Comparison of Damping Control Performance of PID, PSS and TCSC Controllers by Moth Flame Optimization Algorithm

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Abstract. Power system low frequency oscillation problems are created due to faults, sudden change in generation or load demand, poor interconnection of network, switching of lines, large gain and fast acting voltage regulators and several types of disturbances. These oscillations if not controlled properly will grow and cause the power system collapse. In the present work these oscillations are compared and controlled by various methods like the traditional PID, PSS and the state-of-the-art power electronics FACTS-based device, TCSC. The Philips Heffron model is used to represent the system. The parameters of PID, PSS and TCSC controllers are tuned properly by MFO, and it is passed to the Simulink. It is found that performance of FACTS based TCSC device is the best in mitigating and controlling these oscillations. The TCSC provides other benefits also like enhancing the transfer of power flow in the system, improving the transient stability of the system. The Moth Flame optimization technique (MFO)has fast convergence capacity and gives accurate results. It is a nature inspired algorithm and the controllers designed by MFO brought excellent damping improvement in the proposed work. The objective function is based on the speed deviation signal and includes simulation time integration of time multiplied by the absolute value of error. Thus, the present work involves the inclusion of various devices like PID, PSS and Power electronics based TCSC device in the system, all optimised by MFO to improve the damping characteristics of the system. The power quality, system stability, security and efficiency of the system is improved using MOTH Flame based TCSC device

Keywords: Oscillations, stability, power flow, controller, optimization.

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1 Introduction

The power system oscillations can occur under normal operating conditions as well as due to disturbances. So, there can be stability problems of two types which are the large signal and the small signal problems. The small signal stability problems are related to the small disturbances under normal operating conditions. If the oscillations are due to large disturbances, then the power system can be operated insecurely. But if the oscillations are due to small disturbances, it cannot be operated. So small signal stability is very important, and it is the fundamental requirement of the system. In small signal stability the disturbances are considered to be so small that the linearisation of the system is possible. The linearised methods are analysed using the damping torque analysis technique and modal analysis technique. The linearised model of the system is designed based on Heffron-Phillips power system model.

The k constants are derived based on linearised model of the system and the values are calculated based on operating condition. The MATLAB simulation is used in similar works [14, 15, 6, 13, 12, 11] and it is performed with different devices and the results are shown in the figures. The oscillations of the system are mitigated using PID, PSS and TCSC devices all based on MFO algorithm. The system time domain characteristics are improved and showed stability against low frequency oscillations. This is a nature inspired algorithm and gives fast and accurate result. The system designed by MFO is quite robust against parameter variations.

2 Literature Review

The TCSC has been optimized by PSO optimization technique to improve the performance, stability, and damping capacity of the system. The structure of TCSC was conventional lead lag structure and the detailed equation relating the impedance and firing angle was used to calculate the net reactance of the line. The time domain simulation showed the improvement in stabilization of various parameters by using the PSO technique [16]. The modelling of SMIB employing the GA algorithm was used to study the stability enhancement by TCSC. The problem formulation was done using the network, stator rotor and all the other system equations. The gains of the TCSC controller were tuned using genetic algorithm The objective functions used were ISE and ITAE.The time domain results by GA were compared with the results of the parameter without using GA [17].The Real coded genetic algorithm was implanted for tuning the parameters of TCSC based system designed using HP model .In the objective function the fitness function was based on eigen value and the area was D shaped .The different operating conditions were analysed and the system eigen values were calculated with all the different conditions. The TCSC based controller was developed using the linearised equations of the system [5]. The performance of the system was compared using PSO and GA optimization techniques. The controller gains were determined, and the results were compared using both algorithms. The three different loading conditions which are the nominal, the heavy and the medium loading conditions were analysed with change in value of reactance and the change in the values of terminal voltage. The coordination of PSS and TCSC was done for the enhancement of stability. The HP model included various blocks and components of the system in the form of transfer functions for the PSS device and the TCSC device. The objective function used was the deviation in rotor speed and the PSO was used to optimize the parameters of the system [5, 4, 10, 1]. The performance of the system was improved based on optimal control theory approaches like the LQR, H-Infinity and LQG controller. The comparison of the system with PSS and LQR based PSS, With PSS, TCSC and LQR based PSS and TCSC was done [3, 9, 8]. The analysis of the system based on small signal and the application of PSS in the system for the control of local modes of oscillations and the improvement of stability were discussed.

3 Methodology

3.1 Mathematical Modelling and State Space Representation

The present power system consists of a synchronous machine including an excitation system. This machine is then connected to infinite bus through a transmission line. The IEEE type ST1 is selected for the excitation control of the system and for the comparison of different controllers in this work. The different components of the schematic diagram of the system are a synchronous machine, exciter, transmission line, local load. The third order model of generator is implemented using simulation which is developed using the stator and rotor winding equations. The mathematical modelling consists of the torque, rotor, stator, and network equations. The nonlinear and complex system model is linearised around an operating point and the following equations are developed after linearising the system.

$$\dot{\delta} = \omega_B(\omega_m - \omega_{m0}) \tag{1}$$

$$\omega_m = \frac{1}{2H}(-k_d((\omega_m - \omega_{m0}) + T_m - T_e) \tag{2}$$

Where δ is rotor angle of generator, ω the rotor speed , H stands for the inertia constant of the machine,damping constant is kd.

$$T_e = E_d^{'} i_d + E_q^{'} i_q + (x_d^{'} - x_q^{'}) i_d i_q \tag{3}$$

where T_m is the mechanical torque,T_e is the electrical torque, id and iq stands for the d-axis and q-axis component of current respectively, E'd and E'q stands for the d-axis and q-axis transient voltage and x'd, x'q stands for the transient reactance of d-axis and q-axis.

The equations governing the system behaviour are:

$$\Delta P_t = k_1 \Delta\delta + k_2 \Delta E_q^{'} \tag{4}$$

$$\Delta E_q = k_3 \Delta E_q^{'} + K_4 \Delta\delta \tag{5}$$

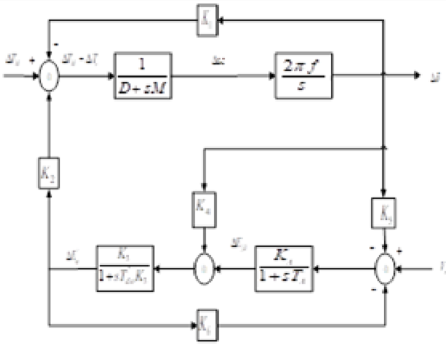

Figure 1: Schematic Block Diagram Representation of the System

$$\Delta V_t = k_5 \Delta\delta + k_6 E_q^{'} \tag{6}$$

3.2 Schematic Block Diagram

It consists of Heffron -Philips model of the present (SMIB) single or one machine infinite bus system. The system is represented by 6 Heffron Phillips k constants which are k1 to k6. The block diagram consists of two parts. The upper part is the linearised equations of rotor and the lower part of the system is the mathematical modelling of the generator field winding and AVR. The upper loop constitutes the oscillation loop of the system, and the lower part of the system is used to provide the (Te) electromagnetic torque to the system. The electromechanical oscillation loop is constituted by a differential equation of second order. The torque from the lower part of the model is divided into two parts which are the damping torque and the synchronising torque. The PSS provide the adequate torque and the synchronizing torque is contributed by Automatic Voltage Regulator (AVR). In this way using these two types of torques these devices improve the stability of the system by damping the low frequency oscillations [7, 2].

3.3 State Space Modelling and Representation

After linearising the system equations, the system is converted into state space model. The model is linearised around a nominal operating point. The system is represented in state space form.The state vector is comprised of angle delta, speed, internal voltage, and field voltage. The control vector is comprised of stabilizing signal of PSS alone and then both PSS and TCSC reactance. The coefficient D and H in the state space stands for mechanical damping and the inertia constant of the machine respectively. The input control vector is first composed of exciter gain and time constants and then in the second modelling of the system the TCSC elements are included. The modelling of the system in state space form is used to identify the location of electromechanical modes of oscillations of the system.

The system is represented in matrix form as

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega_m} \\ \Delta\dot{E_q} \\ \Delta\dot{E_{fd}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{-K_1}{2H} & \frac{-D}{2H} & \frac{-K_1}{2H} & 0 \\ \frac{-K_4}{2H} & 0 & \frac{-1}{T'q_0k_3} & \frac{1}{T'd_0} \\ \frac{-K_Ak_5}{T_A} & 0 & \frac{-K_AK_6}{T_A} & \frac{-1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega_m \\ \Delta E_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{-1}{T_A} \end{bmatrix} \text{U} \tag{7}$$

3.4 Moth Flame Algorithm (MFO)

MFO is proposed in the present work to optimize the parameters of different devices. It is an algorithm based on population where the moths are the solutions, and the positions of moth are the variables of problem. The space where the moth can fly can be 1 dimensional, two or three dimensional and hyper dimensional also. The traverse orientation method is used here for navigation. The optimization is done by MFO after the mathematical modelling of the insects which are trapped in spiral shaped deadly path. The moths should be capable of flying around and reach to light sources which is achieved by using a logarithmic type of spiral. The D is the distance between the moth and the corresponding flame of moth. The novel MFO metal heuristic optimization algorithm was proposed by Seyedali Mirjalili. This algorithm provides excellent computational results and outperforms the convergence characteristics of other algorithms.It is used in solving many challenging and competitive problems of power systems and other related areas.

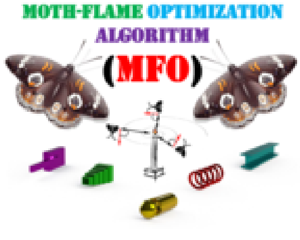

Figure 2: Moth Flame Optimization

4 Simulation Diagrams

4.1 System without any controller

The simulation diagram includes the various blocks like transfer function, 6 k constants, gain block, add representing the single machine infinite bus system dynamics, scope, display, go to and from. The exciter gains and time constants are 50 and 0.05 seconds respectively. The simulation diagram includes the objective Function. For the present work the objective function is the integral time absolute error (ITAE). ITAE is the most popular performance index to solve the optimization problems. The input signal to all the devices is the deviation in rotor speed. The output signal from the device obtained after optimization is stabilising signal which is then passed to the system. The parameters are optimized for all the three controllers using MFO algorithm and the system is properly tuned.

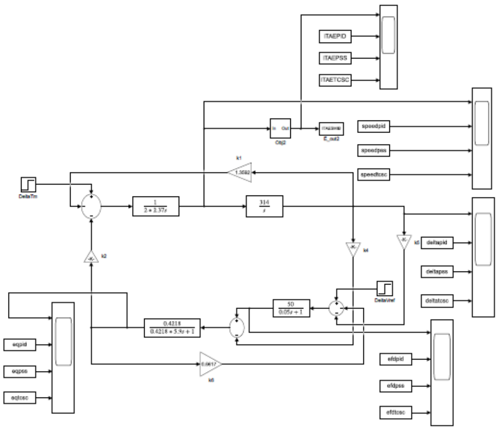

Figure 3: System Without Any controller

4.2 System with PID Controller

Proportional Integral Derivative (PID) controller is the most widely used controller in industries due to its easy to use and simplicity characteristics. Because of flexibility and results it is used in the variety of engineering applications. The PID controller has three main blocks components which are the Proportional block(P), the Integral block (I) and the Derivative block (D). The transfer function of PID includes these three blocks. The PID controller can be considered as a type of phase lead lag compensator Proper tuning of PID is important for achieving good results by the controller. There are different methods of tuning the PID controllers which are the analytical, heuristic, frequency response and optimization algorithms methods First, the PID controller optimized by MFO is installed to improve the damping characteristics of the system. Then the system is tested with other controllers again optimized by MFO.

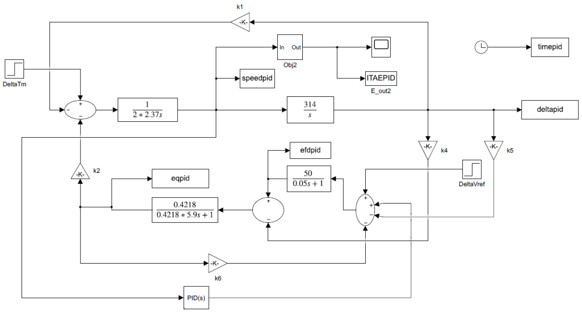

Figure 4: System With PID Controller

The MFO results for PID after optimization are: At iteration 2 ,4,6,8,10,12 the best fitness is 0.076446,0.07616, 0.076105, 0.076001,0.076001, 0.076001 respectively. The MFO best solution is 10.7004, 15, 0. The objective function best optimal value by MFO is 0.076001.

4.3 System with PSS Controller

PSS are implemented in the system to damp the local modes of oscillations by providing suitable damping torque to the system. The equilibrium between the two torques which are the synchronising torque and the damping torque is disturbed due to disturbances. AVRS were used in the system for the problems of low frequency oscillations, but it does not provide the required damping torque due to high gain and fast acting nature. It provided sufficient synchronising torque but lacked the damping torque. So, PSS was added with AVR to provide the necessary damping torque to the system and the combination of AVR and PSS provided both torques. The two torques are necessary otherwise the lack of synchronising torque lead to non-oscillatory instability and the lack of second one damping torque results in the problems of low frequency oscillations. The different blocks of PSS are the wash out filter block, the gain of the stabiliser, the lead -lag compensator block and the limiter. The values of 6 k constants of the system with PSS are calculated after linearising the system equations. PSS can be used in combination with PID and is termed as PID-PSS controller. The PSS parameter can be obtained by various approaches like the pole placement, phase compensation, variable structure method and different optimization methods. In the present work the parameters of the PSS are tuned by MFO algorithm.

The MFO results for PSS after optimization

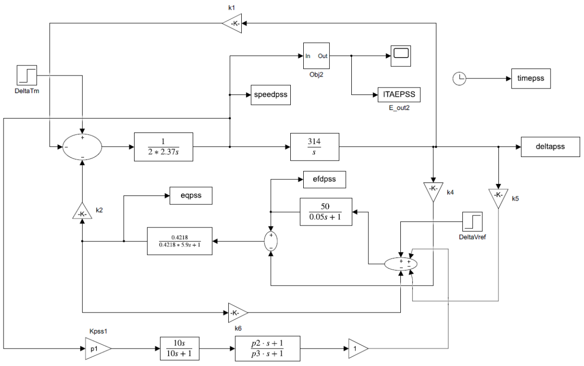

Figure 5: System with PSS Controller

are: At iteration 2,4,6,8,10,12 the best fitness is 0.0032845, 0.0032758, 0.0032367, 0.0032354 ,0.003235, 0.0032206 respectively. The MFO best solution is 1.7802, 6.293,0. 001.The objective function best solution by MFO is 0.0032206

4.4 System with TCSC Controller

The TCSC is added in the system to damp the interarea modes of oscillations. TCSC in addition to damping the system oscillations provide the control of flow of active power (AP) in the system. This is done by varying the impedance of the line according to firing angle. The TCSC circuit consists of a series capacitor in parallel with a TCR which is the thyristor-controlled reactor. The values of TCSC inductor and capacitor should be properly chosen to have both the inductive and capacitive working regions. The TCSC should not be operated in the resonance region. The TCSC provides the variable compensation in place of fixed compensation by series capacitor. The TCSC is designed on the conventional lead lag type of structure. The input signal given to the controller is the rotor speed deviation and the output signal is conduction angle. The TCSC controller consists of a wash out block, a gain block, lead lag compensator blocks. The same Heffron-Phillips model is used to represent the system. But now in the k constants the reactance of TCSC is added in the reactance of the SMIB system. Due to the inclusion of FACTS device the three new constants are generated in the HP model which are kp,kq and kv.

$$\Delta P_t = k_1\Delta\delta + k_2\Delta E_q^{'} + k_p\Delta X_{TCSC} \tag{8}$$

$$\Delta E_q = k_3\Delta E_q^{'} + K_4\Delta + k_q\Delta X_{TCSC} \tag{9}$$

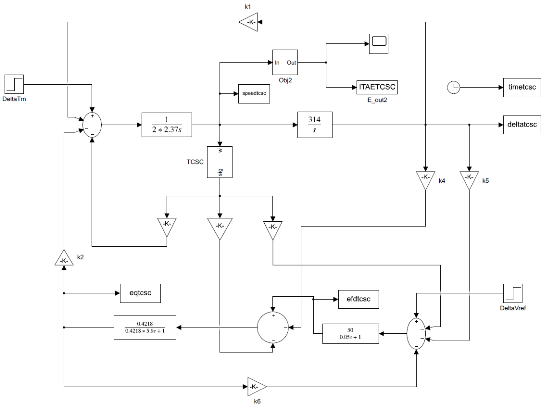

Figure 6: System With TCSC Controller

$$\Delta V_t = k_5\Delta\delta + k_6 E_q^{'} + K_v\Delta X_{TCSC} \tag{10}$$

After the inclusion of TCSC the equations are

$$K_p = \frac{-\partial P_t}{\partial X_{TCSC}} \tag{11}$$

$$K_q = \frac{-\partial E_q}{\partial X_{TCSC}} \tag{12}$$

$$K_v = \frac{-\partial V_t}{\partial X_{TCSC}} \tag{13}$$

The State Space Representation of the system after TCSC inclusion is

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega_m} \\ \Delta\dot{E_q} \\ \Delta\dot{E_{fd}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{-K_1}{2H} & \frac{-D}{2H} & \frac{-K_1}{2H} & 0 \\ \frac{-K_4}{2H} & 0 & \frac{-1}{T'q_0k_3} & \frac{1}{T'd_0} \\ \frac{-K_Ak_5}{T_A} & 0 & \frac{-K_AK_6}{T_A} & \frac{-1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega_m \\ \Delta E_q \\ \Delta E_{fd} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \frac{-K_p}{2H} \\ 0 & \frac{-K_q}{2H} \\ 0 & \frac{-K_AK_v}{T_A} \end{bmatrix} \begin{bmatrix} U_{PSS} \\ \Delta X_{TCSC} \end{bmatrix} \tag{14}$$

The MFO results for TCSC after optimization are: At iteration 2,4,6,8,10,12 the best fitness is 0.0032175, 0.0032175,0.003217,0.0032167,0032167,0. 0032167.The MFO best solution is 14.9901 5.10658 10.6314 6.41476 12. 1727.The objective function best solution obtained by MFO is: 0.0032167

5 Performance Analysis and Results

The parameters of all the controllers have been optimized by MFO as shown above. The design requirements of the system are the minimum rise time, settling

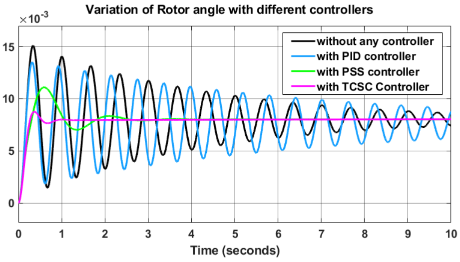

Figure 7: Plotting the deviation in Rotor Angle with different Controllers

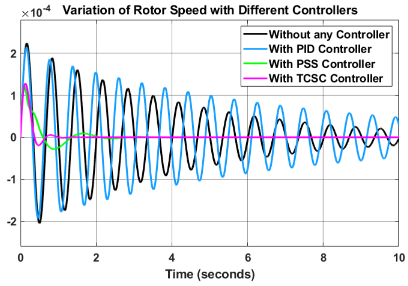

Figure 8: Plotting the deviation in Rotor Speed with different Controllers

time and overshoot. These parameters are observed in the plot of variation given below. The simulation is done on MATLAB and the response of the system with different controllers are compared in these figures.

The time domain simulation results of different state variables without and with different controllers are plotted from fig 7 to fig 10. From the results the stability of the system is seen to be improved using PID, PSS and TCSC based controllers. In the figures 7,8,9,10 the comparison of improvement by different controllers is visible. The parameters of PID, PSS and TCSC have been optimized by MFO and passed to the simulation. The TCSC controller is seen to be best in improving the system performance. The damping ratio reaches the desired point on using the different controllers. These figures are plotted for one operating conditions. By changing the values of P and Q for other loading conditions these figures can be plotted again. There is improvement in settling time and overshoot from the response of various parameters. All the different controller parameters are properly tuned by MFO. The performance capability of the system with PID, PSS and TCSC based controllers is better than the system without any controller. The power transfer capacity of the system is also improved due to the inherent property of power flow control by TCSC. The damping capacity of the system is enhanced due to enhancement of power flow by TCSC. [14,15]

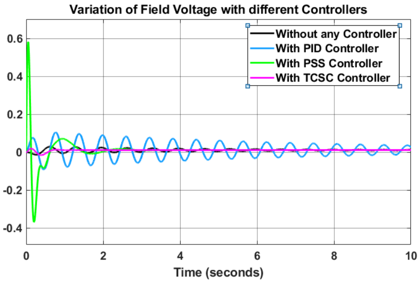

Figure 9: Plotting the deviation in Field Voltage with different Controllers

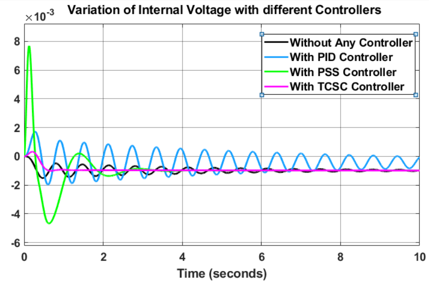

Figure 10: Plotting the deviation in Internal Voltage with different Controllers

6 Variation of objective function with different controllers

The objective function used in the present work is time integral which includes the absolute value of the error (ITAE). The input given to different controllers is the rotor speed deviation signal and the output obtained from the devices is the stabilizing signal which is then given to the system. The integration is taken over 0 to the time range of simulation. This speed deviation signal is so selected as the oscillations in the system are reflected in the generator rotor angle variations. The aim of the optimalization algorithm is to minimise the objective function so that the setting time, overshoot, and other time domain characteristics of the system are improved using different controllers. The other different objective functions like the Integral Square Error (ISE) can also be taken into consideration. The ITAE is taken in the present work than the ISE objective function because ISE takes into consideration only the error and no significance is given to time. The ITAE objective function considers both the error and time so that the oscillations will die out faster.

From the plot of objective function of the system without and with different types of controllers opti-

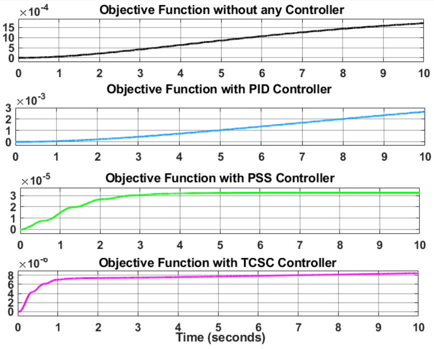

Figure 11: Plotting the Objective Function

mized by MFO it is seen that the results are best with the TCSC based controller. This device settles the objective function faster and has good characteristics. The objective function designed by ITAE die the oscillations of the system to the best using power electronics-based device. In the present work the ITAE objective function is used as in the ISE objective function only the error is taken into consideration and time is given no importance. But for the stability problems both the overshoot and settling time should be less so ITAE is better objective function.

7 Conclusion and Future work

In the present work the damping performance of the system is improved using different controllers optimized by MFO and the comparison of various results are given in above fig 7 to fig 10. The parameters have been properly tuned by MFO and the objective function is calculated and plotted in fig 11. The TCSC controller designed by Lead lag structure is found to be the best in damping capacity and the oscillations are seen to die out faster. The ITAE objective function is taken as it includes both the error and the time of simulation. The power flow capacity of the system and transient stability is also improved due to the basic characteristic of the TCSC. The system is now robust and the system eigen values are shifted to the left half of the s-plane due to damping capacity enhancement by different controllers The control efforts are significantly minimised using MFO based controllers. The various state variables are settled, and the oscillations die out as shown in figures. The MFO optimization algorithm is nature inspired and has remarkable computational and optimization capacities. This work can be extended to multimachine system with MFO. The system can be checked with the application of disturbances and the dynamic performance can be analysed. The system can be designed using a higher order synchronous generator.

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