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Estimation of Synchronous Machine Synchronizing and Damping Torque Coefficients

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Abstract**—**Synchronizing and damping torque coefficients of a synchronous machine can give a quite clear picture for machine behavior during transients. These coefficients are used as a power system transient stability measurement. In this paper, a crow search optimization algorithm is presented and implemented to study the power system stability during transients. The algorithm makes use of the machine responses to perform the stability study in time domain. The problem is formulated as a dynamic estimation problem. An objective function that minimizes the error square in the estimated coefficients is designed. The method is tested using practical system with different study cases. Results are reported and a thorough discussion is presented. The study illustrates that the proposed method can estimate the stability coefficients for the critical stable cases where other methods may fail. The tests proved that the proposed tool is an accurate and reliable tool for estimating the machine coefficients for assessment of power system stability.

Keywords**—**Optimization, estimation, synchronous, machine, crow search.

I. Introduction

IN power system design, operation and control, it is necessary to examine and analyze the behavior of the network when subjected to different kinds of disturbances. The purpose of these studies is to analyze the resultant electro-mechanical dynamic oscillations resulting from machine rotor. Poor damped rotor variations may affect the system stability badly. Power system nature is dynamic due switching operations. This makes the system operating point change always with respect to time. Due to this fact, the system stability should be monitored on-line. Different indicators can be used to perform this job. The commonly used indices are the coefficients of synchronizing and damping torque (K_s and K_D). For stable operation, both of these coefficients must be positive to insure the stable operation of the system [1], [2].

Over years, methodologies have been introduced and implemented to find K_s and K_D coefficients. Linearizing the equations of the system in the frequency domain [3], [4] was one of the simple and direct techniques used to solve the problem. Reference [3] resolved the electromagnetic torque into two parts in the frequency domain. Two equations are formed in terms of the deviation in the power angle then these equations are solved directly. On the other hand, time response can be used directly to form equations in the time domain. The formulated equations are then solved using state estimation algorithms. Either static or dynamic time domain estimation methods were used to find the coefficients.

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The Least error squares (LES) technique represents the family of static state estimation methodologies used in power system for a long time. It is the most popular estimation technique that represents the static family. It has been used for parameter identification in [5]. It has been shown that there are some limitations associated with application of the LES technique. The most significant problem associated with the use of such method appears when dealing with non-stationary signals as in our study. In such cases, estimates should be up-dated always. In other words the algorithm should be provided with a new data window along the time span considered. As an alternative to the static technique, dynamic state estimation algorithms have been employed to overcome such problems. As an example for dynamic estimation, Kalman filtering and its extended version (KF & EKF) algorithms are good examples for dynamic estimation methods used. The main advantage of this filter that it has been used to accomplish the identification process on-line [6]. A similar algorithm is presented in [7]. Reference [7] presented an efficient dynamic algorithm for stochastic on-line estimation of K_s and K_D coefficients. The algorithm is based on discrete dynamic filtering technique. This filter minimizes the sum of the absolute error in the process. Reference [8] gives a full comparison between the LES, KF and genetic algorithms (GA) techniques as used in the area of the system dynamic stability evaluation. However, neither thorough study nor stability analysis studies were conducted regarding the use of GA to support the findings in this reference.

Heuristic search (HS) techniques such as GA, particle swarm optimization (PSO) and Artificial intelligent algorithms (AI) such as artificial neural networks (ANN) have received much attention also in the area of optimization. HS techniques are characterized by using both random variation and selection to achieve the optimal solution in the space. The process is based on a natural process of biological evolution and is implemented in a parallel way over the given search space. HS-based methods have been applied to various works in both static and dynamic forms for evaluation of power system stability [9]-[13]. On the other hand, AI optimization approach is based on training and learning methodology. It needs a big amount of data to capture the phenomenon characteristics before testing. ANN has the advantage of not using any mathematical model for the system. It benefits from the characteristics of human neurons system [14].

This paper uses CS based algorithm as an efficient technique for on-line estimation of damping torque and synchronizing coefficients of synchronous machine during transients. The method is implemented to find an estimate of both stability coefficients K_s and K_D using the machine response. The dataset used consists of three sets: the rotor angle change Δδ(t), the rotor speed deviation Δω(t) and the electromagnetic torque change $\Delta T_e(t)$. The problem is organized and as a dynamic estimation problem. The objective function created is the square error in the estimated coefficients. The proposed crow search technique is employed to find the optimum solution of the organized problem. To investigate the suitability of the method, many simulated tests are considered. To confirm the capability, practicality and feasibility of the proposed method, sophisticated and dynamic scenarios, with various loading conditions, have been implemented in MATLAB SimPowerSystems block set.

II. Mathematical Modeling

Considering a simplified power system with single machine connected to an infinite bus system [9]. The system includes a steam-generator connected to a large power system represented as infinite bus via a tie line. The complete system data is given in [9]. Third order Park's equations is used to model the machine. The stability study is implemented using linearization near the operating point. The equations are organized in the state space form.

The electro-magnetic torque deviation ΔT_e may be witten as in (1). In this equation T_e is expressed as a function of both the rotor angle deviation Δδ(t), and the speed deviation Δω(t) [9].

$$\Delta T_e(t) = \Delta\delta(t) K_s + \Delta\omega(t) K_d \quad (1)$$

Using analogue to digital converter with a proper sampling rate, ΔT_e , Δδ(t) and Δω(t) are sampled to set up a system of n equations in the form of (1). However, an additional noise term is introduced to model any random error that is involved in the sampling process. Thus, (1) may be rewritten in matrix form as:

$$\begin{bmatrix} \Delta T_e(t_1) \\ \Delta T_e(t_2) \\ \vdots \\ \Delta T_e(t_n) \end{bmatrix} = \begin{bmatrix} \Delta\delta(t_1) & \Delta\omega(t_1) \\ \Delta\delta(t_2) & \Delta\omega(t_2) \\ \vdots & \vdots \\ \Delta\delta(t_n) & \Delta\omega(t_n) \end{bmatrix} \begin{bmatrix} K_s \\ K_d \end{bmatrix} + \begin{bmatrix} \varepsilon(t_1) \\ \varepsilon(t_2) \\ \vdots \\ \varepsilon(t_n) \end{bmatrix} \quad (2)$$

Note that K_s and K_d are gains (independent of time) that are basically a function of loading (change in active, reactive power and mechanical power driving the generator). K_s and K_d vary as those loading condition change.

In state space form, which is a suitable form of state estimation, (2) can be modeled as:

$$Z(t) = H(t)X + \varepsilon(t) \quad (3)$$

where Z(t) represents the measurement vector with dimension *nx1*, H(t) *gives the* connection matrix *nx2,* X the unknown vector to be estimated $(K_s , K_d)^{`}$ and $\varepsilon(t)$ is n*x*1 error vector to be minimized.

The given system of equations (3) represents a highly over-determined system. The main task now is to find the optimal estimation of vector X . The optimization problem formulated is unconstrained one. The proposed CS technique suggested is used to find the optimum values of the unknown state vector. The objective function utilized here is the summation of absolute error square $|\varepsilon_i|^2$ in each measurement. The target is to minimize this error.

$$F = \sum_{i=1}^{n} |\varepsilon_i|^2 \quad (4)$$

It is important to mention that the employed model by itself only (i.e. single machine-infinite bus) has been widely validated and successfully applied by many researchers [3], [6], [8] to estimate the damping and synchronizing coefficients. The computation of such coefficients in a multi-machine case is totally different in concept and involves different mathematical approach to analyze and facilitate the computation of the torque components [14]. According to Shaltout and Feilat [14], in a single-machine infinite bus case the dynamic response contains three modes that are distinct and fairly decupled. On the contrary, in a multi-machine case, such modes are strongly coupled and in all situations it is impossible to assign a single mode for each machine. Therefore, there exists a conceptual fundamental difference in calculating and analyzing the damping and synchronizing coefficients between the two cases.

III. Crow Search Optimization

In the last few decades, a wide range of alternative optimization techniques are introduced and used in the area of power system optimization. Each method has its exclusive advantages. One of these recently introduced methods is the crow search (CS) optimization technique. The algorithm was at first presented by Askarzadeh [15], [16]. CS attempts to simulate the social behavior of crow flock and their way of food collection. It has been shown that the CS technique has the advantage of improving the process efficiency over many other optimization algorithms, such as GA and PSO search, in both accuracy and convergence time [17]. CS can be considered as a proper alternative way for solving power system optimization problems

The CS algorithm has two possible scenarios between the food owner *crow j* and the thief *crow i*; in **the first scenario** the *crow j* of food source $\boldsymbol{m_j^k}$ does not know that the *crow i* (thief) follows it therefore the *crow i* reaches to the hide place of owner crow. The process updating of the *crow* i position is done by

$$x_i^{k+1} = x_i^k + r_i fl_i^k (m_j^k - x_i^k) \quad (5)$$

where r_i is random number between 0 and 1, $\boldsymbol{fl_i^k}$ is the flight length of *crow i* at iteration number k.

The second possible scenario is that when the *crow j*

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knows that *crow i* follows it therefore, the *crow j* will cheat *crow i* by flying to another position in the search space.

Updating of the position of *crow i* in this case is achieved by a random position.

$$if r_i \geq p_j^k \begin{cases} \text{update position using (5)} \\ \text{a random position otherwise} \end{cases}$$

where *rj* represents a random number between zero & one and p_i^k is the probability of awareness for the crow j at step k. The parameter fl_i^k is an important one that helps in finding the global optimum solution. A very small value of fl_i^k leads to local minimum while large value guides to the global minimum point. The flock's position at iteration k is updated using (6). The new fitness function is then calculated, the obtained fitness function at any iteration is compared with previous one and the updated flock's position is used.

IV. Time Domain Modeling in the Simulink

In this case a practical power system is simulated to demonstrate the ability of the estimator to track Ks and KD. The system is simulated using Simulink and SimPowerSystems block set as in Fig. 1. The system comprises a three-phase synchronous generator rated 200 MVA, 13.8 kV, 112.5 rpm connected to a large power system (infinite busbar) through a Δ/Y 210 MVA transformer. The system equivalent at the infinite busbar is given by 230 kV and 10,000 MVA. The synchronous generator is powered by hydraulic turbine and equipped with a PID governor system whereas the field voltage is provided through an excitation block that implements IEEE type (1) [18] .

The significance of conducting this experiment is that Simulink model articulates the change in operating condition of a synchronous machine dynamic response in real time situation and therefore, unlike modeling in the frequency domain, modeling in Simulink allows for the calculation of the torque components under various small disturbances. Such disturbances particularly include perturbations in mechanical power driving the generator and different loading scenarios of active and reactive power. This fundamental issue of dynamics stability analysis can easily be implemented using Simulink.

The necessary time responses that are needed for the analysis, i.e. change in electromechanical torque, change in rotor speed and change in rotor angle, were calculated in the same manner and concept as they had been calculated in [13]. In detail, the steady state components of the generator rotor speed and the electrical torque were calculated, and subtracted from the instantaneous speed and torque at each sampling time respectively, giving the deviation of each signal; $\Delta\omega$, ΔT_e . A numerical integration is then conducted to calculate the rotor angle deviation Δδ(t).

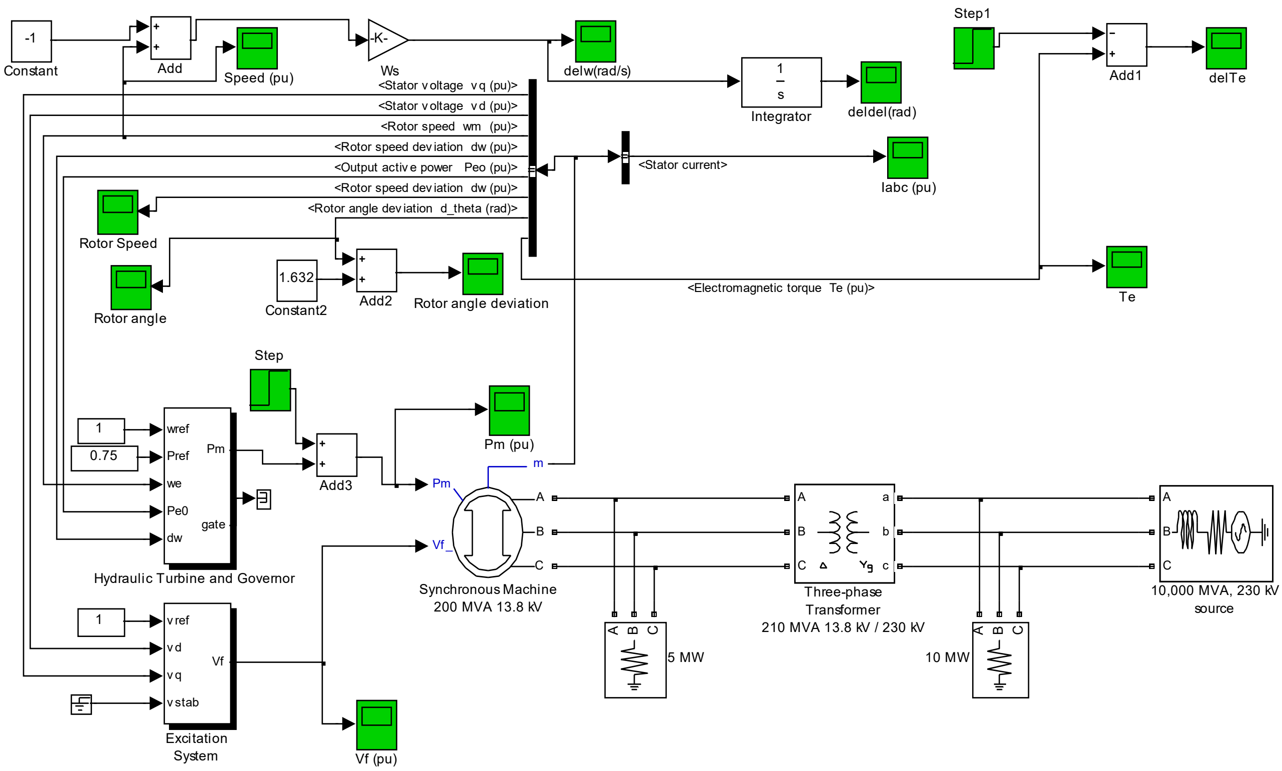

Fig. 1 System under study

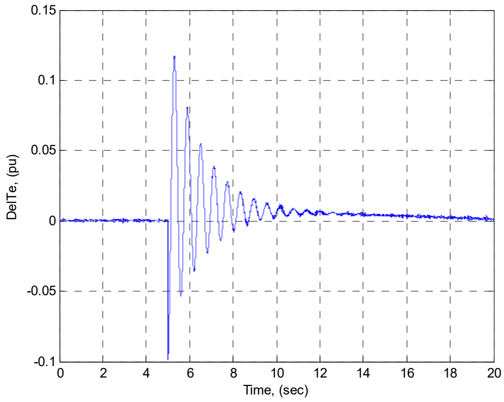

Fig. 2 Electromechanical torque response

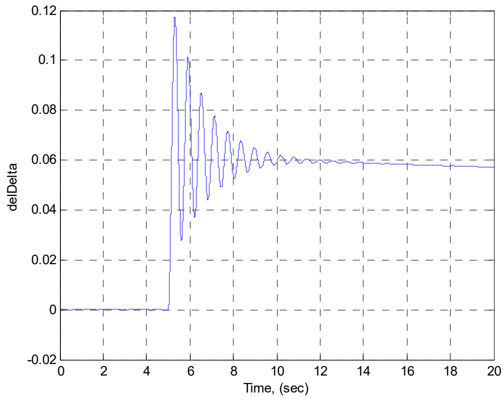

Fig. 3 Rotor angle response

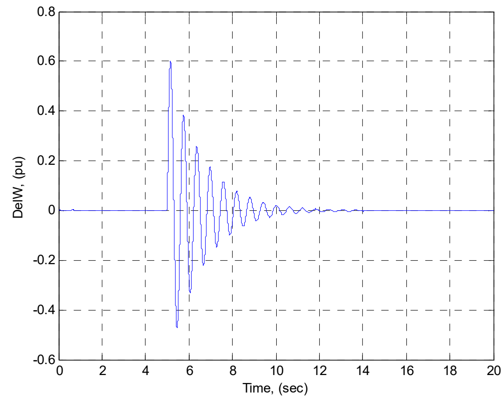

Fig. 4 Rotor speed response

TABLE I
ESTIMATED PARAMETERS WITH VARIOUS LOADING CONDITIONS

Case #	Type of Disturbance	Loading Condition		Crow Search	
		P (pu)	*Q(pu)*	K_s	K_d
1	5% Step in P_m	0.75	0.17	0.2646	0.09390
2	10% Step in P_m	0.75	0.17	0.1001	0.0101
3	15% Step in P_m	0.75	0.17	0.1701	0.0401
4	Load Change	0.95	0.70	0.3347	0.0077
5	Load Change	0.90	-0.3	0.2971	-0.0113
6	Load Change	0.90	-0.2	-0.0812	-0.0073

In order to study the performance of the proposed algorithm and asses its accuracy, different disturbances have been generated to carry out the estimation of the synchronizing and damping torque coefficients. Two types of disturbances are considered. Table I summarizes the study cases and the corresponding results for the estimated coefficients. In the first three cases in this table, the disturbance is generated by changing the loading conditions as shown. In cases from 4 to 6 the disturbance is introduced by a step change (increases) in the mechanical power input. A sample of the response curves is shown in Figs. 2-4. In these figures the change in electromechanical torque, change in rotor speed and change in rotor angle of case 1 are shown. From figures, it is clear that this is stable case. Examining the table reveals that cases 5 and 6 are unstable because of the negative signs obtained, while all other cases are stable.

V. CONCLUSIONS

A practical application of CS optimization technique is presented for optimal estimation of the damping and synchronizing coefficients of a synchronous machine. The problem is tackled as an estimation problem. CS is used to minimize the selected objective function. The minimization criterion used is the sum of the errors square in the process. The method is tested using practical case study. Different simulated cases were applied. Accurate results obtained show that the proposed CS method can be used for either on-line or off-line estimation of machine stability indices. It is shown that the CS algorithm is simple to implement. This makes CS suitable for on-line use. One of the reasons that particle CS is attractive is that there are few parameters to adjust. Therefore, CS could have wide range of applications in the area of system stability and can be regarded as reliable tool in the area of power system stability assessment.

APPENDIX

$X_d = 2.5$, $X_d^{'} = 0.39$, $X_q = 2.1$, $X_e = 0.5$ (all in p.u.)
$T_{do} = 5$ sec., $\omega_s = 377$ r/s, H = 6 sec.
I.C. V_t =1 pu., $V_{I.B.} = 1.05$ p.u.

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