

# Variable Structure Load Frequency Controller: Optimal Design and Chattering Reduction using Particle Swarm Optimization Algorithm

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**Abstract** — This paper presents an optimal design of Variable Structure Load Frequency Controller using Particle Swarm Optimization Algorithm. The optimal design provides a simple systematic way for obtaining optimum feedback gains and switching vector for VSC. It also includes a new method to reduce the chattering associated with the Variable Structure Controllers (VSC). The proposed method has been applied to a single nonreheat area. Comparison with the literature shows the effectiveness of the proposed design approach.

**Index Terms** — Variable Structure Control (VSC), Load Frequency Control (LFC), Particle Swarm optimization.

## I. 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 [1-15]. The purpose of the LFC is tracking 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 [1-4], Optimal control [5], Adaptive control [6], and Neural network methods [7, 8]. Furthermore, Variable Structure Control (VSC) for the LFC problem was investigated by a number of authors [9-15]. Robustness and good transient response are some of the attractive features of VSC. In [9], a VSC controller was compared with conventional and optimal control methods for two equal-area nonreheat and reheat thermal systems. Although that the study confirmed the superiority of VSC in performance to both the conventional and optimal control methods, a systematic method for obtaining the switching vectors and optimum feedback gain settings was not discussed. Moreover, pole placement was utilized in designing the VSC for a single nonreheat system in [10]. However, optimum gain settings were not suggested by the authors. Two area nonreheat and reheat thermal systems were studied in [11] and [12]. The former utilized simple control logic to switch between proportional and integral controllers. Sliding mode was not used. In [12], the same control logic

was used to switch between VSC and simple Integral controller. Parameters of the controllers were optimized using Integral Squared Error (ISE) technique. Improvement in the dynamic response was achieved in comparison to conventional integral controller. Using an approximating control law and a new switching function with integral action, a robust controller was designed in [13]. The method was claimed to reduce chattering effect of VSC and ensure existence of sliding mode. However, the author did not show the behavior of the control effort. Also, the frequency response of the designed controller showed questionable response with 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 generation will cause more degradation in the performance of the controller. Furthermore, Fuzzy control was combined to equivalent and switching control in [14] to design a robust Sliding Mode Control. Simulations of the system showed both better performance and reduced chatter.

This paper will discuss a new optimal method to design a VSC for the LFC. The paper is considered an extension to previous work in [15] where only the feedback gains of the VSC were optimized. In [15], the switching vector was obtained from previous designs in literature using pole placement method. In this paper, both the feedback gains and switching vector will be designed optimally using Particle Swarm Optimization algorithm (PSO). PSO [16] is a new evolutionary computation technique which has been applied recently to some practical problems [17]. Furthermore, the design method also incorporates a simple optimal method to obtain a design that reduces the chattering effect.

## II. LOAD FREQUENCY CONTROL

The model for LFC of a nonreheat turbine for single area power system is shown in Fig. 1 [10]. Since the power system is usually exposed to small load changes during its normal operation, the linearized model will be considered. The dynamic model in state variable form can be obtained from the transfer function model and is given as

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

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.

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

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

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

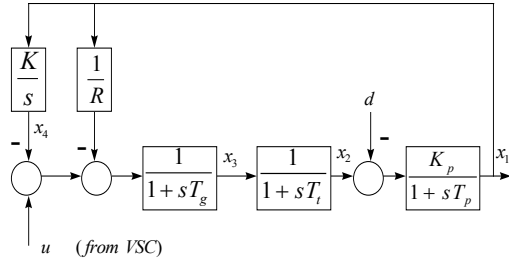


Fig.1. Block diagram of single area

$T_p$  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  $u$ .

### III. THEORY OF VSC

The fundamental theory of variable structure systems may be found in [18]. 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

$$\dot{X} = AX + BU \quad (2)$$

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

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

where the feedback gains are given as

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

and

$$\sigma_i(X) = C_i^T X = 0, \quad i = 1, \dots, m$$

where  $C_i$  are the switching vectors which are determined usually via a pole placement technique.

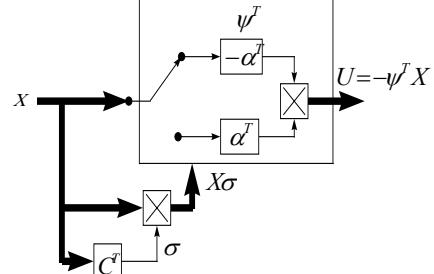


Fig. 2. Block diagram of variable structure controller

The design procedure for selecting the constant switching vector  $C_i$  can be found in [10].

### IV. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is an evolutionary computation technique developed by Eberhart and Kennedy [16] inspired by social behaviour and bird flocking or fish schooling. The PSO algorithm applied in this study can be described briefly as follows:

1) Initialize a population (array) of particles with random positions and velocities  $v$  on  $d$  dimension in the problem space. The particles are generated by randomly selecting a value with uniform probability over the  $d^{\text{th}}$  optimized search space  $[x_d^{\min}, x_d^{\max}]$ . Set the time counter  $t = 0$ .

2) For each particle  $x$ , evaluate the desired optimization fitness function,  $J$ , in  $d$  variables.

3) Compare particles fitness evaluation with  $x_{pbest}$ , which is the particle with best local fitness value. If the current value is better than that of  $x_{pbest}$ , then set  $x_{pbest}$  equal to the current value and  $x_{pbest}$  locations equal to the current locations in  $d$ -dimensional space.

4) Compare fitness evaluation with population overall previous best. If current value is better than  $x_{gbest}$ , the global best fitness value then reset  $x_{gbest}$  to the current particle's array index and value.

5) Update the time counter  $t$ , inertia weight  $w$ , velocity  $v$ , and position of  $x$  according to the following equations

$$\text{Time counter update: } t = t + 1$$

$$\text{Inertia weight update: } w(t) = w_{\min} + (w_{\max} - w_{\min}) \left( \frac{m-t}{m-1} \right)$$

Velocity update:

$$v_{id}(t) = w(t)v_{id}(t-1) + 2\alpha(x_{idpbest}(t-1) - x_{id}(t-1)) + 2\alpha(x_{idgbest}(t-1) - x_{id}(t-1))$$

Position of  $x$  update:  $x_{id}(t) = v_{id}(t) + x_{id}(t-1)$

where  $w_{min}$  and  $w_{max}$  are the maximum and minimum values of the inertia weight  $w$ ,  $m$  is the maximum number of iterations,  $i$  is the number of the particles that goes from 1 to  $n$ ,  $d$  is the dimension of the variables, and  $\alpha$  is a uniformly distributed random number in (0,1). The particle velocity in the  $d^{th}$  dimension is limited by some maximum value  $v_d^{max}$ . This limit improves the exploration of the problem space. In this study,  $v_d^{max}$  is proposed as

$$v_d^{max} = kx_d^{max}$$

where  $k$  is a small constant value chosen by the user, usually between 0.1-0.2 of  $x_d^{max}$  [20].

6) Loop to 2, until a criterion is met, usually a good fitness value or a maximum number of iterations (generations)  $m$  is reached.

More details about PSO can be found in [16, 20].

#### V. PROPOSED VSC DESIGN USING PSO

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

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

2) Evaluate a performance index that reflects the objective of the design. In this study we propose three objective functions as follows:

$$J_1 = \int_0^{\infty} \Delta w^2 dt \quad (13)$$

$$J_2 = \int_0^{\infty} q_1 \Delta w^2 + q_2 u^2 dt \quad (14)$$

$$J_3 = \int_0^{\infty} q_1 \Delta w^2 + q_2 \Delta u^2 dt \quad (15)$$

$J_1$ : reflects the objective of the LFC where the deviation in frequency  $\Delta\omega$  is minimized.

$J_2$ : includes the control effort. In this way, the control effort will be minimized and therefore the chattering effect will be reduced.

$J_3$ : deviation of the chattering is included here. Since chattering is characterized by a dramatic change in the control force, inclusion of deviation of the control effort in the performance index will allow smoothening of the control signal and thus reduce chattering.

3) Use PSO (number of particles, dimension, and maximum number of iterations) to generate new feedback gains and switching vector values as described in section IV.

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 or if the maximum number of iterations is reached, otherwise go to step 3.

#### VI. SIMULATION RESULTS

The LFC system described in section II was simulated. The following parameters are used [10]:

$$\begin{aligned} T_p &= 20 \text{ s} & K_p &= 120 \text{ Hz p.u. MW}^{-1} \\ T_i &= 0.3 \text{ s} & K &= 0.6 \text{ p.u. MW rad}^{-1} \\ T_g &= 0.08 \text{ s} & R &= 2.4 \text{ Hz p.u. MW}^{-1} \end{aligned}$$

In [10], the design procedure in section III was applied with pole placement technique to obtain the switching vector. The feedback gains were obtained by trial and error.

The proposed VSC design using PSO algorithm described in section V has been applied to minimize the performance indices in equations (13-15) for optimal selection of the switching vector and feedback gains. The PSO parameters used are the number of particles  $n = 15$ , maximum number of iterations  $m = 500$ , dimension  $d = 4$ ,  $w_{max} = 0.9$ ,  $w_{min} = 0.4$ , and the maximum velocity constant factor  $k = 0.1$ . Maximum iteration of 500 was applied. The algorithm is terminated when there is no significant improvement in the value of the performance index. The PSO design procedure described in section V was applied to arrive at the optimal switching vectors and feedback gains that minimizes the performance index  $J$  when the system is subjected to a step load change of 0.03 (3%). Table I shows the performance indices and weighting coefficients used in different designs. The optimal switching vectors and feedback gains are given in Table II.

Design No.1 values in Table II were taken from [10], where pole placement is used to obtain the switching vector. The feedback gains were obtained by trial and error. In designs No. 2 and 3 [15], the authors used GA to arrive at the optimal feedback gains. The switching vector was obtained from [10].

The other designs show the application of the design method proposed in section V. Different performance indices were used with different weighting factors  $q_1$  and  $q_2$ .

TABLE I  
PERFORMANCE INDICES AND WEIGHTING COEFFICIENTS FOR DIFFERENT DESIGNS

No.	Performance Index, $J$	$q_1$	$q_2$
1	-	-	-
2	$J_1$	-	-
3	$J_2$	1	1
4	$J_1$	-	-
5	$J_2$	1	1
6	$J_2$	1	0.5
7	$J_3$	1	1
8	$J_3$	1	0.5

TABLE II

SWITCHING VECTORS,  $C$ , AND FEEDBACK GAINS,  $\alpha$  OF VSC DESIGNS. DESIGNS NUMBER 1 AND 2 WERE OBTAINED FROM [10]. DESIGN NUMBER 3 WAS OBTAINED FROM [15]

No.	$C$	$\alpha$
1	[5.16 4.39 1 16]	[6 6 2 0]
2	[5.16 4.39 1 16]	[2.08 0.025 1.40 0]
3	[5.16 4.39 1 16]	[0.76 0.002 1.40 0]
4	[4.62 1.39 0.085 30]	[3 3 3 3]
5	[1.97 1.65 0.28 2.44]	[0.76 0 0 0]
6	[3.25 0 2.32 2.34]	[1.11 0 0 0]
7	[2.77 0.75 0.84 4.95]	[2 0.005 0.797 1.06]
8	[5 0.7423 1.7130 5]	[2 0 0 2]
9	$C$ and $\alpha$ same as No. 4; at $t_s = 1s$ $\alpha = m \cdot \alpha$ ( $m=0.3$ )	

Fig. 3 shows the convergence of the performance index for the different designs of Table II. The dynamic performance of the system for the optimum switching vectors and feedback gains is shown in Fig. 4 – 9.

The following can be concluded from the shown results:

1) The new design method gives a tradeoff between improved frequency response and chattering reduction. Designs number 5-8 gave a significant reduction in chattering, Fig. 7, with some degradation in frequency response, Fig. 5.

2) Therefore, the designer can control the compromise between frequency and chattering reduction by altering the values of  $q_1$  and  $q_2$  of equations (13-15).

3) In design number 4, a significant improvement in the frequency deviation was achieved, Fig. 4. However, there was an increased chattering in the control effort as shown in Fig. 6. To reduce this chattering, the feedback gains of the controller can be reduced when the system is in steady state. This was done in design number 9 of Table II.  $\alpha$  was replaced by  $m \cdot \alpha$  at settling time  $t_s = 1s$ .  $m = 0.3$  was used in this study.

Fig. 8 shows the result of this replacement. A significant reduction in chatter was obtained with no degradation in the frequency response. In this way, the chattering in the control effort is reduced while preserving the improved frequency response.

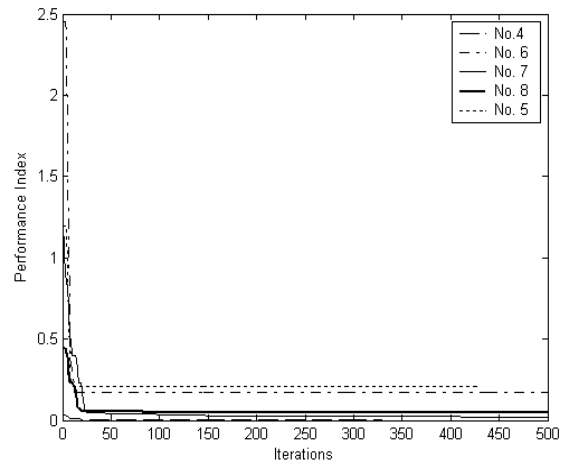


Fig. 3. Convergence of the objective functions for the designs of Tables I and II

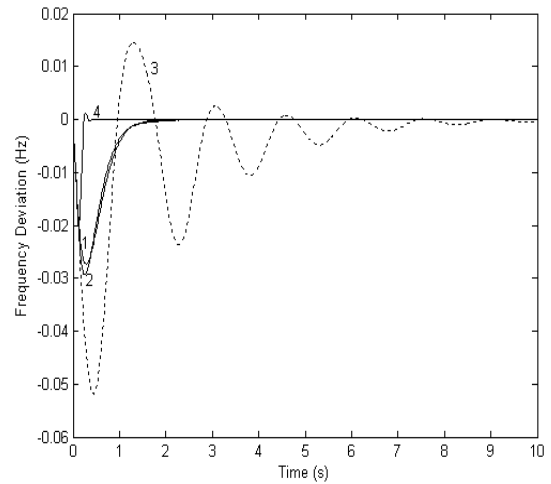


Fig. 4. Frequency deviation for designs number 1-4 of Tables I and II

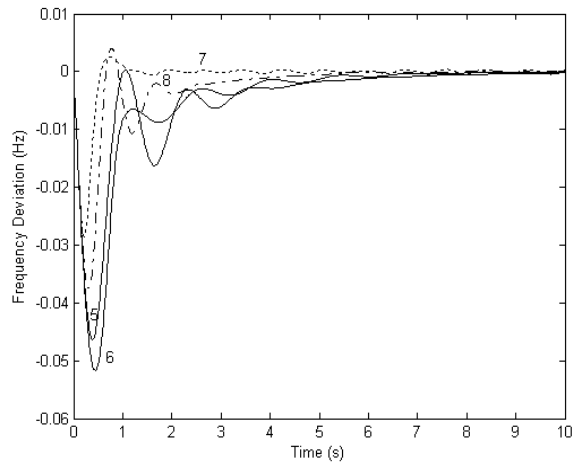


Fig. 5. Frequency deviation for designs 5 – 8 of Tables I and II

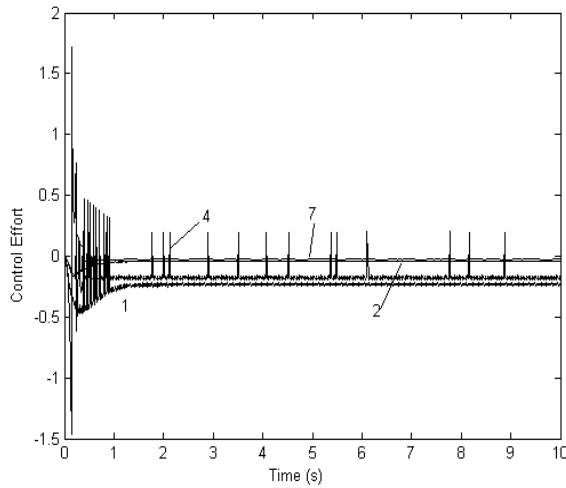


Fig. 6. Control effort for designs number 1, 2, 4, and 7 of Tables I and II

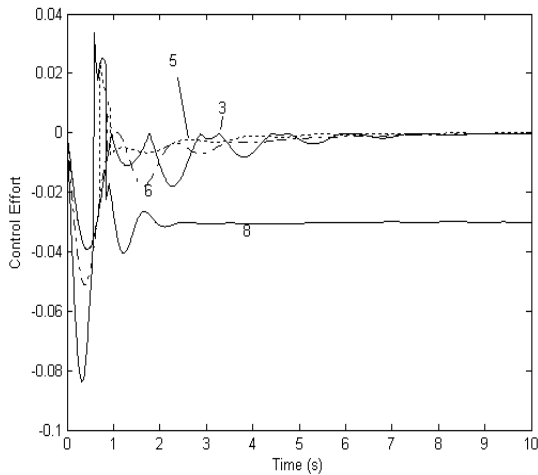
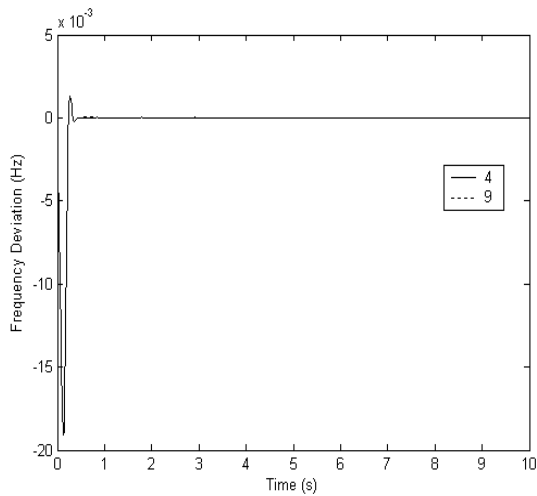


Fig. 7. Control effort for designs number 3, 5, 6, and 8 of Tables I and II



(a)

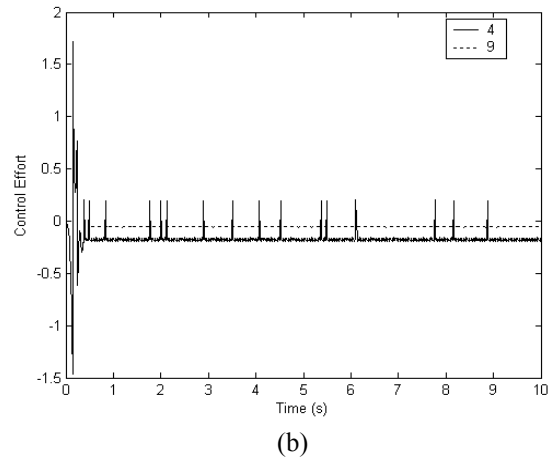


Fig. 8. Comparison between designs number 4 and 9 (a) Frequency Deviation (b) Control effort

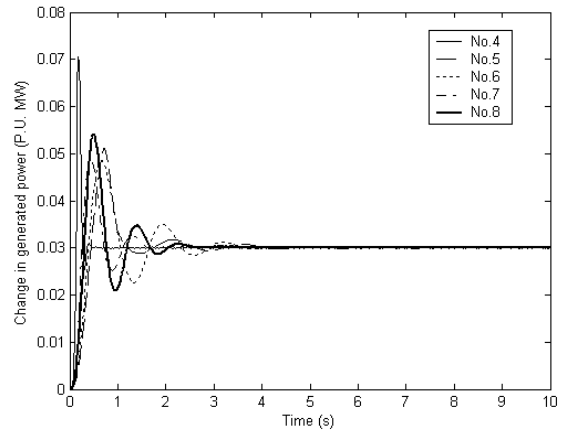


Fig. 9. Change in generated power for designs number 4-8

## VII. CONCLUSION

A new optimal design method for the VSC applied to the LFC problem is proposed in this paper. PSO was used to optimize the feedback gains and switching vector of the VSC. Furthermore, the design includes a simple method to achieve a VSC controller with reduced chattering. The proposed design method was compared to a method reported in literature. The new method showed promising results in terms of frequency response and reduced chattering.

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