FF Algorithm for design of SSSC-based FACTS controller

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Abstract

Power-system stability improvement by a static synchronous series compensator (SSSC)-based damping controller considering dynamic power system load is thoroughly investigated in this paper. Only remote input signal is used as input to the SSSC-based controller. For the controller design, Firefly algorithm is used to find out the optimal controller parameters. To check for the robustness and effectiveness of the proposed controller, the system is subjected to various disturbances for both single-machine infinite bus power system and multi-machine power system. Detailed analysis regarding dynamic load is done taking practical power system loads into consideration. Simulation results are presented.

Keywords : Static synchronous series compensator; dynamic power system load; power system stability; firefly algorithm; single-machine infinite-bus power system.

1 Introduction

The main function of power system is to convert energy from one of the naturally available forms of electricity. But, electrical energy cannot be stored in large quantities. So, to maintain the balance between what is demanded and generated, many controllers and equipments are used which further introduces non-linearity in power system. This non-linearity gives rise to many instability problems. Electrical power oscillations are a type of these instability problems. The root cause of electrical power oscillations are the unbalance between power demand and available power at a period of time. It mainly occurs when large power systems are interconnected by relatively weak tie lines. If no adequate system damping is available, then, these oscillations causes large fluctuations in output power, current and voltage [1]. One of the many ways to counteract this problem is the use of flexible ac transmission systems (FACTS) controllers in power systems [2]. SSSC is the FACTS device that

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is under consideration in this paper. It is a series device and has the capability to increase or decrease the overall reactive voltage drop across the line thereby controlling the power flow [3], [4]. Several literatures can be found related to applications of SSSC which ranges from power oscillation damping, improvement of transient stability to frequency stabilization. [[5], [6], [7]]. Several deterministic optimization techniques such as gradient method, linear programming [8], non-linear programming [9], quadratic programming [10] and dynamic programming [11] have already been used for the FACTS based damping controllers. But, these methods are very time-consuming as it requires enormous computational efforts. Also, these methods have the tendency to converge to local solutions instead of global solutions if the initial guess is possibly nearer to the local solution. These methods include Tabu Search (TS), Hopfield Neural Networks, Particle Swarm Optimization (PSO) [12], an improved coordinated aggregation-based particle swarm optimization (ICA-PSO), Genetic Algorithm (GA) [13], Real-Coded Genetic Algorithm (RCGA) [14], Differential Evolution (DE) [15], Bacterial Foraging (BF) and Firefly Algorithm (FFA) [16]. In this paper, Firefly Algorithm is used to find out the optimal values of the parameters of the controller. Firefly algorithm is a stochastic optimization method minimizing an objective function that can model the problem's objectives while incorporating constraints. It is quite effective in nonlinear constraint optimization and is useful for optimizing multi-modal search spaces as given in [17]. Power system load can be considered as the most uncertain and difficult components to model. Its modeling is mainly classified into static load model and dynamic load model. The different loads are grouped into industrial, residential, commercial and agricultural load. Industrial loads include electric heating processes such as heating and most of the loads correspond to motors. Residential loads include air conditioner units. Similarly, commercial loads include discharge lighting and agricultural load consists of induction motors for driving pumps [18]. [19]. Selection of the input signal is an important criterion in the design of an efficient damping controller. Property of input signal is to give accurate control actions when a disturbance occurs in the power system. It can mainly be classified into two types of signals i.e. local and remote signal [15]. This paper considers speed deviation as the remote input signal to the proposed SSSC based damping controller.

2 Single Machine Infinite Bus Model With SSSC

Fig. 1 shows a single-machine infinite-bus system with SSSC. The system consists of a synchronous generator connected to an infinite-bus through a step-up transformer and a SSSC followed by a double circuit transmission line. The generator is a subsystem which contains hydraulic turbine, governor (HTG) and excitation system [20].

In Fig. 1, T/F represents the transformer; V_S and V_R are the generator terminal and infinite-bus voltages respectively; V_1 and V_2 are the bus voltages; V_DC and V_cnv are the DC voltage source and output voltage of the SSSC converter respectively; I is the line current and P_L and P_L1 are the total real power flow in the transmission lines and that in one line respectively. A dynamic load is connected to bus 1.All the relevant parameters are given in appendix A. The SSSC is a voltage source converter (VSC) that is connected in series with the transmission line. It operates without an external energy source as a series compensator whose output voltage is in quadrature with and

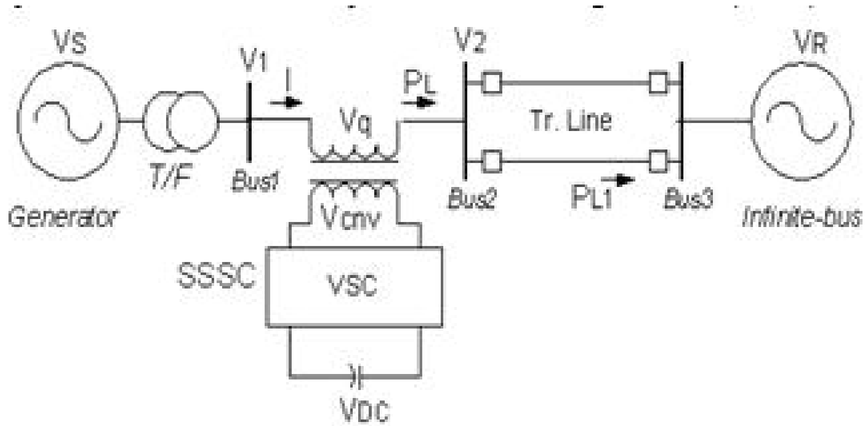

Figure 1: Single-machine infinite-bus power system with SSSC.

controllable independently of the line current. The voltage injected (Vq) by the SSSC is (almost) in quadrature with the transmission line current such that it emulates the behavior of a series inductor or capacitor so as to influence the power flow in the transmission lines [1] , [2]. VSC is connected on the secondary side of a coupling transformer which is responsible for variation in Vq. A capacitor connected on the DC side of the VSC. As presented in [12], [21] and [22], VSC using IGBT-based PWM inverters is used in the present study. A 3-ph, 3-wire dynamic load is connected to bus 1. Its active power P and reactive power Q vary as a function of positive sequence voltage. When the terminal voltage is greater than the Vmin value, the active power P and reactive power Q of the load vary as eq. (1):-

$$P(s) = P_o(\frac{V}{V_o})^{n_p}\frac{(1+T_{p_1}s)}{(1+T_{p_2}s)}$$
$$Q(s) = Q_o(\frac{V}{V_o})^{n_q}\frac{(1+T_{q_1}s)}{(1+T_{q_2}s)} \quad (1)$$

V_o:- Initial positive sequence voltage. P_o,Q_o:- Initial active and reactive powers at initial voltage V:- Positive sequence voltage. n_p,n_q:- Exponents controlling the nature of load. It varies from 1 to 3. T_p1 and T_p2:- Time constants controlling dynamics of P. T_q1 and T_q2:- Time constants controlling dynamics of Q.

If $n_p = 1$, $n_q = 1$,then, dynamic load acts as constant current load. If $n_p = 2$, $n_q = 2$,then, dynamic load acts as a constant impedance load.

Load Component	n_p	n_q
Resistance Space Heater	2.00	0.00
Pumps, fans and other motors	0.08	1.60
Large industrial motors	0.05	0.50
Small industrial motors	0.10	0.60

Table 1: Common Values for the exponents n_p , n_q for different load components

3 The Proposed Approach

3.1 Structure Of SSSC-based Damping Controller

Only one structure is used in this study to modulate the SSSC injected voltage i.e. lead-lag structure as shown in fig.2. Input signal to the structure is speed deviation and its output is the injected voltage [15]. This structure consists of a gain block, washout block and two stage lead-lag block. The two stage lead-lag block provides the appropriate phase-lead characteristics to compensate for the phase lag between input and the output signals. The washout block acts as a high pass filter with the time constant TW to allow signals associated with oscillations to pass as it is.

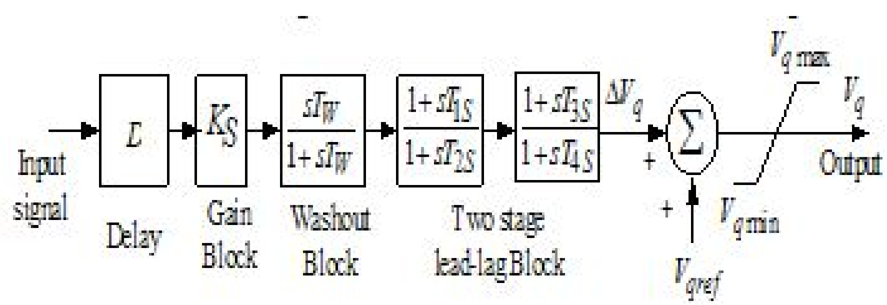

Figure 2: Structure of proposed SSSC-based damping controller.

Range of T_W is in the range of 1 to 20 seconds [1]. T_1S, T_2S and T_3S, T_4S are the time constants for the two stage lead-lag block. Vqref is the reference injected voltage as required by the steady state power flow control loop.

3.2 Problem Formulation

In the lead-lag structured controllers, the washout time constants T_W is already known [2], [21], [22]. In this paper, washout time constant T_W is taken to be 10s. The controller gain K_S and the time constants T_1S, T_2S , T_3S and T_4S are to be determined. During steady state conditions ΔVq and V_qref are constant. The effective Vq in dynamic conditions is given below.

$$V_q = V_q ref + \Delta V q$$

To obtain remote signals, additional costs associated with communication have to be incurred. For remote signals a signal transmission delay of 50 ms is considered along with the sensor time constant of 15 ms. In the present study, an integral time absolute error (ITAE) of the speed deviation is taken as the objective function J is expressed as:-

$$J = \int_{t=0}^{t=t_{sim}} |\Delta\omega| t \, dt$$

It is aimed to minimize this objective function in order to improve the system response in terms of the settling time and overshoots as in [15]. Therefore, the design problem can be formulated as the following optimization problem.

Minimize J
Subject to

$$K_S^{min} \le K_S \le K_S^{max}$$
$$T_{1S}^{min} \le T_{1S} \le T_{1S}^{max}$$
$$T_{2S}^{min} \le T_{2S} \le T_{2S}^{max}$$
$$T_{3S}^{min} \le T_{3S} \le T_{3S}^{max}$$
$$T_{4S}^{min} \le T_{4S} \le T_{4S}^{max}$$

4 Firefly Algorithm

Fireflies are an unique kind of species and produce short and rhythmic flashes. The flashing light is produced by a process of bioluminescence. They use such flashes to attract mating partners and to attract potential prey. Light Intensity at a particular distance r from the light source obeys the inverse square law. The light intensity I decreases as the square of the distance r increases . The idealized behavior of the flashing characteristics of fireflies are:

• All fireflies are unisex so that one firefly is attracted to other fireflies regardless of their sex;
• Attractiveness is proportional to their brightness, thus for any two flashing fireflies, the less bright one will move towards the brighter one. If no one is brighter than a particular firefly, it moves randomly;
• The brightness or light intensity of a firefly is affected or determined by the landscape of the objective function to be optimized [23].

Firefly Algorithm (FFA)
Objective function f(x),

$$x = (x_1 ... x_d)^T$$

Initialize a population of fireflies

$$x_i (i = 1, 2, ..., n)$$

Define light absorption coefficient γ
while (t < MaxGeneration)
for i = 1: n all n fireflies
for j = 1: i all n fireflies
Light intensity I_i at x_i is determined by f(x_i)
if

$$I_j > I_i$$

Move firefly i towards j in all d dimensions
end if
Attractiveness varies with distance r via

$$exp[-\gamma r^2]$$

Evaluate new solutions and update light intensity
end for j
end for i
Rank the fireflies and find the current best
end while
Post process results and visualization

The movement of a firefly i is attracted to another more attractive (brighter) firefly j is determined by:-

$$x_i^(t+1) = x_i^t + B_0 e^(-\gamma r)_i j^2)(x_i^t - x_i^t) + \alpha \epsilon_i^t$$

The distance between any two fireflies i and j at x_i and x_j can be the Cartesian distance

$$r_i j = ||x_i - x_j||_2$$

Condition	K_S	T_1S	T_2S	T_3S	T_4S	Obj Function Value
Set-1	83.77	0.36	0.32	0.06	0.04	0.00150
Set-2	74.79	0.39	0.36	0.06	0.05	0.00175
Set-3	76.93	0.22	0.31	0.37	0.26	0.00223

Table 2: SSSC based controller parameters for SMIB power system in nominal loading condition considering different values of n_p and n_q

Loading Condition	P_e in pu
Nominal	0.8
Light	0.6
Heavy	1.0

Table 3: Loading conditions considered

5 Implementation Of Algorithm

The model of the system under study has been developed using SimPowerSystem Toolbox in MATLAB/SIMULINK environment and FFA program has been written in .m file. The population size, number of generations and controller parameters initial guess are specified in the program itself. For every individual in the population, time –domain simulation is performed and the objective function value of the SIMULINK model is evaluated and moved to workspace. Implementation of Firefly Algorithm requires the determination of fundamental issues: randomness (α), light absorption coefficient (γ), attractiveness at r = 0 (B_0) and the number of population.Due to the random nature of this algorithm, the parameters cannot be set or determined in single run only. The best, worst and mean objective function value was determined for every set of parameters in 20 trials. The parameters α, B_0 were varied from 0.1 to 1.0 with a increase of 0.1 each time. Similarly, population size was varied from 5 to 30 with a step increase of 5.

6 Results and Discussions

Linearized models were developed to represent the non-linear differential equations depicting the behavior of synchronous machine with excitation system. In the present study, dynamic power system load is considered. So, in the first step, we found out the best controller parameters using firefly algorithm considering its different values in nominal loading condition as given in table 2. The minimum objective function value was obtained in case of set-1 for the nominal loading condition.
Set1-$n_p = 1$, $n_q = 1$
Set 2- $n_p = 2$, $n_q = 2$
Set 3- $n_p = 3$, $n_q = 3$

Load Component	Result Analysis	Objective Function Value
Resistance Space Heater	Set-1 gives minimum value	0.002066
Pumps, fans and other motors	Set-1 gives minimum value	0.001080
Large industrial motors	Set-1 gives minimum value	0.001116
Small industrial motors	Set-1 gives minimum value	0.001058

Table 4: Result analysis for different loading conditions for different practical loads considering all set of parameters

7 Simulation Results

To assess the effectiveness and robustness of the proposed controller, three different operating conditions as given in Table 4 are considered.

7.1 Nominal loading, 3-ph fault

A 3-phase self clearing fault of 100 ms duration is applied at the middle of one transmission line connecting bus 2 and bus 3, at t = 1.0 s.

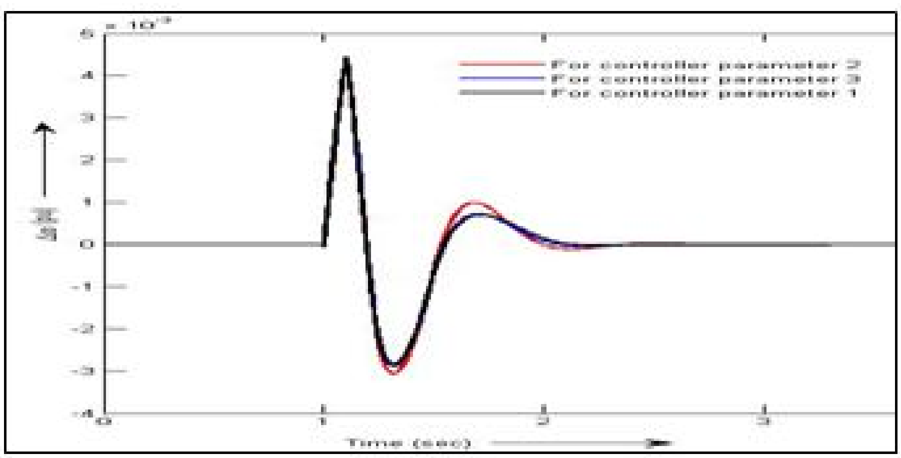

Figure 3: Speed deviation response for 100ms 3-phase fault in transmission line with nominal loading considering different controller parameters found for different exponents.

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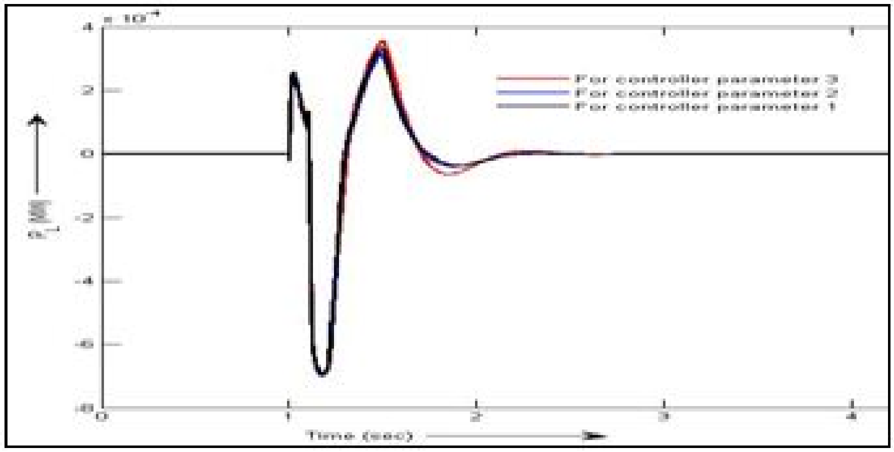

Figure 4: Tie-line power flow response for 100 ms 3-phase fault in transmission line with nominal loading considering different controller parameters found for different exponents.

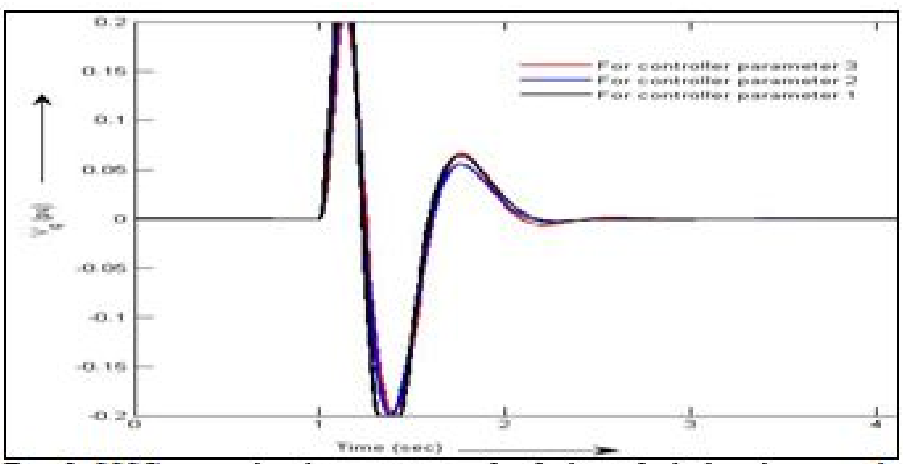

Figure 5: SSSC injected voltage variation for 3-phase fault disturbance with nominal loading considering different controller parameters found for different exponents.

7.2 Light loading,3-ph fault cleared by line outage

A 100 ms 3-phase fault is assumed in one of the parallel transmission line near bus 2 at t=1.0 s. The fault is cleared by tripping the faulted line and the lines are reclosed after 100 ms. The system

Response is shown in Fig. 6

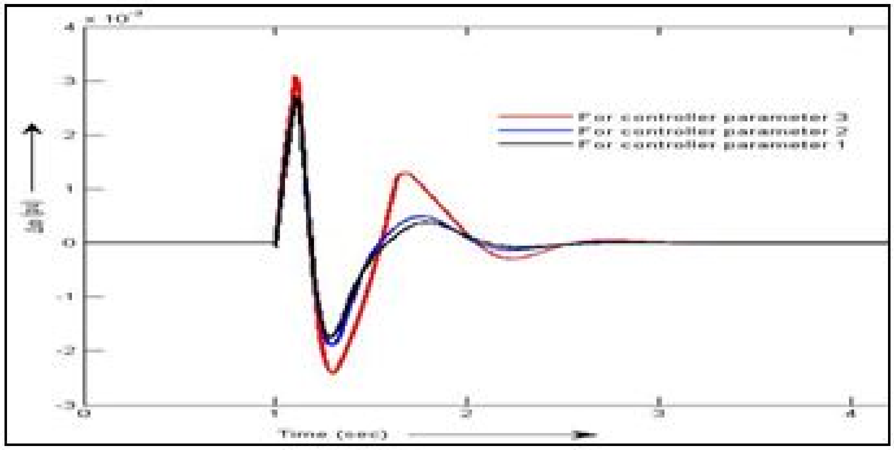

Figure 6: Speed deviation response for 100ms 3-phase fault in transmission line with light loading considering different controller parameters found for different exponents.

7.3 Heavy loading

7.4 Considering Practical loads,3-phase fault

Common values for the exponents of the model [19], for different load components are included in Table 1. As mentioned in the previous section, the best controller parameter set obtained .

8 Conclusion

In this study, power system stability improvement by a static synchronous series compensator (SSSC)-based damping controller taking a dynamic load into consideration is thoroughly investigated. As, remote input signal is considered, sensor time constant and signal transmission delays are considered specified. Firefly algorithm (FFA) is used to search for the optimal controller parameters of the controller design problem which is formulated as an optimization problem.

APPENDIX
System data: All data are in pu unless specified otherwise. Generator: S_B = 2100 MVA, H =3.7 s, V_B = 13.8 kV, f = 60 Hz, RS = 2.8544 e -3, X_d =1.305, X_d'= 0.296, X_d"= 0.252, X_q = 0.474, X_q' = 0.243, X_q" = 0.18, T_d = 1.01 s, T_d' = 0.053 s, $T_q o$"= 0.1 Load at Bus2: 250MW
Transformer: 3-Ph, 60 Hz, Length = 300 km each, R_1 = 0.02546 Ω/ km, R_0= 0.3864 Ω/ km, L_1=

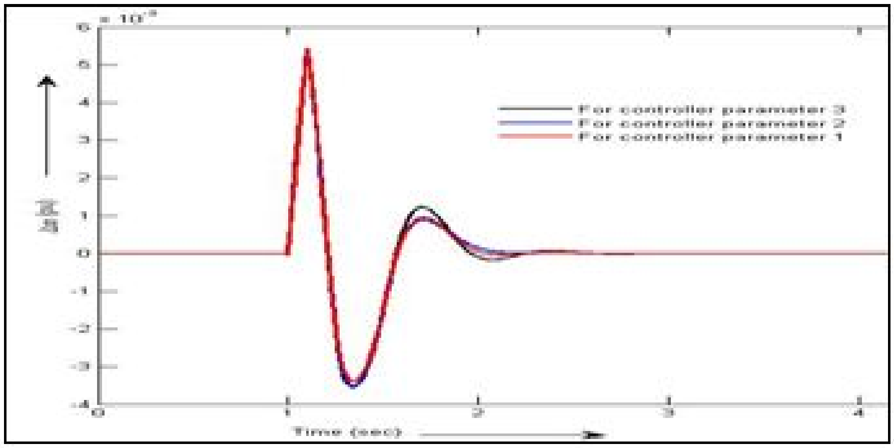

Figure 7: Speed deviation response for 100ms 3-phase fault in transmission line with heavy loading considering different controller parameters found for different exponents.

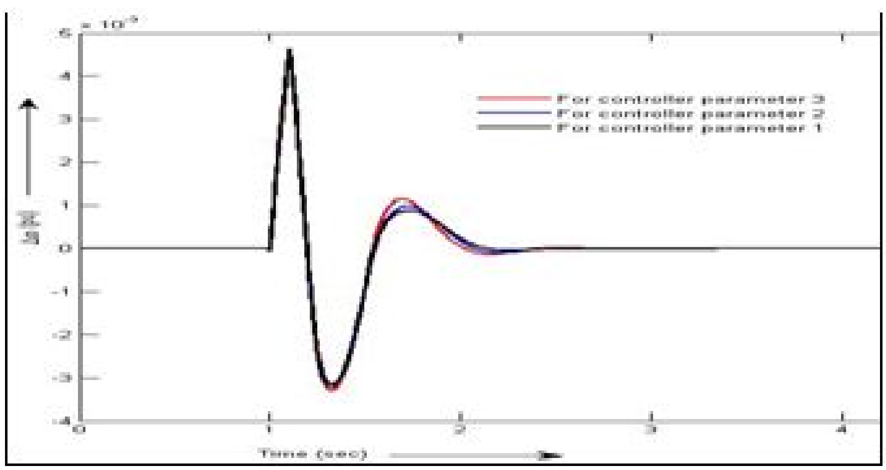

Figure 8: Speed deviation response for Resistance space heater load.

0.9337e-3 H/km, L_0 = 4.1264e-3 H/ km, C_1 = 12.74e-9 F/ km, C_0 = 7.751e-9 F/ km
Transmission line: 3-Ph, 60 Hz, Length = 300 km each, R_1 = 0.02546 Ω/ km, R_0= 0.3864 Ω/ km, L_1= 0.9337e-3 H/km, L_0 = 4.1264e-3 H/ km, C_1 = 12.74e-9 F/ km, C_0 = 7.751e-9 F/ km
Hydraulic turbine and governor: K_a = 3.33, T_a = 0.07, G_min = 0.01, G_max = 0.97518, V_gmin = -

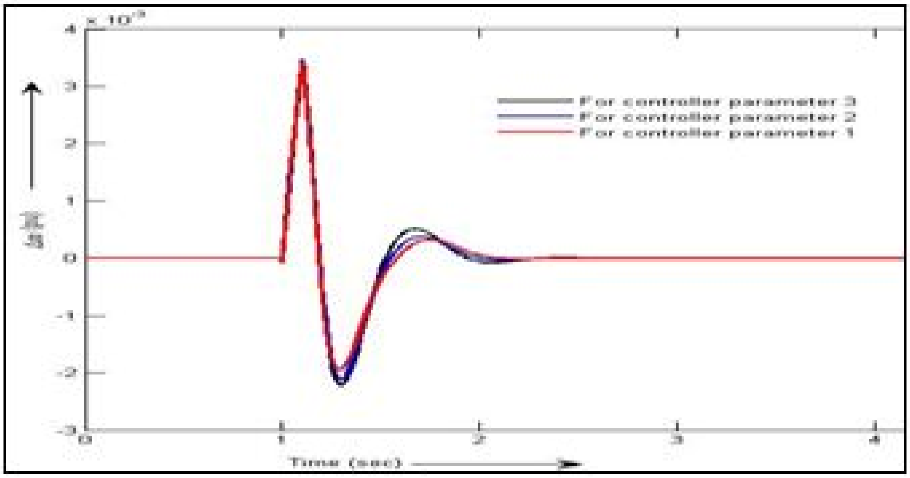

Figure 9: Speed deviation response for pumps, fans and other motor loads.

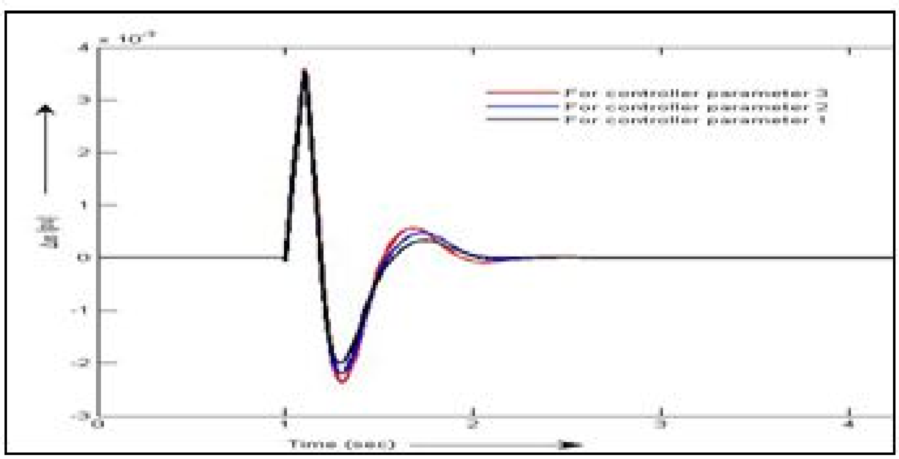

Figure 10: Speed deviation response for large industrial motor loads.

0.1 pu/s, $V_g max = 0.1$ pu/s, $R_p = 0.05$, $K_p = 1.163$, $K_i = 0.105$, $K_d = 0$, $T_d = 0.01$ s, $T_w = 2.67$ s
Excitation system: $T_L P = 0.02$ s, K_a =200, $T_a = 0.001$ s, K_e =1, T_e =0, $T_b = 0$, T_c =0, K_f = 0.001, $T_f = 0.1$ s, $E_f min = 0$, $E_f max = 7$, $K_p = 0$
SSSC: Converter rating = 100 MVA, System nominal voltage = 500 kV, Frequency: f = 60 Hz, Maximum rate of change of reference voltage $V_q ref = 3$ pu/s, Converter impedances: R = 0.00533,

L = 0.16, DC link nominal voltage = 40 kV, DC link equivalent capacitance= 375 x 10 -6 F, Injected Voltage regulator gains K_p= 0.00375,K_i = 0.1875, DC Voltage regulator gains: K_p=0.1 x 10 -3,K_i= 20 x 10 -3, Injected voltage magnitude limit= ± 0.2.

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