC) [7]. Other techniques of designing the secondary control loop for the LFC include Neural Network methods [8, 9], Superconducting Magnetic Energy Storage (SMES) unit applications [10], and spline techniques [11]. Furthermore, the application of VSC to the LFC problem was considered by many authors [12–16]. VSC possess some attractive features, mainly robustness and good transient response. In [12], a VSC controller was compared with conventional and optimal control methods for two equal-area nonreheat and reheat thermal systems. However, a systematic method for obtaining the switching vectors and optimum feedback gains of the VSC was not discussed. The pole placement technique was utilized in designing the VSC for a single nonreheat LFC system in [13]. The feedback gains were selected by trial and error. In practice, LFC models are nonlinear. Unfortunately, conventional control design methods are not efficient when nonlinearities are introduced to the incremental models of control systems. Thus, other methods should be proposed for the design of the controllers. One of the most reliable techniques is the utilization of iterative heuristic optimization algorithms in tuning the controllers to obtain their optimum settings. Some of the recent attempts applied to the variable structure LFC problems (for linearized models) can be found in [14-16]. In [14], the Genetic Algorithm (GA) was used to optimize the feedback gains of the VSC applied to a single area non-reheat LFC. In [15], Particle Swarm Optimization (PSO) was used for the same purpose. In both [15] and [16], only the feedback gains were selected optimally. On the other hand, the switching vector was obtained from other design methods reported in literature.

This paper proposes to design the whole variable structure load frequency controller parameters (both the feedback gains and the switching vectors) optimally using the Tabu Search algorithm. TS is a general heuristic opti-

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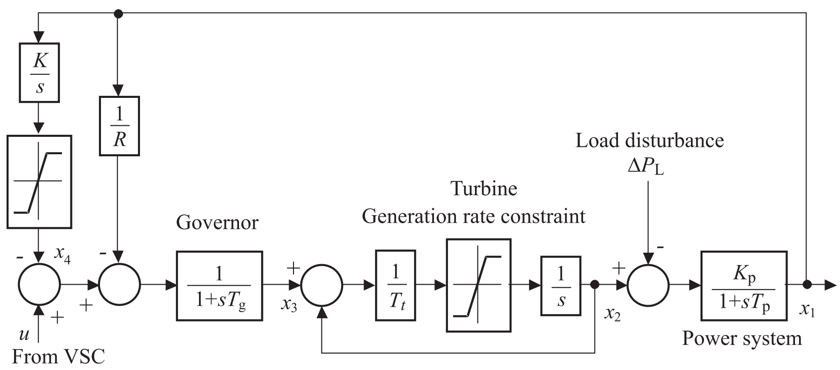

Fig. 1. Single LFC area with nonlinearities.

mization method that has been applied recently to some power system problems [17–19]. The proposed VSC design will be compared to other methods reported in literature. Furthermore, the complexity of the VSC can be highly reduced if only the accessible states are used in the design. This issue has been also investigated in this paper. The organization of this paper will be as follows: First, an explanation of a nonlinear LFC model will be presented in Section 2 followed by a brief introduction to the VSC theory, in section three. Section 4 presents an overview of the TS algorithm. The proposed design of VSC is explained in section five. Simulations results and comparison with an LFC design method reported in literature is presented in section six. Finally, conclusions are presented in Section 7.

2 LFC NONLINEAR MODEL

The linearized model for a single LFC area is given in many references [13]. 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 (4×4 system matrix), B (4×1 input vector), and F (4×1 disturbance vector) are given as follows:

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

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

$$F^\top = \begin{bmatrix} \frac{K_p}{T_p} & 0 & 0 & 0 \end{bmatrix}.$$

$T_p(s)$ is the plant model time constant, $T_t(s)$ is the turbine time constant, $T_g(s)$ is the governor time constant, K_p (Hz/p.u. MW) is the plant gain, K is the integral control gain, and R (Hz/p.u. MW) 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 paper, nonlinearities will be included in the LFC model as shown in Fig. 1. The model includes the effect of Generation Rate Constraint (GRC) which is caused by the mechanical and thermodynamic constraints in practical steam turbines systems [7]. Also, a limiter on the integral control value is included to prevent excessive control.

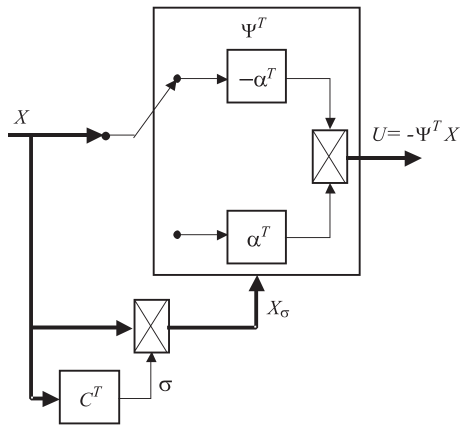

Fig. 2. Block diagram of variable structure controller.

3 OVERVIEW OF VSC

The fundamental theory of variable structure systems can be found in [20]. A block diagram of the VSC is shown in Fig. 2, 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 $n\times n$ system matrix, and B is $n\times m$ input matrix.

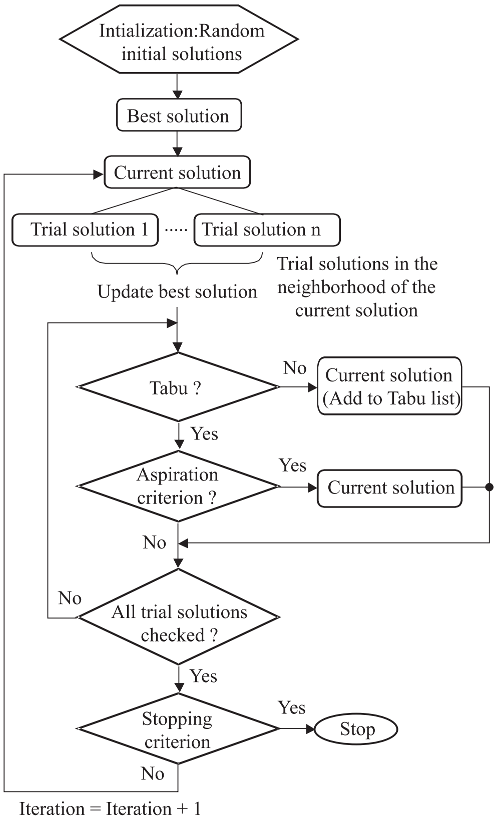

Fig. 3. Flow chart of TS algorithm.

The VSC control laws for the system of (2) are given by

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

where the feedback gains are given as

$$\psi_{ij} = \begin{cases} \alpha_{ij} \, , & \text{if } x_j \sigma_i > 0 \, ; \; i = 1, \dots, m \, , \\ -\alpha_{ij} \, , & \text{if } x_j \sigma_i < 0 \, ; \; j = 1, \dots, n \, , \end{cases}$$

and

$$\sigma_i(X) = C_i^\top X = 0 \, , \; i = 1, \dots, m \, ,$$

C_i are the switching vectors. A systematic design procedure reported in the literature for selecting the elements of the switching vectors C_i (for linearized LFC models) can be found in [13].

4 OVERVIEW OF TABU SEARCH ALGORITHM

The Tabu Search Algorithm was proposed a few years ago by Fred Glover [23, 24] as a general iterative heuristic method for solving combinatorial optimization problems. TS is a conceptually simple and elegant heuristic method. It has now become an established optimization methodology that is rapidly spreading in various fields. Planning and scheduling, transportation, routing and network design, continuous and stochastic optimization, manufacturing and financial analysis are some of these applications [17]. The search method for the optimum solution is partially based on the hill climbing method that finds a solution through creating a neighborhood around a solution and moving towards the best solution within the neighborhood. TS succeed in escaping local minimas by using a tabu list that records the forbidden moves. Moves are classified as forbidden if certain conditions imposed on the moves are satisfied. The purpose of maintaining a tabu list is to force the search process to avoid cycling and thus impose diversification.

At initialization, the objective is to make a broad examination of the solution space, diversification, but as candidate locations are recognized the search is narrowed to give local optimal solutions in a process of intensification. 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 neighborhood 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 [17, 23, and 24]. The criteria used here is to override the tabu status of a move if it produces a better solution than the best solution, xbest, 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 is shown in Fig. 3 and can be described by the following steps:

Step 1: Generate Random initial solutions, $x_{initial}$. 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 the best solution objective function value. If a better solution is obtained, then $x_{best} = x_{trial}$.

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.

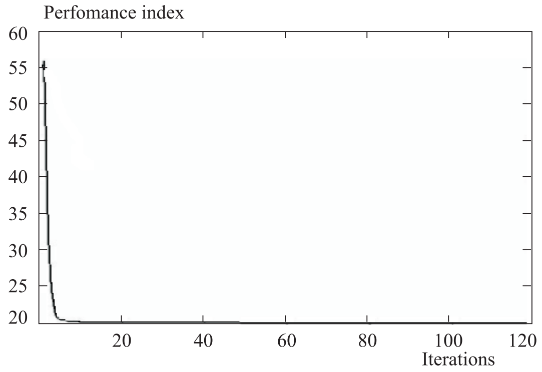

Fig. 4. Convergence of performance index (J).

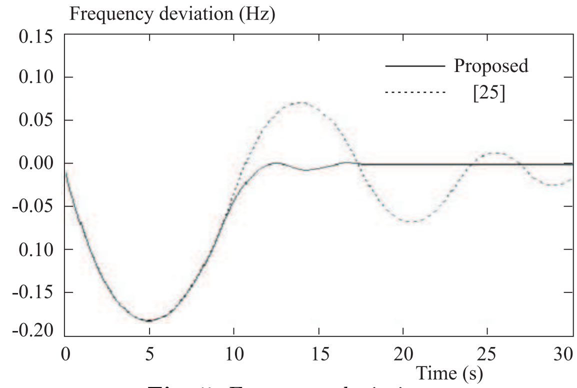

Fig. 5. Frequency deviation.

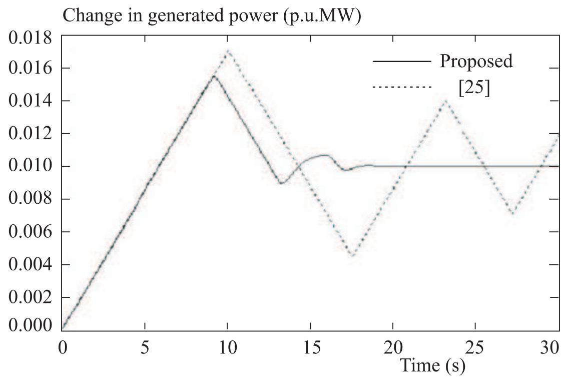

Fig. 6. Change in generated power.

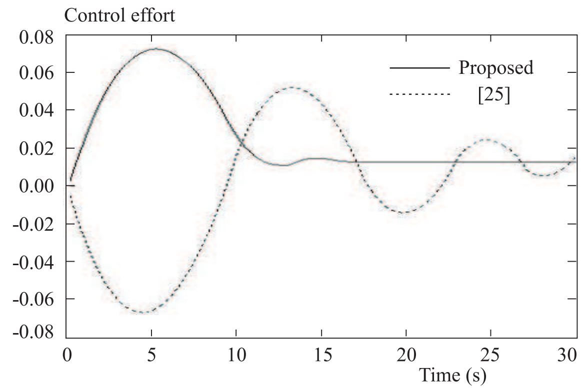

Fig. 7. Control effort.

5 PROPOSED VSC DESIGN USING TS

In conventional methods of designing VSC, the nonlinear system has to be transformed into a suitable controllable form before the feedback control theory techniques, such as linear optimal control and pole placement can be applied. In addition, the feedback gains α_{ij} were selected by trial and error. To overcome the above mentioned two difficulties in the design of VSC, the present work proposes an optimal design using TS algorithm. The proposed design provides a simple and more systematic way of arriving at the optimal settings of the VSC and cuts down the need for nonlinear or coordinate transformations when studying nonlinear LFC models. Therefore, both the elements of the switching vector and feedback gains of the VS controller, C_i and α_{ij}, are determined optimally using the TS algorithm 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 function is used:

$$J = \int_0^\infty q_1 \Delta\omega^2 + q_2 \Delta\omega^2 \mathrm{d}t \,. \tag{4}$$

The Objective function, J, includes a scaled value of the square of the deviation in frequency. This will minimize the fluctuations in the frequency of the area. It also includes a scaled value of the deviation in the control effort to reduce the chattering in the control signal. The effect of inclusion of this value and a comparison of different objective functions for different scaling coefficients q_1 and q_2 can be found in [16] for linearized LFC models.

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

To validate the effectiveness of the proposed VSC design for nonlinear LFC models, comparison is made with a robust controller design method reported in the literature [25]. The following are the parameters of the investigated system:

$$1/T_p = 0.0665\,\mathrm{s}^{-1} \qquad 1/RT_g = 6.86$$
$$1/T_t = 3.663\,\mathrm{s}^{-1} \qquad K_p/T_p = 8$$
$$1/T_g = 13.736\,\mathrm{s}^{-1} \qquad K = 0.6$$

A GRC of 0.1 p.u. MW per minute = 0.0017 p.u. MW/sec was included in the model. For comparison purposes, the system is simulated for a 0.01 p.u. load disturbance.

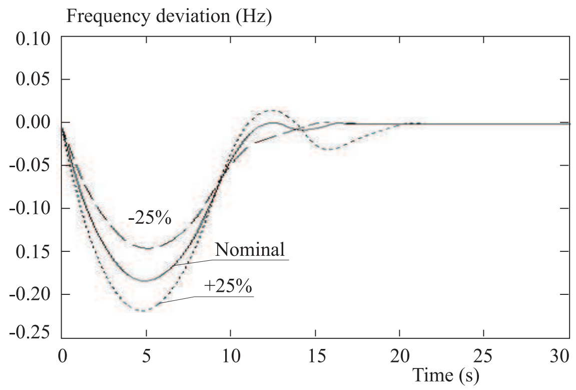

Fig. 8. Frequency deviation for change in parameters of LFC system.

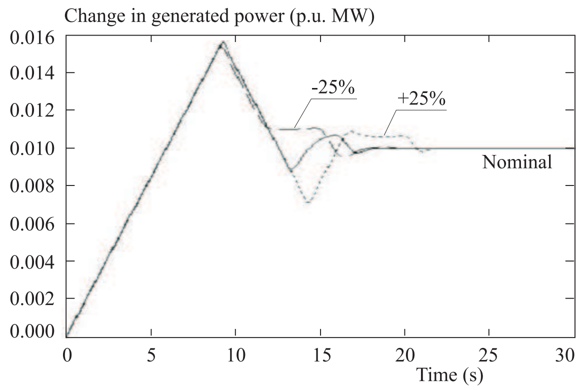

Fig. 9. Change in generated power for variation in parameters of the LFC system.

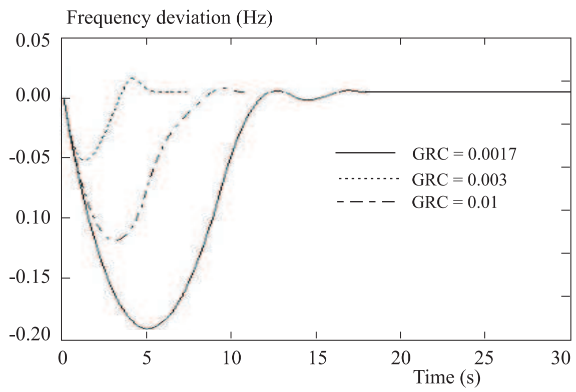

Fig. 10. Frequency deviation for different GRC values.

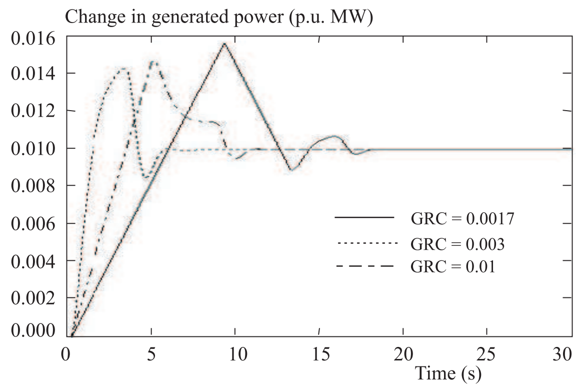

Fig. 11. Change in generated power for different GRC values.

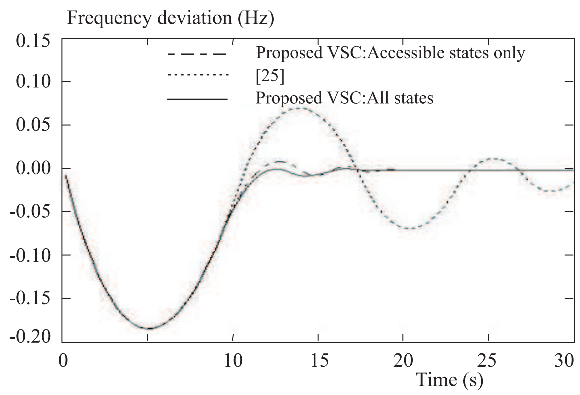

Fig. 12. Frequency deviation: Accessible states design (ASVSC).

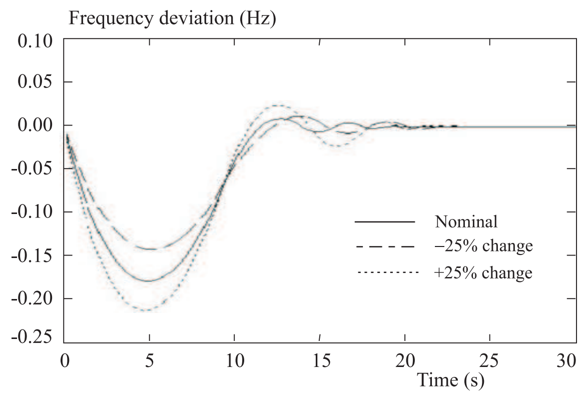

Fig. 13. Robustness of proposed ASVSC: Accessible states design.

The proposed TS design procedure described in section five is applied to arrive at the optimal switching vectors and feedback gains of the VSC. The Tabu list size and the maximum number of iterations are taken at 7 and 500, respectively. The performance index of equation (4) is used with scaling coefficients of $q_1 = q_2 = 1$. As a result, the following optimal settings of VSC are obtained:

$$C = [1.6384 \quad 28.9077 \quad 9.3736 \quad 6.8697]^\top$$

$$\alpha = [0.2616 \quad 0.3022 \quad 0.8951 \quad 0.0335]^\top$$

Figure 4 shows the quick convergence of the performance index. The dynamical behaviour of the designed system is shown in Figs. 5 and 6. It is quite clear that the proposed controller design reveals a much faster dynamical behaviour in terms of frequency deviation and generated power. In addition, the control effort reaches a steady value faster than that proposed in [25], Fig. 7. It is also worth mentioning that the VSC chattering is almost eliminated.

The robustness of the proposed controller against the model parameters variation has also been investigated. Figures 8 and 9 show, respectively, the frequency deviation and change in generated power for 25 % change in $1/T_p$, $1/T_g$, $1/RT_g$, $1/T_t$, and K_p/T_p. It can be seen that the proposed design is very robust against changes in the parameters of the studied system. Furthermore, the effect of changing the value of GRC on the dynamical behaviour of the designed controller is shown in Figs. 10 and 11. The controller performance is still satisfactory.

In practice, it is well known that engineers try to use only accessible states when designing a controller. Their aim is to rend a less complex and more practical controller. Therefore, the proposed design procedure of the VSC is applied again to the nonlinear LFC model of [25], with only the accessible states, x_1 (frequency deviation) and x_2 (change in generated power), used as feedback to the controller. The same objective function, J, is used for optimizing the parameters of the VSC using TS algorithm. The following are the optimum values of the present VS controller, named as ASVSC:

$$C = [\,0.2225 \quad 26.697\,]^{\top} \,,$$
$$\alpha = [\,0.3689 \quad 0.6368\,]^{\top} \,.$$

Figure 12 shows the dynamical behavior of the system with the proposed ASVSC when compared to the controllers designed in [25] and the present controller with all accessible states. It is clear that the proposed ASVSC improves the dynamics of the LFC system even when only the accessible states are used in the design. In addition, the proposed ASVSC maintains its robustness against parameters variation, Figure 13.

7 CONCLUSIONS

In this paper, a robust variable structure controller applied to nonlinear LFC problem has been presented. To select the VSC settings, the proposed method formulates the design as an optimization problem and utilizes the Tabu Search Algorithm as an optimization tool. The effectiveness of the proposed design is validated by comparing it with other methods reported in literature. The outcomes of this study can be summarized as follows:

1) The proposed design of VSC using the TS algorithm improves the dynamical behavior of the LFC system in comparison with other design methods reported in literature.

2) A smooth control signal was obtained. This was realized optimally by including the deviation of the control signal into the objective function.

3) The proposed design of VSC applied to LFC showed a robust behavior against model parameters variation.

4) The proposed VSC design can be more practical and less complex when using only the accessible states as feedback to the controller. This reduction in complexity of the controller is accompanied with a maintained improved dynamical behavior and robustness against model parameters variation.

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