

IMPROVEMENT OF POWER SYSTEM DYNAMIC STABILITY INCLUDING WIND FARM INTERCONNECTED MULTIMACHINE SYSTEM

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Abstract—Wind farms influences dynamic performance in power system and so wind energy penetration in power grid has increased tremendously over the time. The wind farm performance now became a concern such as to make appropriate stability analysis and their system models. This study aids to develop stability for the power system model in which aggregated wind machines like induction machine and conventional machines like synchronous machine operate together. The developed model is to be tested using stability analysis techniques such as state space matrix system, eigen solution method and time domain response. In the system the induction generator operating with a synchronous generator is proposed and compared with a synchronous-synchronous generator model. The results of time domain response for both generator models show the effective operation of proposed model. Recently, particle swarm optimization (PSO) technique appeared as a promising algorithm for handling the optimization problems. PSO based power system stabilizers (PSS) controllers on synchronous generators linked with wind power generation is also considered to improve the performance of the system by damping the power system oscillations.

Key words: Synchronous generator, Induction generator, Particle swarm optimization, Power system stabilizer

1. Introduction

In the recent years wind power is becoming an increasingly important source of energy. A major development on renewable energy resources has predominantly increased such as wind generation as it is mitigating against the problems of global warming. Reducing the pollution of air by decreasing the carbon dioxide content became the global agenda around the

world. The community is looking more towards wind power as a renewable source of energy, with the rising prices of fuel and increasing concern over the existence of greenhouse gases in the atmosphere. During the last decade the capacity of wind power has increased at an outstanding rate and the prices of harnessing wind energy have been continuously decreasing [1]. Growing interest to extract power from the wind has made to increase in capacity of wind power generation and thus having significant contribution to grid power [2]. Thus interest is generated to understand power system dynamics when wind farms are integrated with conventional power systems. Many of the new turbines are variable speed turbines which use induction generators to extract more energy. Induction generators such as doubly fed induction generators (DFIGs) are used for capability of reactive power control and for some other advantages [3].

This study aids to develop two models for power system stability in which for one model, combined wind farm machines like induction generator and conventional type synchronous generator operate together. In other model, the combination of two synchronous and synchronous generators operates together. In this paper, for the former model i.e., combination of synchronous and induction generator are equipped with a controller like power system stabilizer (PSS) [4] to improve the power system dynamic performance. This PSS controller provides a supplementary input signal to the generator excitation system to improve the dynamic performance by damping oscillations of power system. Recently, nature inspired algorithms like

particle swarm optimization (PSO) technique are emerging trends for handling the optimization problems. It is a population based optimization technique, inspired by natural social behavior of bird flocking [5]. So a PSO based PSS is also designed for better dynamic performance for the proosed model. In the following sections first a combined model of synchronous-induction generator system is studied and then the algorithms to design the PSS and PSO based PSS are developed.

2. Case Study

Generation of wind power uses different technologies which depend on power system requirements. The induction generator is the heart of wind power applications because of its inherent advantages. The squirrel cage induction generator is focused in the wind power generation.

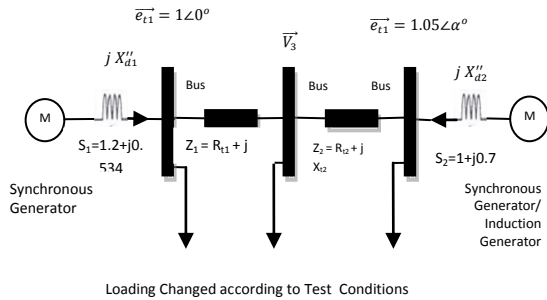


Figure1. 2 machine-3 bus system

The synchronous multi-machine system considered is a 2 machine, 3 bus system and also the induction - synchronous generator system has been studied by replacing one synchronous generator with an induction generator in the 2 machine system [6]. The network is given in figure 1.

The imaginary Part (reactive power) S2 value indicated is applied only for synchronous multi-machine system as for the induction/synchronous generator system, the induction generator of squirrel cage type absorbs reactive power.

3. Modeling

The synchronous generator can be modeled by either its transient or sub transient emfs acting behind

appropriate reactance. During any perturbation, rotor and stator flux changes are engaged in correcting or opposing the change by influencing the changes to the transient, sub transient, and electromechanical variables. Differential equations in detail for the synchronous machine expressed in two axis variables are represented by some equations. In a two machine system, in figure 1 the differential equations of the i^{th} machine are stated as follows [7, 8, 9].

$$\begin{aligned}\dot{\omega}_{i\Delta} &= \frac{1}{2H_i} [P_{mi\Delta} - D_i\omega_i - P_{ei\Delta}] \\ \dot{E}'_{qi\Delta} &= \frac{1}{T'_{di0}} [E'_{fdi\Delta} - E'_{qi\Delta} - (X_{di} - X'_{di})I_{di\Delta}] \\ \dot{E}''_{qi\Delta} &= \frac{1}{T''_{di0}} [E'_{fdi\Delta} - E''_{qi\Delta} - (X'_{di} - X''_{di})I_{di\Delta}] \\ &\quad + E'_{qi\Delta} \\ \dot{E}''_{di\Delta} &= \frac{1}{T''_{qi0}} [E''_{di\Delta} - (X'_{di} - X''_{di})I_{di\Delta}] \\ \dot{E}'_{di\Delta} &= \frac{1}{T'_{qi0}} [E'_{qi\Delta} - (X_{di} - X'_{di})I_{qi\Delta}] \\ \dot{\delta}_{1\Delta} &= \omega_{i0} \omega_{i\Delta}, \text{ for } i = 1, 2, \dots, n, \text{ where } n \text{ is} \\ &\quad \text{number of machines}\end{aligned}\quad (1)$$

4. Linear Analysis/Modal Analysis

In order to evaluate the stability of a system comprising a large number of synchronous machines, a mathematical model has to be developed that relates the equations of machine and system interactions. When such a relationship is established through state variables, simulations can be undertaken to evaluate the system stability. The state of each synchronous machine can be described mathematically by the following equation

$$\dot{x} = f(x, v, T_m, t) \quad (2)$$

where, x is a vector of state variables, v is a vector of voltages, and T_m is the mechanical torque.

For the two machine system, a 5th order model state space matrix A has dimension of 9 x 9, from 9 (4+4+1) state variables, 4 differential equations for each machine and one angle difference differential equation as shown below.

Combined model with 5th order synchronous generators

$$A = \begin{bmatrix} \omega_{1\Delta} & E'_{q1\Delta} & E''_{q1\Delta} & E''_{d1\Delta} & \omega_{2\Delta} & E'_{q2\Delta} & E''_{q2\Delta} & E''_{d2\Delta} & \delta_{12\Delta} \end{bmatrix}$$

$$\begin{bmatrix} -1.171 & 0 & -0.2418 & 0.0831 & 0 & 0 & 0.0323 & -0.2066 & -0.0531 \\ 0 & -0.1901 & -0.4104 & -0.0962 & 0 & 0 & 0.3457 & -0.1361 & -0.3048 \\ 0 & 35.524 & -45.480 & -2.2887 & 0 & 0 & 8.2269 & -3.2565 & -6.6444 \\ 0 & 0 & 2.1983 & -15.874 & 0 & 0 & 3.1780 & 8.0740 & 6.7227 \\ 0 & 0 & 0.0638 & -0.2161 & -1.171 & 0 & -0.2291 & 0.1062 & 0.2292 \\ 0 & 0 & 0.3674 & -0.0551 & 0 & -0.1901 & -0.4104 & -0.0962 & 0.2455 \\ 0 & 0 & 8.7436 & -1.3101 & 0 & 35.524 & -45.480 & -2.2887 & 5.3519 \\ 0 & 0 & 1.2857 & 8.5811 & 0 & 0 & 2.1983 & -15.874 & 7.0657 \\ 314 & 0 & 0 & 0 & -314 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} P_{m1\Delta} & V_{t1\Delta} & P_{m2\Delta} & V_{t2\Delta} \end{bmatrix}$$

$$\begin{bmatrix} 0.1171 & 0 & 0 & 0 \\ 0 & 0.1901 & 0 & 0 \\ 0 & 0.1901 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1171 & 0 \\ 0 & 0 & 0 & 0.1901 \\ 0 & 0 & 0 & 0.1901 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1.0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.551 & 0.381 & 0 & 0 & 0.287 & 0.0802 & -0.0558 \\ 0 & 0 & 0 & 0 & 1.0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.337 & 0.055 & 0 & 0 & 0.589 & 0.2951 & 0.1051 \end{bmatrix} \quad D = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The state space matrices for the 3rd order induction generator model are dimensioned as A-9x9, B- 9x3, C-4x9, D- 4x3. From these, time domain responses are simulated and response curves obtained.

Combined model with 3rd Order Induction Generator Model

$$A = \begin{bmatrix} \omega_{1\Delta} & E'_{q1\Delta} & E''_{q1\Delta} & E''_{d1\Delta} & \omega_{2\Delta} & E'_{q2\Delta} & E'_{d2\Delta} & \delta_{12\Delta} \end{bmatrix}$$

$$\begin{bmatrix} -1.171 & 0 & -0.31798 & 0.049113 & 0 & 0.3374 & 0.0190 & -0.2799 \\ 0 & -0.1901 & -0.57101 & -0.030463 & 0 & 0.3062 & 0.4685 & 0.5099 \\ 0 & 35.524 & -49.302 & -0.7249 & 0 & 7.2866 & 11.16 & 11.115 \\ 0 & 0 & 0.69625 & -19.624 & 0 & 10.943 & 7.1511 & 4.6743 \\ 0 & 0 & 0.29815 & -0.020655 & -1.171 & 0.0583 & -0.3404 & 0.05901 \\ 0 & 0 & 1.3376 & -4.7594 & 0 & -11.931 & -1.22 & 5.2876 \\ 0 & 0 & 4.7594 & 1.3376 & 35.524 & 1.22 & -11.931 & 12.95 \\ 314.1 & 0 & 0 & 0 & -315.03 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} P_{m1\Delta} & V_{t1\Delta} & P_{m2\Delta} \\ 0.1171 & 0 & 0 \\ 0 & 0.1901 & 0 \\ 0 & 0.1901 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0.1171 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1.0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.2783 & 0.3776 & 0 & -0.1146 & 0.3544 & 0.3168 \\ 0 & 0 & 0 & 0 & 1.0 & 0 & 0 & 0 \\ 0 & 0 & -0.6198 & -0.6036 & 0 & 0.2786 & -0.9218 & -0.7139 \end{bmatrix} \quad D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

4.1 Power System Stabiliser

The function of a power system stabiliser (PSS) is to provide damping to the oscillations of rotor by producing a damping torque to the machine. Damping is provided by adding an auxilliary signal to exciter of generator. PSS controllers based on soft computing techniques like Fuzzy, Genetic algorithm (GA) based are discussed in [10] A linear power oscillation damping signal are signal generated by PSS which is designated by V_{PSS} to improve damping and stabilisation in the power system.

The general form of a PSS controller is given in the figure 2.

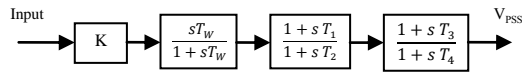


Fig.2 Power system Stabilizer

The transfer function of PSS from the block diagram is given by

$$U_i = k_i \left(\frac{sT_w}{1+sT_w} \right) \left[\frac{(1+sT_{1i})(1+sT_{3i})}{(1+sT_{2i})(1+sT_{4i})} \right] \quad (3)$$

The gain K is a first block, while the washout filter with time constant T_w is the second block. The last connected two blocks are cascaded filters.

This controller structure contains a washout block which is used to reduce the damping over response during severe events. Since the PSS produces electrical torque component in phase with speed deviation. The phase lead block compensates for the lag between the PSS output and control action, the electrical torque. The gain of PSS is an important factor as the damping offered by the PSS get increases in proportion to gain up to a certain critical gain value and after which the damping begins to reduce.

4.2 Particle Swarm Optimization (PSO)[11]

The basic idea of particle swarm inspired by natural flocking and swarm behavior of birds. The PSO method is a population based search algorithm where each individual is referred to as particle and represents a candidate solution. Each particle keeps track of its coordinates in the problem space which is associated with the best solution (fitness) it has achieved so far [11].

Each particle has a memory and hence capable of remembering the best position in the search space ever visited by it. The best previous position of particle that corresponds with the minimum fitness value represented as pbest and the best position of all particles in the population is denoted as gbest. In each iteration, the value of gbest and pbest are calculated. For the n^{th} iteration velocity and particle's position are updated as shown in the following equations respectively.

$$v_{id}^{n+1} = wv_{id}^n + c_1r_1^n(p_{id}^n - x_{id}^n) + c_2r_2^n(p_{gd}^n - x_{id}^n) \quad (4)$$

$$x_{id}^{n+1} = x_{id}^n + v_{id}^{n+1} \quad (5)$$

Where, p_{id} = pbest of particle i

p_{gd} = gbest of the group

w = inertia weight.

c_1, c_2 = cognitive and social acceleration, respectively.

r_1, r_2 = random numbers uniformly distributed in the range (0, 1).

In PSO, each particle moves in the search space with a velocity according to its own previous best solution and its group's previous best solution. The velocity update in PSO consists of three parts; namely momentum, cognitive and social parts. The balance among these parts determines the performance of a PSO

algorithm. The parameters c_1, c_2 determine the relative pull of pbest and gbest and the parameters r_1 and r_2 help in stochastically varying these pulls. Figure.1 shows the position updates of a particle for a two-dimensional parameter space.

5. PSO Algorithm[11]

The various steps involved in PSO model reduction are as follows [11]:

Step 1: Specify the parameters of PSO

Step 2: Generate the initial population for the particles

Step 3: Find the fitness value ISE for the initial population

Step 4: The velocity and position of all particles are randomly set to within pre-defined ranges

Step 5: At each iteration, the velocities and positions of all particles are updated

Step 6: Update the memory by updating p_{id} and

p_{gd} when condition is met

$p_{id} = p_i$ if $f(p_i) > f(p_{id})$

$p_{gd} = g_i$ if $f(g_i) > f(p_{gd})$

Here $f(x)$ is the objective function to be optimized.

Step7: Stopping Condition–The algorithm repeats steps 5 to 7 until certain stopping conditions are met, such as a pre-defined number of iterations. Once stopped, the algorithm reports the values of g_i and $f(g_i)$ as its solution.

Parameters used for PSO algorithm are shown in table1.

Parameters	Value
Swarm Size	20
Max. Generations	100
c_1, c_2	0.2, 0.2
w_{start}, w_{end}	0.9, 0.4

Table1. Parameters for PSO algorithm

The approach of PSO with the dual input power system stabilizer is discussed in [12].

6. Results and Discussions

The comparison of two models i.e. synchronous-synchronous and synchronous-induction generators for rotor angle and angular frequency outputs are shown in the figures 3a and 3b respectively. The outputs are simulated with a +5% step change for both voltage and power simulations. The eigen values and

oscillatory modes for combined synchronous – induction generator is shown in the table2.

Eigen Values	Oscillation frequency	Damping
-1.14	1.000	1.14
-1.51+ 4.97 i	0.291	5.20
-1.51- 4.97 i	0.291	5.20
-5.22	1.000	5.22
-5.28 + 8.91 i	0.510	10.4
-5.28 - 8.91i	0.510	10.4
-2.45	1.000	24.5
-50.9	1.000	50.9

Table 2. Eigen Values and oscillatory modes for combined synchronous-induction generator

S.No	Technique	K_{PSS}	T_1	T_2
1	PSS	2.173	0.1303	0.186
2	PSO based PSS	2.219	0.1410	0.19

Table 3. Gain and Time constants of PSSs

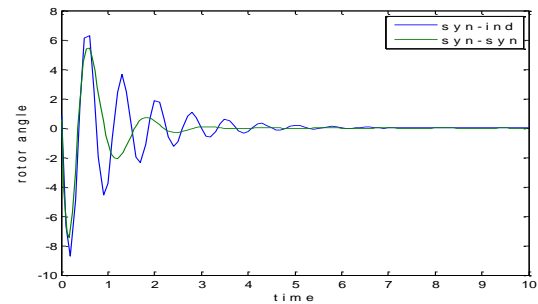


Figure 3(a). Rotor angle response for combined synchronous-synchronous and synchronous-induction generator

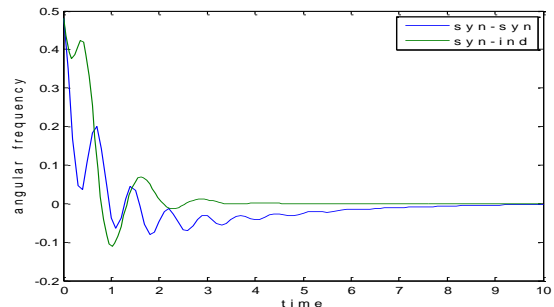


Figure 3b. Angular speed response for both synchronous-synchronous and synchronous induction generators.

The rotor voltages of induction generator can be independently regulated by a controller, which takes input signals measured from the power system in order to improve the dynamic response of Induction generator. A PSS implemented for the induction generator by adding an additional signal to the controller is designed to improve the damping in the power system. The gain and time constants of PSS at Induction generator is shown in the table 3. Here $T_1 = T_3$ and $T_2 = T_4$.

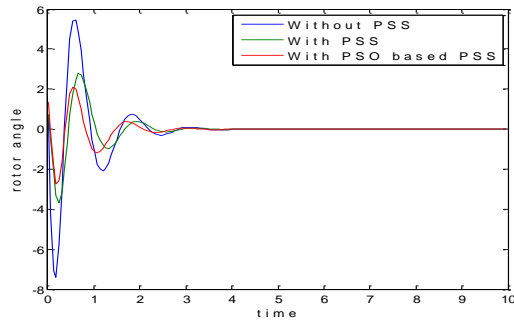


Figure 4(a). Rotor angle response for combined synchronous induction generator with PSS

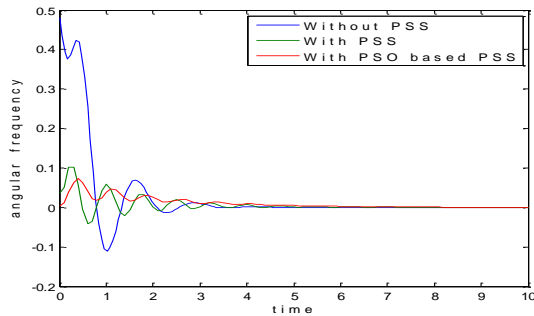


Figure 4(b). Angular speed response for combined synchronous induction generator with PSS

The PSS detects the change in generator output power, controls the excitation value, and reduces the rapid power fluctuation. With PSS transients and settling time will be reduced and can come to stable state. For the combined synchronous–induction generator, the transients in rotor angles and angular frequency are reduced with PSS controller as shown in the figures 4(a) and 4(b).

7. Conclusions

In this paper a model is proposed which combines the wind farm aggregated induction machine model with the synchronous machine model for the purpose of dynamic stability studies. This is achieved by linking variables which can brought about clear and meaningful relationship and interactions amongst different variables from different machines. This study set out to develop, program, and test a combined model for dynamic stability study of aggregated induction generator operation with synchronous generator. It is observed that from the dynamic stability results of the proposed combined model of induction – synchronous generator system is reliable and produces quite effective results. Power system stabilizers (PSS) on synchronous generators linked with wind power generation is considered to

improve the performance of the system by damping the power system oscillations. Later particle swarm optimization (PSO) based power system stabilizer (PSS) is also designed for the proposed generator model to give better response than that of the conventional stabilizer.

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