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Multi machine power system identification by using recursive least square method

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Abstract

Electric power systems are nonlinear and complicate in nature. Along with increasing size of power systems, their complexity becomes more. Besides, by using additional and auxiliary components such as Flexible AC Transmission Systems (FACTS) devises, Power System Stabilizers (PSSs), excitation systems, turbine-governor systems and etc, the dynamic model of network is increased and power system becomes more complicate. The nonlinear dynamic model of these large power systems is easily obtained. But, the complexity makes it difficult to obtain a linear dynamic model of power system. Obtaining an appropriate linear model is necessary in order to analysis and study of power system. In tradition method, a linear dynamic model of power system is obtained by linearization of nonlinear dynamic model around an operating condition. But in large electric power systems, the linearization technique is very sophisticate and maybe impossible. Concerning this matter, in this paper a Recursive Least Square (RLS) technique is used to parameter identification in a multi machine electric power system. In this method a linear model is assumed for power system and its parameters are accurately computed by using RLS method. In order to verifying the results, the obtained linear model is compared with the nonlinear model. The simulation results show the validity of identified model, as the response of identified linear model is very near to nonlinear model.

Keywords: Recursive Least Square, multi machine electric power system, nonlinear simulation, System identification.

Introduction

System identification is a procedure by which a mathematical description of component dynamic behavior is extracted from test data. It can be thought of as an inverse of simulation. The usual application of System identification is in large nonlinear systems; because in these systems, it is not easy to obtain a straightforward mathematical model (Astrom *et al.,* 1994). System identification has been successfully carried out in all fields of engineering and science (Krneta *et al.,* 2005; Li *et al.,* 2007; Rodriguez *et al.,* 2007; Paleologu *et al.,* 2008; Mehdi Nikzad *et al.*, 2011; Reza Hemmati *et al.*, 2011;Sayed Mojtaba Shirvani Boroujeni *et al.*, 2011; Shoorangiz Shams Shamsabad Farahani *et al.*, 2011a,b). In this paper we focus on the system identification in electric power systems.

As referred before, the nonlinear nature of large interconnected power system makes it difficult to obtain a linear model of network, although is it easy to obtain a nonlinear dynamic model of system. The usual way to obtain a linear model is to linearization of nonlinear equations around an operating condition by using mathematical linearization technique. But applying the proposed method in large electric power systems it is very sophisticate and troublesome. Meanwhile, the obtained linear model is not exact, because of some simplifies. Since, many studies such as system stability analysis, controller design and etc, are carried out based on linear model; thus it is important to obtain an exact and suitable linear model of power system.

With regarding to the problem, in this paper a Recursive Least Square (RLS) technique is used to parameter identification in a multi machine electric power system. In this method a linear model is assumed for power system and its parameters are accurately computed by using RLS method. In order to verifying the results, the obtained linear model is compared with the results of nonlinear simulation. The simulation results show the validity of identified model, as the response of identified linear model is very near to nonlinear model.

System identification

System identification is on-line determination of process parameters. The key elements in system identification are selection of model structure, experiment design, parameter estimation and validation. The experiment design is crucial for successful system identification. In control problems this boils down to selection of the input signal. Choosing an input signal requires some knowledge of the process and the intended use of the model. In some systems, the parameters of process change continuously, so it is necessary to have estimation methods that update the parameters recursively. Also in solving identification problems, it is important to validate the results (Astrom *et al.,* 1994). The least square method is a basic technique for parameter estimation. The method is particularly simple if the model has property of being linear in the parameters. In this case the least square estimate can be calculated analytically (Astrom *et al.,* 1994).

Least squares method

According to least square method, the unknown parameters of a mathematical model should be chosen in such a way that the sum of the squares of the differences between the actual observed and the computed values, multiplied by numbers that measure the degree of precision, is a minimum (Astrom *et al.,* 1994). The least square method can be applied to large variety of

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problems. It is particulary simple for a mathematical model that can be written as shown by (1).

$$y(i)=\varphi_1(i)\theta_1^0+\varphi_2(i)\theta_2^0+\cdots+\varphi_n(i)\theta_n^0=\varphi^T(i)\theta^0 \quad (1)$$

Where y is the observd variable, $\theta_1^0,\theta_2^0,\cdots,\theta_n^0$ are parameters of the model to be determined, and $\varphi_1,\varphi_2,\cdots,\varphi_n$ are known functions that may depend on other known variables. The vectors (2) have also been introduced. The model indexed by the variable *i*, which often denotes time.

$$\varphi^T(i)=[\varphi_1(i)\quad \varphi_2(i)\quad \ldots \quad \varphi_n(i)]$$
$$\theta^0=\left[\theta_1^0\quad \theta_2^0\quad \ldots\quad \theta_n^0\right]^T \quad (2)$$

It will be assumed initially that the index set is a discrete set. The variables φ_i are called the regresion variables or the regressors and the model in (1) is also called a regression model. Pairs of observations and regressors {*y(i)*, $\varphi(i)$, *i=1,2,...,t*} are obtined from an expriment.

The problem is to determinate the parameters in such a way that outputs computed from the model in (1) agree as closly as possible with the measured variables *y(i)* in the sense of least squraes. That is the parametr θ should be chosen to minimize the least square loss function (3).

$$V(\theta(t),t)=\frac{1}{2}\sum_{i=1}^{t}\left(y(i)-\varphi^T(i)\theta\right)^2 \quad (3)$$

Since the measured variable *y* is linear in parameters θ^0 and the least squares criterion is quadratic, the problem admits an analytical solution. Introduce the following notations:

$$Y(t)=[y(1)\quad y(2)\quad \ldots\quad y(n)]^T$$
$$E(t)=[\varepsilon(1)\quad \varepsilon(2)\quad \ldots\quad \varepsilon(n)]^T$$
$$\Phi^T(t)=\begin{bmatrix}\varphi^T(1)\\ \varphi^T(2)\\ \vdots\\ \varphi^T(t)\end{bmatrix} \quad (4)$$
$$P(t)=\left(\Phi^T(t)\Phi(t)\right)^{-1}=\left(\sum_{i=1}^{t}\varphi(i)\varphi^T(i)\right)^{-1}$$

Where the residuals *ε(i)* are defined by (5).

$$\varepsilon(i)=y(i)-\varphi^T\theta \quad (5)$$

With these notations the loss function (3) can be rewritten as (6).

$$V(\theta(t),t)=\frac{1}{2}\sum_{i=1}^{t}\varepsilon^2(i)=\frac{1}{2}E^TE=\frac{1}{2}\|E\|^2 \quad (6)$$

Where, *E* can be rewritten as (7).

$$E=Y-\Phi\theta \quad (7)$$

The solution of least square problem is given by the following theorem. The function of (3) is minimal for parameters θ such that:

$$\Phi^T\Phi\theta=\Phi^TY \quad (8)$$

If the matrix $\Phi^T\Phi$ is nonsingular, the minimal is unique and given by (9).

$$\hat{\theta}=\left(\Phi^T\Phi\right)^{-1}\Phi^TY \quad (9)$$

Recursive computation

In practical systems osrvations are obtained sequentially in real time. It is the desribed to make the computations recursiveedly save computation time. Computation of least squrae estimation can be rearang in such a way that the results obtained at time *t-1* can be used to get the estimates at time *t*. the solution in (3) to least sqsuare problem will be rewritten in a recursive form. Let *θ(t-1)* denotes the least squares estimate based on *t-1* measurments. Assume that the matrix $\Phi^T\ \Phi$ is nonsingular for all *t*. It Follows from the definition of *P(t)* in (4) as (10).

$$P^{-1}(t)=\Phi^T(t)\Phi(t)=\sum_{i=1}^{t}\varphi(i)\varphi^T(i)$$
$$=\sum_{i=1}^{t-1}\varphi(i)\varphi^T(i)+\varphi(t)\varphi^T(t)=P^{-1}(t-1)+\varphi(t)\varphi^T(t) \quad (10)$$

The least squares estimate *θ(t)* is given by (11).

$$\hat{\theta}(t)=P(t)\left(\sum_{i=1}^{t}\varphi(i)y(i)\right)=P(t)\left(\sum_{i=1}^{t-1}\varphi(i)y(i)+\varphi(t)y(t)\right) \quad (11)$$

It follows from (9) and (10) that:

$$\sum_{i=1}^{t-1}\varphi(i)y(i)=P^{-1}(t-1)\hat{\theta}(t-1)$$
$$=P^{-1}(t)\hat{\theta}(t-1)-\varphi(t)\varphi^T(t)\hat{\theta}(t-1) \quad (12)$$

The estimate at time *t* can now be witten as (13).

$$\hat{\theta}(t)=\hat{\theta}(t-1)-P(t)\varphi(t)\varphi^T(t)\hat{\theta}(t-1)+P(t)\varphi(t)y(t)$$
$$=\hat{\theta}(t-1)+P(t)\varphi(t)\left(y(t)-\varphi^T(t)\hat{\theta}(t-1)\right)$$
$$=\hat{\theta}(t-1)+K(t)\varepsilon(t) \quad (13)$$

Where,

$$\varepsilon(t)=y(t)-\varphi^T(t)\hat{\theta}(t-1)$$
$$P(t)=\left(\Phi(t)\Phi^T(t)\right)^{-1}=\left(\Phi^T(t-1)\Phi(t-1)+\varphi(t)\varphi^T(t)\right)^{-1}$$
$$=\left(P(t-1)^{-1}+\varphi(t)\varphi^T(t)\right)^{-1}$$
$$=P(t-1)-P(t-1)\varphi(t)\left(I+\varphi^T(t)P(t-1)\varphi(t)\right)^{-1}\varphi^T(t)P(t-1)$$
$$K(t)=P(t)\varphi(t)=P(t-1)\varphi(t)\left(I+\varphi^T(t)P(t-1)\varphi(t)\right)^{-1}$$

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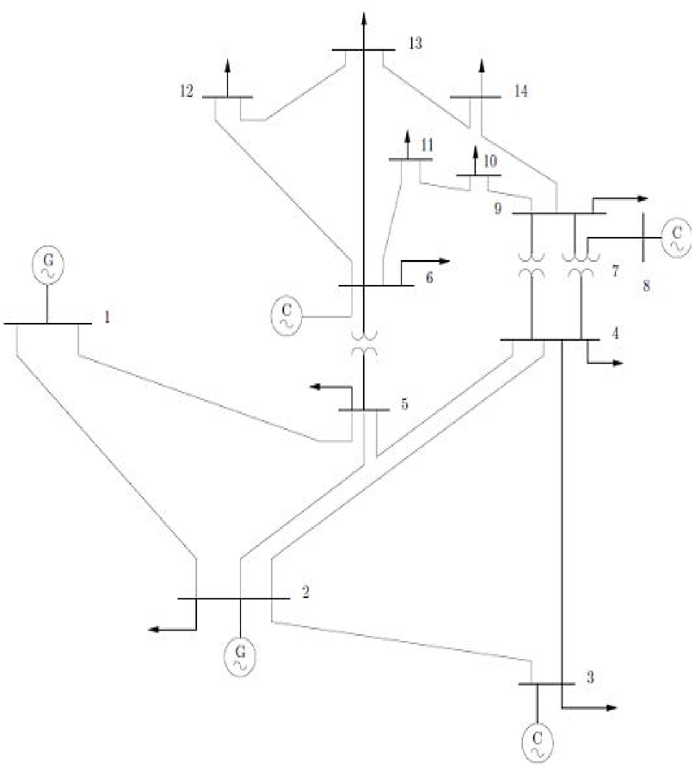
System under study

Fig.1. IEEE 14 bus test system



In this paper IEEE 14 bus test system is considered to evaluate the proposed method. The system data are completely given in IEEE standards (University of Washington). Fig.1 shows the proposed test system. In this system, all five generators are equipped with excitation system. Also generators 1 and 2 are equipped with turbine governor system and in order to stability issues; a PSS is installed on the generator 1.

Nonlinear dynamic model of the system

The nonlinear dynamic model of the system is given as follows:

$$\begin{cases} \dot{\omega}_i = \dfrac{(P_m - P_e - D\omega)}{M} \\ \dot{\delta}_i = \omega_0(\omega - 1) \\ \dot{E}'_{qi} = \dfrac{(-E_q + E_{fd})}{T'_{do}} \\ \dot{E}_{fdi} = \dfrac{-E_{fd} + K_a(V_{ref} - V_t)}{T_a} \end{cases} \qquad (14)$$

where i=1, 2, 3, 4,5 (the generators: 1 to 4); δ, rotor angle; ω, rotor speed; P_m, mechanical input power; P_e, electrical output power; E'_q, internal voltage behind x'_d; E_{fd}, equivalent excitation voltage; Te, electric torque; T'_{do}, time constant of excitation circuit; K_a, regulator gain; T_a, regulator time constant; V_{ref}, reference voltage; V_t, terminal voltage.

Linear dynamic model of the system

In many studies it is important to obtain a linear dynamic model of system in the transfer function form. In this scope, the power system is usually linearized in order to perform the small signal analysis. Therefore, the system in (14) is linearized around an equilibrium operating condition of the power system. Equation (15) describes the linear model of the power system:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \qquad (15)$$

Where, A is the power system state matrix, B is the input matrix, C is the output matrix, D is the feed-forward matrix. But the proposed linearization is appropriately performed in small power systems, not in large and multi machine networks. Concerning this matter, in this paper a linear model of system is obtained by using the method presented in section 2.

Power system identification by using RLS method

The proposed method presented in section 2 is used to identification of power system parameters. A linear dynamic model is considered for power system given in section 3 and then its parameters are obtained by using RLS method. A transfer function model from any input to any output can be evaluated by using the proposed method. But computing a usual transfer function is more favorable. So, the following transfer functions are evaluated here:

i. Transfer functions from excitation system inputs to speed ω
ii. Transfer functions from reference mechanical power inputs to speed ω

The proposed transfer functions are very important in power system issues, because of their applications in PSSs design. It is worth to mention that, the proposed transfer functions are considered as example and any other transfer functions can be evaluated by using the proposed method.

Determination of model

In system identification, it is very important to determine a proper model. Determination of model requires some knowledge of the system and also designer's experiment. For example in multi machine electric power systems, the determined model depends on the order of dynamic model of machines. Also the dynamic model of the other components such as excitation systems, turbine governor systems, FACTS devises and PSSs should be incorporated. Concerning test system given in section 3, there are five generators, five excitation systems, two turbine governor systems and one PSS. Therefore, the order of model is chosen equal to 57. In order to accuracy, the order of zeros in transfer function is changed from 50 to 57 till the best solution is obtained. Then the RLS method is carried out to compute the parameters of the proposed transfer functions. The resulted sampled transfer functions are listed in Table 1.

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Table 1 - Identified linear transfer functions

(a)Transfer function from excitation system of generator 1 to speed of generator 1
-1.679e004 s^52 - 9.37e007 s^51 - 2.193e011 s^50 - 2.792e014 s^49 - 2.105e017 s^48 - 9.707e019 s^47 - 2.821e022 s^46 - 5.538e024 s^45 - 7.808e026 s^44 - 8.273e028 s^43 - 6.813e030 s^42 - 4.47e032 s^41 - 2.383e034 s^40 - 1.047e036 s^39 - 3.846e037 s^38 - 1.192e039 s^37 - 3.145e040 s^36 - 7.12e041 s^35 - 1.392e043 s^34 - 2.362e044 s^33 - 3.494e045 s^32 - 4.517e046 s^31 - 5.112e047 s^30 - 5.065e048 s^29 - 4.39e049 s^28 - 3.319e050 s^27 - 2.178e051 s^26 - 1.232e052 s^25 - 5.944e052 s^24 - 2.405e053 s^23 - 7.918e053 s^22 - 1.987e054 s^21 - 3.041e054 s^20 + 1.809e054 s^19 + 3.168e055 s^18 + 1.288e056 s^17 + 3.563e056 s^16 + 7.661e056 s^15 + 1.337e057 s^14 + 1.929e057 s^13 + 2.317e057 s^12 + 2.321e057 s^11 + 1.932e057 s^10 + 1.326e057 s^9 + 7.419e056 s^8 + 3.318e056 s^7 + 1.155e056 s^6 + 3.003e055 s^5 + 5.473e054 s^4 + 6.284e053 s^3 + 3.759e052 s^2 + 9.037e050 s + 7.277e048
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s^57 + 5678 s^56 + 1.361e007 s^55 + 1.791e010 s^54 + 1.418e013 s^53 + 7.042e015 s^52 + 2.276e018 s^51 + 5.093e020 s^50 + 8.341e022 s^49 + 1.043e025 s^48 + 1.027e027 s^47 + 8.164e028 s^46 + 5.338e030 s^45 + 2.915e032 s^44 + 1.347e034 s^43 + 5.321e035 s^42 + 1.815e037 s^41 + 5.386e038 s^40 + 1.402e040 s^39 + 3.218e041 s^38 + 6.551e042 s^37 + 1.189e044 s^36 + 1.929e045 s^35 + 2.807e046 s^34 + 3.674e047 s^33 + 4.33e048 s^32 + 4.602e049 s^31 + 4.413e050 s^30 + 3.819e051 s^29 + 2.981e052 s^28 + 2.096e053 s^27 + 1.327e054 s^26 + 7.542e054 s^25 + 3.841e055 s^24 + 1.747e056 s^23 + 7.073e056 s^22 + 2.539e057 s^21 + 8.052e057 s^20 + 2.247e058 s^19 + 5.502e058 s^18 + 1.178e059 s^17 + 2.2e059 s^16 + 3.574e059 s^15 + 5.034e059 s^14 + 6.124e059 s^13 + 6.405e059 s^12 + 5.723e059 s^11 + 4.335e059 s^10 + 2.754e059 s^9 + 1.447e059 s^8 + 6.173e058 s^7 + 2.084e058 s^6 + 5.371e057 s^5 + 1.002e057 s^4 + 1.247e056 s^3 + 9.117e054 s^2 + 3.234e053 s + 3.672e051
(b)Transfer function from excitation system of generator 1 to speed of generator 2
9.754e004 s^52 + 5.448e008 s^51 + 1.276e012 s^50 + 1.627e015 s^49 + 1.229e018 s^48 + 5.684e020 s^47 + 1.659e023 s^46 + 3.275e025 s^45 + 4.646e027 s^44 + 4.957e029 s^43 + 4.113e031 s^42 + 2.721e033 s^41 + 1.463e035 s^40 + 6.495e036 s^39 + 2.41e038 s^38 + 7.554e039 s^37 + 2.018e041 s^36 + 4.634e042 s^35 + 9.2e043 s^34 + 1.589e045 s^33 + 2.396e046 s^32 + 3.169e047 s^31 + 3.683e048 s^30 + 3.768e049 s^29 + 3.395e050 s^28 + 2.693e051 s^27 + 1.879e052 s^26 + 1.152e053 s^25 + 6.196e053 s^24 + 2.918e054 s^23 + 1.202e055 s^22 + 4.325e055 s^21 + 1.36e056 s^20 + 3.739e056 s^19 + 8.983e056 s^18 + 1.886e057 s^17 + 3.456e057 s^16 + 5.518e057 s^15 + 7.657e057 s^14 + 9.197e057 s^13 + 9.512e057 s^12 + 8.412e057 s^11 + 6.305e057 s^10 + 3.958e057 s^9 + 2.05e057 s^8 + 8.579e056 s^7 + 2.817e056 s^6 + 6.964e055 s^5 + 1.215e055 s^4 + 1.345e054 s^3 + 7.833e052 s^2 + 1.843e051 s + 1.455e049
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s^57 + 5678 s^56 + 1.361e007 s^55 + 1.791e010 s^54 + 1.418e013 s^53 + 7.042e015 s^52 + 2.276e018 s^51 + 5.093e020 s^50 + 8.341e022 s^49 + 1.043e025 s^48 + 1.027e027 s^47 + 8.164e028 s^46 + 5.338e030 s^45 + 2.915e032 s^44 + 1.347e034 s^43 + 5.321e035 s^42 + 1.815e037 s^41 + 5.386e038 s^40 + 1.402e040 s^39 + 3.218e041 s^38 + 6.551e042 s^37 + 1.189e044 s^36 + 1.929e045 s^35 + 2.807e046 s^34 + 3.674e047 s^33 + 4.33e048 s^32 + 4.602e049 s^31 + 4.413e050 s^30 + 3.819e051 s^29 + 2.981e052 s^28 + 2.096e053 s^27 + 1.327e054 s^26 + 7.542e054 s^25 + 3.841e055 s^24 + 1.747e056 s^23 + 7.073e056 s^22 + 2.539e057 s^21 + 8.052e057 s^20 + 2.247e058 s^19 + 5.502e058 s^18 + 1.178e059 s^17 + 2.2e059 s^16 + 3.574e059 s^15 + 5.034e059 s^14 + 6.124e059 s^13 + 6.405e059 s^12 + 5.723e059 s^11 + 4.335e059 s^10 + 2.754e059 s^9 + 1.447e059 s^8 + 6.173e058 s^7 + 2.084e058 s^6 + 5.371e057 s^5 + 1.002e057 s^4 + 1.247e056 s^3 + 9.117e054 s^2 + 3.234e053 s + 3.672e051
(c)Transfer function from mechanical reference torque of generator 1 to speed of generator 1
1.467e005 s^54 + 3.506e008 s^53 + 4.596e011 s^52 + 3.617e014 s^51 + 1.779e017 s^50 + 5.672e019 s^49 + 1.248e022 s^48 + 2.003e024 s^47 + 2.446e026 s^46 + 2.347e028 s^45 + 1.811e030 s^44 + 1.145e032 s^43 + 6.022e033 s^42 + 2.667e035 s^41 + 1.005e037 s^40 + 3.251e038 s^39 + 9.106e039 s^38 + 2.224e041 s^37 + 4.77e042 s^36 + 9.034e043 s^35 + 1.519e045 s^34 + 2.276e046 s^33 + 3.05e047 s^32 + 3.667e048 s^31 + 3.963e049 s^30 + 3.852e050 s^29 + 3.37e051 s^28 + 2.652e052 s^27 + 1.875e053 s^26 + 1.189e054 s^25 + 6.738e054 s^24 + 3.401e055 s^23 + 1.523e056 s^22 + 6.014e056 s^21 + 2.084e057 s^20 + 6.302e057 s^19 + 1.654e058 s^18 + 3.749e058 s^17 + 7.312e058 s^16 + 1.222e059 s^15 + 1.742e059 s^14 + 2.11e059 s^13 + 2.158e059 s^12 + 1.85e059 s^11 + 1.316e059 s^10 + 7.671e058 s^9 + 3.595e058 s^8 + 1.321e058 s^7 + 3.674e057 s^6 + 7.328e056 s^5 + 9.658e055 s^4 + 7.39e054 s^3 + 2.73e053 s^2 + 3.169e051 s - 3.758e035
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s^57 + 1.361e007 s^56 + 1.791e010 s^55 + 1.418e013 s^54 + 7.042e015 s^53 + 2.276e018 s^52 + 5.093e020 s^51 + 8.341e022 s^50 + 1.043e025 s^49 + 1.027e027 s^48 + 8.164e028 s^47 + 5.338e030 s^46 + 2.915e032 s^45 + 1.347e034 s^44 + 5.321e035 s^43 + 1.815e037 s^42 + 5.386e038 s^41 + 1.402e040 s^40 + 3.218e041 s^39 + 6.551e042 s^38 + 1.189e044 s^37 + 1.929e045 s^36 + 2.807e046 s^35 + 3.674e047 s^34 + 4.33e048 s^33 + 4.602e049 s^32 + 4.413e050 s^31 + 3.819e051 s^30 + 2.981e052 s^29 + 2.096e053 s^28 + 1.327e054 s^27 + 7.542e054 s^26 + 3.841e055 s^25 + 1.747e056 s^24 + 7.073e056 s^23 + 2.539e057 s^22 + 8.052e057 s^21 + 2.247e058 s^20 + 5.502e058 s^19 + 1.178e059 s^18 + 2.2e059 s^17 + 3.574e059 s^16 + 5.034e059 s^15 + 6.124e059 s^14 + 6.405e059 s^13 + 5.723e059 s^12 + 4.335e059 s^11 + 2.754e059 s^10 + 1.447e059 s^9 + 6.173e058 s^8 + 2.084e058 s^7 + 5.371e057 s^6 + 1.002e057 s^5 + 1.247e056 s^4 + 9.117e054 s^3 + 3.234e053 s^2 + 3.672e051 s - 1.127e038

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Fig.2. Speed of generator 1 following scenario 1 Solid (nonlinear model); dashed (linear identified model)

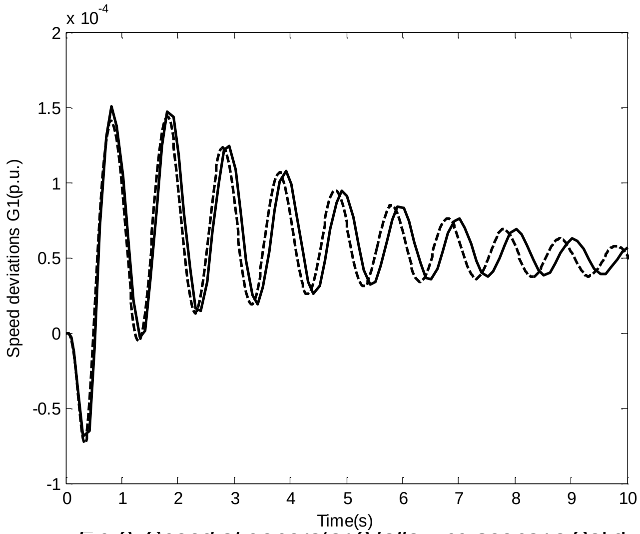


Fig.3. Speed of generator 2 following scenario Solid (nonlinear model); dashed (linear identified model)

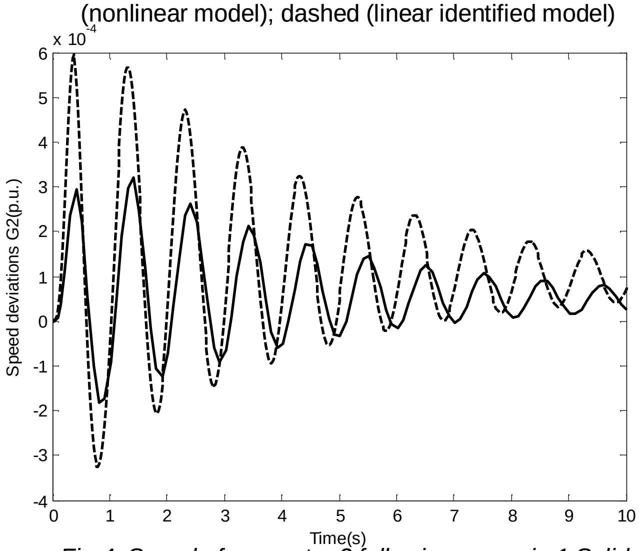


Fig.4. Speed of generator 3 following scenario 1 Solid (nonlinear model); dashed (linear identified model)

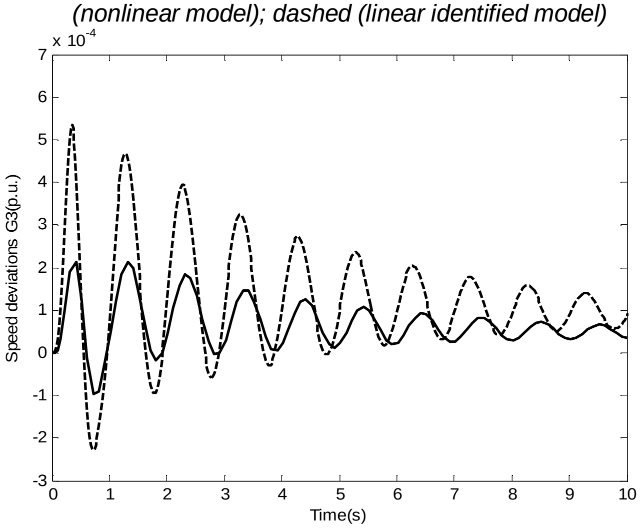


Fig.5. Speed of generator 1 following scenario 2 Solid (nonlinear model); dashed (linear identified model)

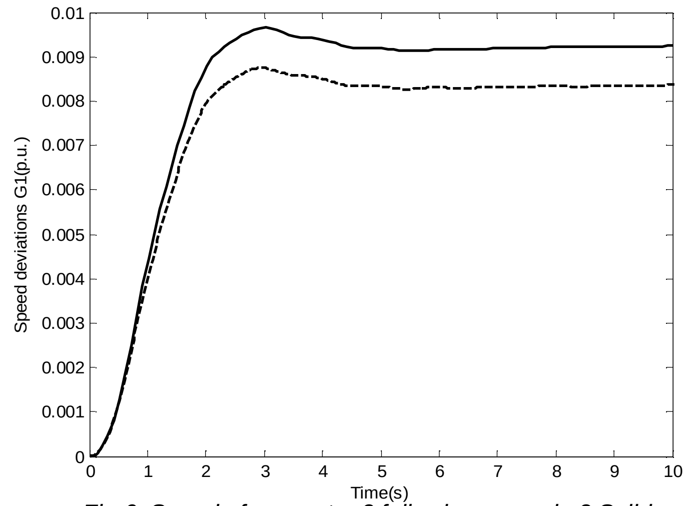


Fig.6. Speed of generator 2 following scenario 2 Solid (nonlinear model); dashed (linear identified model)

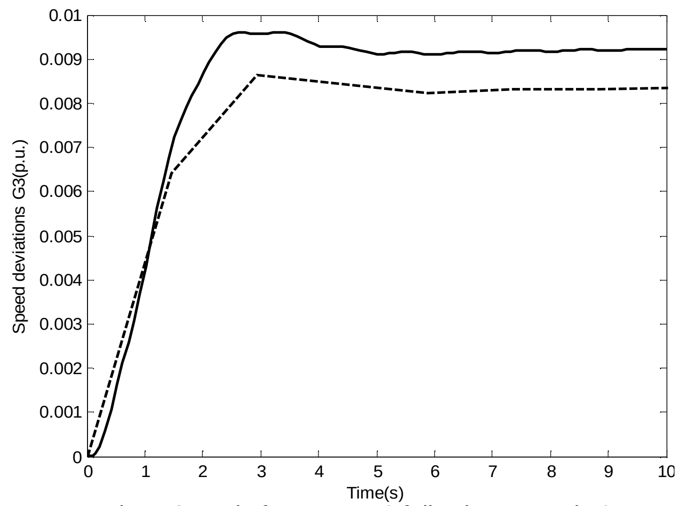
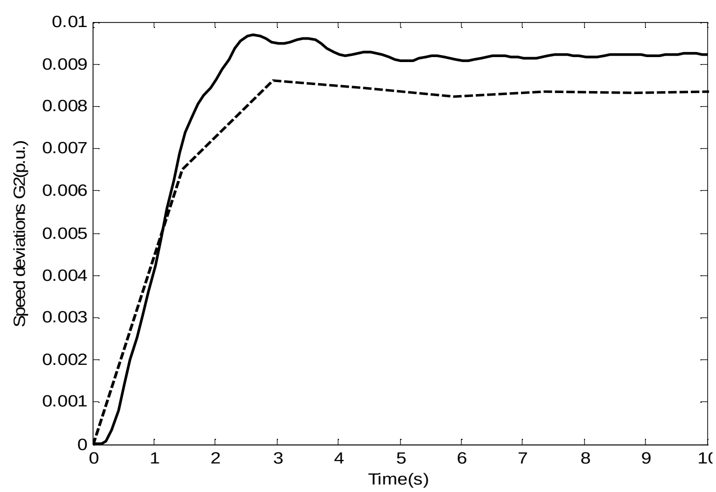


Fig.7. Speed of generator 2 following scenario 2 Solid (nonlinear model); dashed (linear identified model)



Simulation results

In order to evaluate the validity of the proposed linear models, following scenarios are considered as disturbance:

Scenario 1: 2% Step increase in the reference voltage of excitation system of generator 1

Scenario 2: 1% Step increase in the reference mechanical power of generator 1

The speed of generators following proposed scenarios are depicted in Fig.2-7. Each figure contains two plots as dashed line (linear identified model) and solid line (nonlinear model). It should be noted that the nonlinear results are obtained by using numerical simulation of nonlinear dynamic model of system presented in (14). Also, in order to comparison purposes, we have eliminated the initial value of nonlinear parameters; where the nonlinear simulations are started from zero just like the linear simulations. Fig.2-4. shows the results of identified model and real model following scenario 1. It is obviously seen that the identified model is as closely as possible with the real model. The validity of the proposed linear model is shown via comparison with the nonlinear model. Also the results following scenario 2 are depicted in Fig.5-7. The identified model exhibits a performance just like the nonlinear model in all results.

Conclusions

A new method for power system identification presented in this paper. Recursive least square method successfully carried out in modeling a multi machine electric power system. A linear model obtained in the form of transfer function. Comparison with the nonlinear model demonstrated the validity of the proposed identified model. This paper opens the door for modeling bulk power systems containing supplementary components.

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