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Online Synchronous Generator Parameters Estimation Considering AVR System

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ABSTRACT

In this paper prediction error measurement (PEM) method is used for online synchronous generator parameters estimation. Unlike the usual off-line standard methods, in the proposed method instead of removing the automatic voltage regulator (AVR) from the circuit and manually disturbing the excitation voltage, a change in the reference signal of the AVR is applied and the parameters are estimated for the AVR-generator interconnected system. To adapt this modeling to real conditions, the input and output signals are mixed with noise. Since the direct application of the PEM method on noisy signals will cause a significant estimation error, the wavelet transform is used as a signal-denoising tool. Using Matlab/Simulink, synchronous generator parameters are estimated under colored noise and white noise conditions. To validate the estimated parameters, the results compare with the standard standstill frequency response (SSFR) test that was applied to the Shahid Rajaee power plant. Moreover, a three-phase short circuit to earth for a period of 2.5 cycles at the generator terminal is simulated and analyzed. The results indicate the proper accuracy of the proposed parameter estimation.

1. Introduction

To determine the safe and stable operation margin, it is necessary to model the dynamics of the power system with its all components. One of the main components is the synchronous generator, which has a wide dynamic operation, and it is necessary to use the most accurate models in dynamic studies. So far, several methods have been used to model and determine the synchronous generator parameters, which have gradually become more complete with the growth of science and technology. In the 1960s the characteristics of the machine were obtained by the experiments of short circuit tests. In general, these tests are usually very expensive and there is also the possibility of damage to the generator during these tests. Another problem was that there was no suitable method to determine the parameters of the q-axis while these parameters have a significant effect on the machine performance. In 1972, the operational impedance conversion function had raised to compare the measurable quantities, in 1973, this had discussed [1]. Considering the weaknesses mentioned for the short-circuit test method, some researchers tried to present modified methods in order to more accurately determine the parameters of the synchronous generator using the short-circuit test [2, 3]. The most important feature of the proposed methods is the use of rotor current measurements during the short circuit test to determine the characteristics of the excitation circuit more precisely. However, the main weaknesses of these methods remained, i.e. the inability to determine the parameters of the q-axis and the severe shock to the machine. But it remains the main weak points include disability the determination of wide axis parameters and stretching the strong shock to the machine. In 1977, the use of the transport test was proposed as a method to determine the parameters of the synchronous generator [4], [5]. This test is similar to a short circuit test; in the sense that the time reactions of

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machine variables following the occurrence of a sudden disturbance are used to determine machines' characteristics. In contrast to the aforementioned methods, other methods were proposed that can specify a complete set of generator parameters. The method of estimating the parameters of the synchronous generator based on the tests of the machine's frequency response in the stationary state is among these methods, which can fully estimate the parameters of the synchronous generator and is presented as an IEEE standard method [1]. Opposite to the aforementioned methods, other methods were proposed that can specify a complete set of generator parameters. The method of estimating the parameters of the synchronous generator based on the tests of the machine's frequency response in the stationary state is among these methods, which is able to fully estimate the parameters of the synchronous generator and is presented as an IEEE standard method. These methods can be used when the machine is outside of service [6]. In recent years, identification methods based on online measurements have been considered to overcome the weaknesses of classical methods [7-8].
These methods can be divided into three categories: black box, white box, and gray box. In the first category, the synchronous generator is modeled as the black box by using input and output data [8-10]. In these modeling, the structure of the system is unknown and the mapping between input and output must be determined through the measured data set.
In the white-box method, the parameters and mathematical model are known and tests are carried out to validate the existing information.
In the last category by assuming the structure of the synchronous generator, the parameters of the model are estimated using online measurements [11-12].
In [13] parameter estimation of synchronous generator has been proposed using load rejection tests data and fitting curve method to the experimental data considering the operational limitations of real power plants.
Due to conditions such as saturation, temperature, aging, etc., parameters changes. In the online methods, the generator does not need to be disconnected from the grid. In addition, which makes it necessary to estimate the parameters on the line.
In many works, the model of the excitation system and AVR of the generator has not been considered, and only the change in the voltage of the excitation coil has been considered as the input of Park's equations. The generator is considered an independent system from AVR with its own inputs and outputs. To create dynamic conditions in the generator, the voltage of the excitation coil is directly disturbed. Since creating a direct disturbance in the voltage of the excitation coil requires the AVR system to be removed from the circuit.
A genetic algorithm-based method is proposed in [14] to identify the parameters of the Heffron-Phillips model of synchronous generator and excitation system by using online measurement data.
In [15], by using the data of the digital protective relay a constrained iterative Unscented Kalman Filter (UKF) approach is used for synchronous generator parameters estimation.
In [16] a new method is proposed to estimate field voltage signal using other measurements of the synchronous generator for parameter estimation purposes.
In [17], parameter estimation of synchronous generator and exciter has been presented where the measurement for the field voltage and current are available, while it is not the case for the brushless systems.
In this article, the model and specifications of the Shahid Rajaee power plant have been used. The PEM method as an iterative identification method is used to estimate the parameters of the studied system. The rest of the paper is organized as follows: in section 2 machine model and the standard SSFR test for obtaining parameters are given, in section 3, the parameter estimation method is discussed, in section 4, online testing has been discussed and finally in section 5 conclusion remarks are given.

2. Machine modeling

The synchronous machine model in this paper is a standard second-order model with one damper on the d-axis and two dampers on the q-axis which is shown in Figure 1 [9]. The degree of the applied model is selected based on synchronous generator type, rotor structure, and IEEE-Std-1110 considerations. Parameter definitions are listed in Table 1.

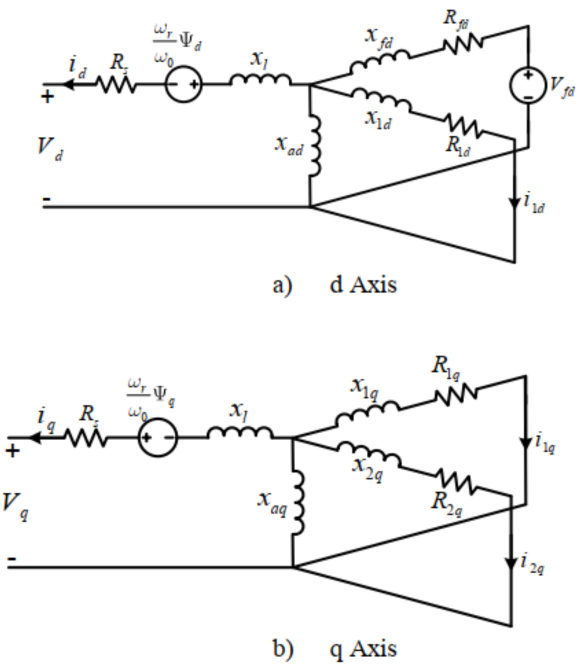


Fig.1. Synchronous generator equivalent circuits according to 2-2 model of IEEE Std. 1110

Table 1. Synchronous generator parameter definitions

Parameters	Parameters definition
x_l	Armature leakage inductance
x_{ad}	d- axis armature reactance
x_{aq}	q- axis armature reactance
X_d	d- axis synchronous reactance
X_q	q- axis synchronous reactance
X'_d	d- axis transient reactance
X'_q	q- axis transient reactance
X''_d	d- axis subtransient reactance
X''_q	q- axis subtransient reactance
T'_{do}	d- axis transient O.C time constant
T''_d	d- axis subtransient O.C time constant
x_{fd}	Field winding leakage inductance
x_{1d}, x_{1q}, x_{2q}	Damper winding leakage inductance
R_a	AC Armature resistances
R_f	Field winding resistance
R_{1d}, R_{1q}, R_{2q}	Damper winding resistances
V_d	d- axis operational resistances
V_{fd}	direct axis armature voltage
V_q	field voltage
	quadrate axis armature voltage

Relations between parameters are as follows:

$$X_d = x_l + x_{ad} \quad (1)$$

$$X_q = x_l + x_{aq} \quad (2)$$

$$X'_d = x_l + x_{ad} \| x_{fd} = x_l + \frac{x_{ad} x_{fd}}{x_{ad} + x_{fd}} \quad (3)$$

$$X'_q = x_l + x_{aq} \| x_{1q} = x_l + \frac{x_{aq} x_{1q}}{x_{aq} + x_{1q}} \quad (4)$$

$$X''_d = x_l + x_{ad} \| x_{fd} \| x_{1d} = x_l + \frac{x_{ad} x_{fd} x_{1d}}{x_{ad} x_{fd} + x_{ad} x_{1d} + x_{fd} x_{1d}} \quad (5)$$

$$X''_q = x_l + x_{aa} \| x_{1q} \| x_{2q} = x_l + \frac{x_{aq} x_{1q} x_{2q}}{x_{aq} x_{1q} + x_{aq} x_{2q} + x_{1q} x_{2q}} \quad (6)$$

$$T'_{do} = \frac{1}{\omega_0 R_{fd}} \left(x_{fd} + x_{ad} \right) \quad (7)$$

$$T'_{qo} = \frac{1}{\omega_0 R_{1q}} \left(x_{1q} + x_{aq} \right) \quad (8)$$

$$T''_{do} = \frac{1}{\omega_0 R_{1d}} \left(x_{1d} + x_{fd} \| x_{ad} \right) = \frac{1}{\omega_0 R_{1d}} \left(x_{1d} + \frac{x_{fd} x_{ad}}{x_{fd} + x_{ad}} \right) \quad (9)$$

$$T''_{qo} = \frac{1}{\omega_0 R_{2q}} \left(x_{2q} + x_{1q} \| x_{aq} \right) = \frac{1}{\omega_0 R_{2q}} \left(x_{2q} + \frac{x_{1q} x_{aq}}{x_{1q} + x_{aq}} \right) \quad (10)$$

The following plausibility relations should be held in the estimated parameters:

$$X_d \geq X_q > X'_q \geq X'_d > X''_q \geq X''_d$$
$$X_{d(sat)} \geq X_{q(sat)} \geq X'_{q(sat)} \geq X'_{d(sat)} \geq X''_{q(sat)} \geq X''_{d(sat)}$$
$$T'_{do} \geq T'_d > T''_{do} > T''_d > T_{kd}$$

The proposed model for AVR in this study is extracted from IEEE standard 421.5 – 1992 [18]. Figure 1 shows the block diagram of the AVR model.

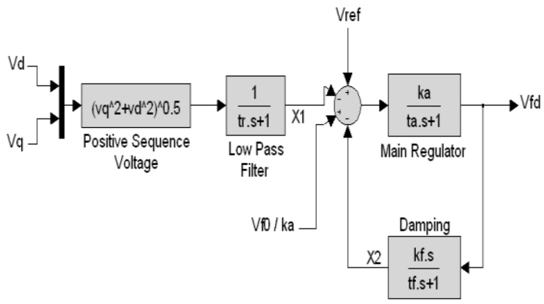


Fig .2. AVR block diagram

To have a better comparison, synchronous generator parameters are also obtained using the off-line standard SSFR test. In doing this time-consuming test, machine should be shut down; disconnected from its turning gear and electrically isolated. Moreover all connections to the field should be taken off by removing the brush gear and in the case of a brushless exciter, electrically disconnecting. Table 2 shows the required measurements and related equations [19]. For more details please see [20]. Estimated parameters using SSFR are shown in Table 3.

Table 2. SSFR Tests [20]

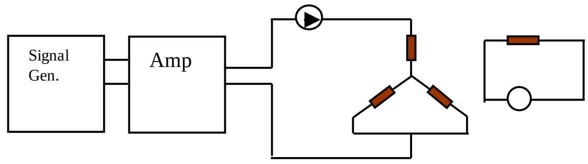
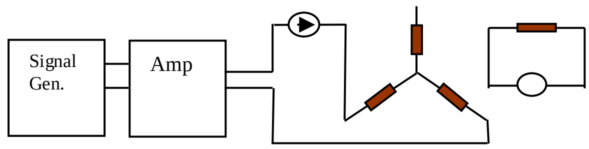
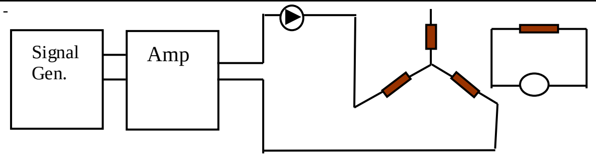
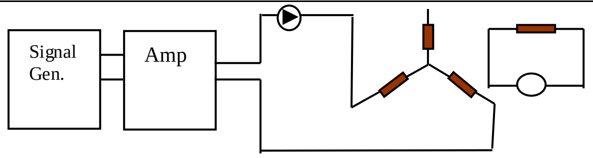
NO.	measurements	Circuit Test	Measurement Values	Equations
1	q-Axis operational Impedance $Z_q(s)$		U_{stator} I_{stator} U_{rotor} (about 0)	$Z_q(s) = -\frac{\Delta e_q(s)}{\Delta i_q(s)}\Big\|_{\Delta e_{fd}=0}$
2	d-Axis operational Impedance $Z_d(s)$		U_{stator} I_{stator} U_{rotor} (max)	$Z_d(s) = -\frac{\Delta e_d(s)}{\Delta i_d(s)}\Big\|_{\Delta e_{fd}=0}$
3	Standstill armature to field transfer function $sG(s)$		U_{stator} I_{stator} I_{rotor}	$sG(s) = -\frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\Big\|_{\Delta e_{fd}=0}$
4	Standstill armature to field transfer impedance Z_{afo}		U_{rotor} I_{stator} Irotor (about-0)	$Z_{afo}(s) = -\frac{\Delta e_{fd}(s)}{\Delta i_d(s)}\Big\|_{\Delta i_{fd}=0}$

Table 3. Impedances and constant times of generator from SSFR test

Parameter name:	X'_q (pu)	X'_d (pu)	X_q (pu)	X_d (pu)	X''_d (pu)
Parameter value:	0.811	0.27	1.92	1.92	0.17
Parameter name:	T''_{do} (s)	T'_{qo} (s)	T'_{do} (s)	X''_q (pu)	T''_{qo} (s)
Parameter value:	0.011	0.79	7.69	0.26	0.01

3. Online parameter estimation method

Prediction Error Measurement (PEM) is a method based on input-output data collected from the process to form a cost function. The parameters are then estimated as the solution of the optimization of a cost function. When the dynamical equations are available, the parameters of the system can be selected in such a way that for the same input, the output obtained from simulating the model with the output obtained from the result of the measurement have equal values. If the measured output vector of the system at sample time i is shown as y_i and the output vector of the estimated model at sample time i is shown with $\hat{y}_i$; the parameters are estimated as the solution of the optimization of following cost function:

$$s = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{11}$$

If unknown parameters of a dynamic system are shown with a vector $\underline{\theta}$ then the aim is to find $\underline{\theta}$ such that the value of s becomes minimized. The PEM method uses the Newton algorithm to find the optimal solution. Newton's method is a recursive method to find the stem of a nonlinear equation. The mathematical description of Newton's method can be written as follows:

$$\theta_{i+1} = \theta_i - S'(\theta_i).[S''(\theta_i)]^{-1} \tag{12}$$

If the relation between input u_i , and output y_i of the nonlinear system can be expressed as:

$$y_i = f(u_i, \underline{\theta}) \tag{13}$$

Thus, the objective function becomes:

$$s = \sum_{t=1}^{N}[y - f(u, \underline{\theta})]^2 \tag{14}$$

4. Testing and providing the necessary data for the estimation of the system's parameters

The specifications of the generator and AVR extracted from the Shahid Rajaee power plant documents are given in Tables 4-6.

Table 4. Impedances and times constant of the generator

Parameter name:	X'_q (pu)	X'_d (pu)	X_q (pu)	X_d (pu)	X''_d (pu)
Parameter value:	0.46	0.27	1.89	1.95	0.23
Parameter name:	T''_{do} (s)	T'_{qo} (s)	T'_{do} (s)	X''_q (pu)	T''_{qo} (s)
Parameter value:	0.017	0.78	8.78	0.23	0.03

Table 5. AVR parameters

Parameter name:	t_f (s)	k_f (pu)	t_a (s)	k_a (pu)	t_r (s)	V_{f0} (pu)
Parameter value:	0.24	0.01	0.03	50	0.02	1.8705

Table 6. Steady-state value of variables

Parameter name	Parameter value	Parameter name	Parameter value
$S_{base}(MVA)$	312.5	f_n	50
$V_{base}(kV)$	19	$P_{mech}(pu)$	0.8019
$V_{genLL}(pu)$	1	$V_{ref}(pu)$	1
$P_{gen}(pu)$	0.8	$V_{exciter}(pu)$	1.8705
$Q_{gen}(pu)$	0.01544		

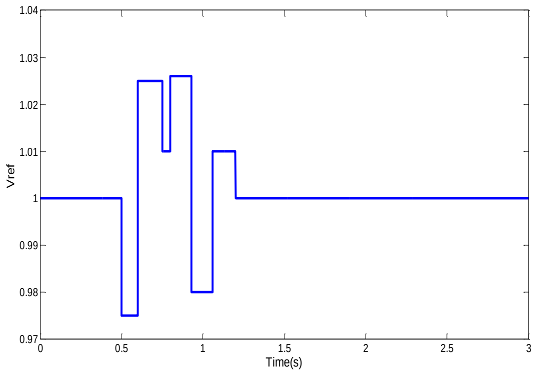


Fig.3. A reference signal of AVR

Figure 3, shows the AVR source signal. As it is mentioned, in the standard synchronous generator parameters identification tests, excitation systems should be separated from AVR to change directly the stimulation voltage. In this section, the AVR and generator set is considered as a single system and an attempt is made to estimate system parameters, Therefore, the parameters of the generator are estimated without causing problems in the interconnected set and without the need for knowing the data of the excitation current and voltage signals. In fact, the proposed method can be very practical in terms of technical limitations. There are 10 unknown parameters and, the system inputs are considered as ω, v_{erf} , v_q, v_d, and the system outputs are i_q , and i_d . Table 7, shows the estimated values and real values of the AVR–generator system.

A change in the AVR source signal will cause a change in excitation voltage *V*ref, d-axes voltage (V_d), q-axis voltage (V_q) and mechanical speed as the system's inputs and current signals as the system's output.
The sampling time is considered as 0.001s, that selected sufficiently smaller than the minimum system time's constant T_{do} = 0.017 (Sec).

4.1. Parameters estimation through noisy signals

To provide a real test condition, parameter estimation is performed under two kinds of noises; white noise and colored.

Table 7. Comparison between the estimated value and real value

Parameters name	Estimated values	SSFR Test	Real values	Error w.r.t real values (%)
$X_d(pu)$	1.9518	1.92	1.95	0.09
$X_q(pu)$	1.8945	1.92	1.89	0.24
$X_d^{'}(pu)$	0.2717	0.27	0.27	0.63
$X_q^{'}(pu)$	0.4244	0.81	0.46	7.74
$X_d^{''}(pu)$	0.223	0.17	0.23	3.04
$X_q^{''}(pu)$	0.235	0.26	0.23	2.17
$T_{do}^{'}(s)$	8.755	7.69	8.78	0.28
$T_{qo}^{'}(s)$	0.788	0.79	0.78	1.02
$T_{do}^{''}(s)$	0.014	0.01	0.017	17.46
$T_{qo}^{''}(s)$	0.042	0.01	0.03	40

4.1.1. Signals containing white noise

Figure 4, shows the generator input signals and Figure 5, shows the generator output signals.

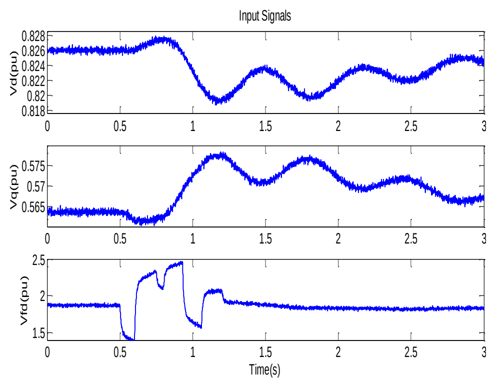


Fig.4. Input signals of generator with white noise

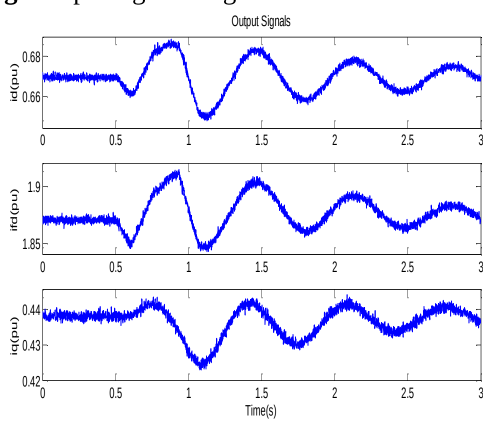


Fig.5. Output signals of generator with white noise

The direct application of the PEM method to evaluate the generator parameters will be accompanied by a significant error. To solve this problem; first, the input and output signal noises are removed, and then the PEM method is applied to the denoised signals. To eliminate noises wavelet tool is applied [21]. Figures 6 and 7 show input and output signals after noise removal, respectively.

4.1.2. Signals containing colored noise:

In this section, colored noise has been added to the measured signals to approach a real test situation. The relationship between color and white noise is as follows:

$$e(k) = H(z).v(k) \tag{14}$$

where $v(k)$ is white noise, $e(k)$ is colored noise and $H(z)$ shows the relation between the white and colored noise. The number of poles and zeros $H(z)$ and their values depend on environmental conditions and are often not known. In this study, a distinct and random function $H(z)$ was chosen for each of the input and output signals. Then, similar to the previous case, by removing colored noise and using input and output signals, system parameters were estimated. Table 8 shows the evaluation error of generator-AVR parameters compared to noisy and non-noised signals, which is acceptable.

The results of Table 8 show the fact that the average error of q-axis parameter estimation is higher than the average error of d-axis parameter estimation, and the average parameter estimation error T''_{qo} is very large. Therefore, it can be concluded that the input signal was not rich enough to obtain more accurate q-axis parameters and the excitation coil (which is placed on the d-axis) cannot cause sufficient excitation of the modes on the q-axis.

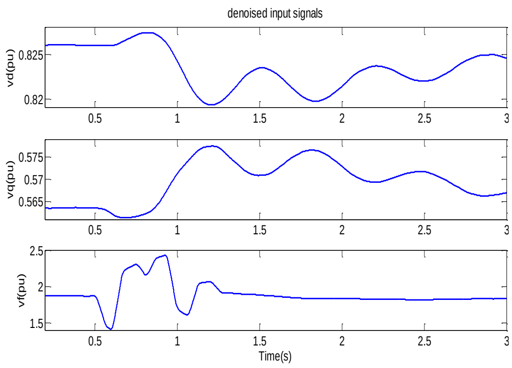


Fig.6. Input signals of the generator after white noise removal

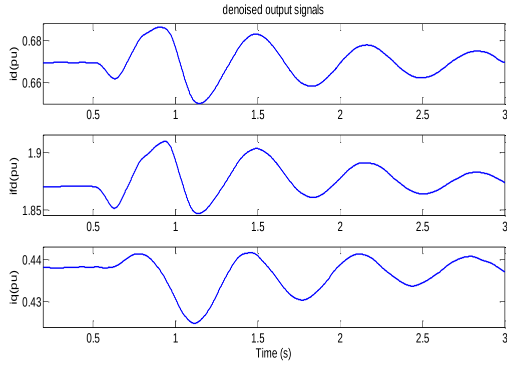


Fig.7. Output signals of the generator after white noise removal

Table 8. Comparison between the estimation error obtained by signals without noise and noisy signals

PARAMETER NAME	REAL VALUE	ERROR (%)			
		Signals without noise	Signals with white noise	Signals with color noise	*average*
$X_d(pu)$	1.9518	0.09	0.12	0.25	*0.15*
$X_q(pu)$	1.8945	0.24	0.24	0.43	*0.31*
$X_d'(pu)$	0.2717	0.63	0.74	1.59	*0.98*
$X_q'(pu)$	0.4244	7.74	6.19	8.67	*7.53*
$X_d''(pu)$	0.223	3.04	6.95	7.26	*5.75*
$X_q''(pu)$	0.235	2.17	3.91	3.74	*3.27*
$T_{do}'(s)$	8.755	0.28	0.79	0.79	*0.62*
$T_{qo}'(s)$	0.788	1.02	6.41	6.28	*4.57*
$T_{do}''(s)$	0.014	17.64	18.82	18.94	*18.46*
$T_{qo}''(s)$	0.042	40	42	50	*44*

5. The evaluation and validation of estimated models

To create completely different conditions from the experimental conditions of the previous section, we studied the short circuit of 3-phases to earth for a period of 2.5 cycles at the generator terminal, and the results were analyzed to validate the model.

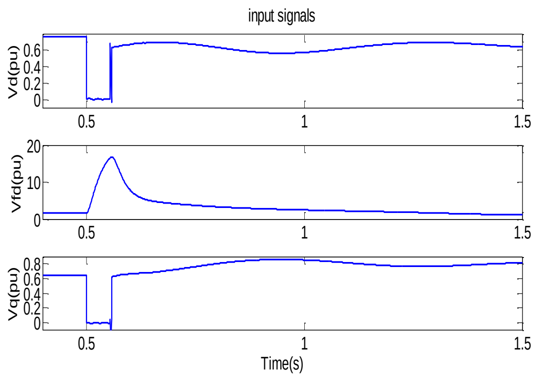


Fig 8. The waveform of input signals of the generator for the validation test

Table 9 shows the utilization values for the synchronous generator short circuit test. Figure 8, shows the inputs of the generator in the short circuit conditions. Table 10 shows fitness values between model output and real output in the short circuit test. Figures 9-11 show the output signals of the model in comparison with the actual signals of the studied system for the short circuit test and indicate the proper accuracy of parameter estimation.

Table 9. Steady-state value of variables in short circuit test

Parameter name:	Parameter value:	Parameter name:	Parameter value:
$S_{base}(MVA)$	*312.5*	f_n	*50*
$V_{base}(kV)$	*19*	$P_{mech}(pu)$	*0.6412*
$V_{genLL}(pu)$	*1*	$V_{ref}(pu)$	*1*
$P_{gen}(pu)$	*0.64*	$V_{exciter}(pu)$	*1.6058*
$Q_{gen}(pu)$	*0.00456*		

Table 10. Fitness values between models output and real output in short circuit test

List of parameters model	Output name	
	i_d	i_q
Parameter illustrated in Table 4	94.59	95.01
Parameter illustrated in Table 5 (White noise)	93.1	95.07
Parameter illustrated in Table 4 (colored noise)	92.72	95.44

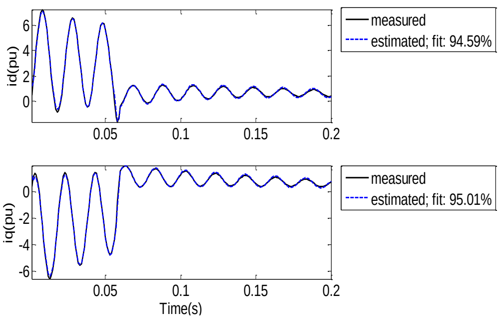


Fig.9. Comparison between the outputs of the generator in the short circuit test, measured and simulated by parameters shown in Table 4

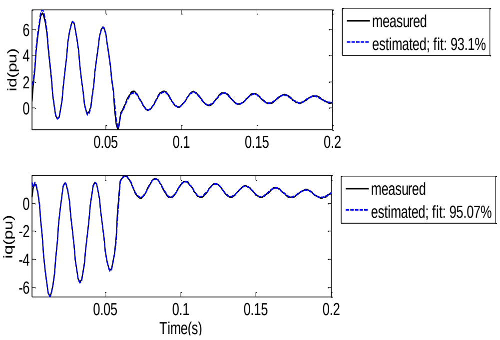


Fig.10. Comparison between the outputs of the generator in a short circuit test, measured and simulated by parameters obtained by white noise signals

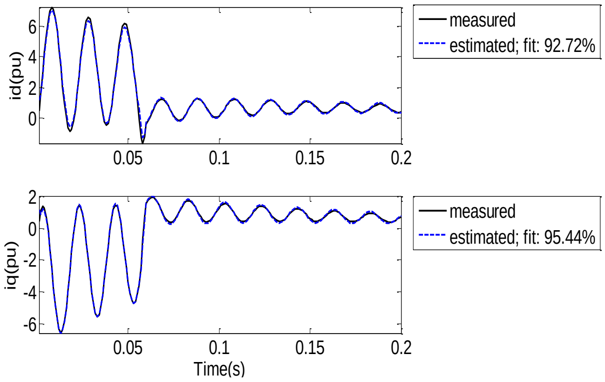


Fig.11. Comparison between outputs of generator in short circuit test, measured and simulated by parameter obtained by colored noisy signals

6. Conclusion

Usually, to create a disturbance in the excitation system, the AVR is separated from the generator and changed manually, and the AVR model is not considered. In this article, in order to bring the test conditions closer to the normal operating conditions, the signal at the AVR reference point was changed and the AVR-generator set was seen as a single set. The parameters of the AVR-generator system were estimated using the PEM method. The obtained results show high estimation accuracy.

References

1- IEEE Std. 1110, "IEEE Guide for Synchronous Generator Modeling Practices and Application in Power System Stability Analysis," 2002.

2- Canay, I. M.,(1993) "Determination of Model Parameters of Machines from the Reactance Operators xd(p),xq(p) (Evaluation of Standstill Frequency Response Test)," IEEE Transactions on Energy Conversion, 8(2), 272-279.

3- Coultes, M. E., & Watson, W. (1981). Synchronous machine models by standstill frequency response tests. *IEEE Transactions on Power Apparatus and Systems*, (4), 1480-1489.

4- Melgoza, J. J. R., Heydt, G. T., Keyhani, A., Agrawal, B. L., & Selin, D. (2001). An algebraic approach for identifying operating point dependent parameters of synchronous machines using orthogonal series expansions. *IEEE Transactions on Energy Conversion*, *16*(1), 92-98.

5- Melgoza, J. R., Heydt, G. T., Keyhani, A., Agrawal, B. L., & Selin, D. (2001). Synchronous machine parameter estimation using the Hartley series. *IEEE transactions on energy conversion*, *16*(1), 49-54.

6- Pourgholi, M., Aghamohammadi, M. R., & Majd, V. J. (2007, September). Method experience with SSFR test for synchronous generator model identification using Hook-Jeeves optimization method. In *Proceedings of the 7th WSEAS International Conference on Simulation, Modelling and Optimization* (pp. 489-494).

7- Lai, L. L., & Ma, J. T. (1996). Application of evolutionary programming to transient and subtransient parameter estimation. *IEEE transactions on energy conversion*, *11*(3), 523-530.

8- Karrari, M., & Malik, O. P. (2005). Identification of synchronous generators using adaptive wavelet networks. *International Journal of Electrical Power & Energy Systems*, *27*(2), 113-120.

9- Shamsollahi, P., & Malik, O. P. (1996, May). On-line identification of synchronous generator using neural networks. In *Proceedings of 1996 Canadian Conference on Electrical and Computer Engineering* (Vol. 2, pp. 595-598). IEEE.

10- Zaker, B., Gharehpetian, G. B., Mirsalim, M., & Moaddabi, N. (2013, May). PMU-based linear and nonlinear black-box modelling of power systems. In *2013 21st Iranian Conference on Electrical Engineering (ICEE)* (pp. 1-6). IEEE.

11- Lidenholm, J., & Lundin, U. (2010). Estimation of hydropower generator parameters through field simulations of standard tests. *IEEE transactions on energy conversion*, *25*(4), 931-939.

12- Shackshaft, G., & Poray, A. T. (1977, December). Implementation of new approach to determination of synchronous-machine parameters from tests. In *Proceedings of the Institution of Electrical Engineers* (Vol. 124, No. 12, pp. 1170-1178). IET Digital Library.

13- Arastou, A., M. Karrari, and B. Zaker. "New method for synchronous generator parameters estimation using load rejection tests data considering operational limitations." *Electric Power Systems Research* 192 (2021): 106999.

14- Zaker, B., G. B. Gharehpetian, and N. Moaddabi. "Parameter identification of Heffron-Phillips model considering AVR using on-line measurements data." *Proceedings of International Conference on Renewable Energies and Power Quality (ICREPQ'14)*. 2014.

15- Challa, K. K., & Gurrala, G. (2020). Dynamic state and parameter estimation of synchronous generator from digital relay records. *Electric Power Systems Research*, *189*, 106743

16- Zaker, B., Khodadadi, A., & Karrari, M. (2022). A new approach to parameter identification of generation unit equipped with brushless exciter using estimated field voltage. *International Journal of Electrical Power & Energy Systems*, *141*, 108122.

17- Paszek, S., Bobon, A., Berhausen, S., Majka, L., Nocon, A., Pruski, P., & Pruski, P. (2020). Method, Algorithm and Module of a Parameter Estimation Program for Mathematical Models of Synchronous Generator and Excitation Systems. *Synchronous Generators and Excitation Systems Operating in a Power System: Measurement Methods and Modeling*, 71-98.

18- Report, I. C. (1981). Excitation system models for power system stability studies. *IEEE Transactions on power apparatus and systems*, (2), 494-509.

19- Donoho, D. L., & Johnstone, I. M. (1994). Ideal denoising in an orthonormal basis chosen from a library of bases. *Comptes rendus de l'Académie des sciences. Serie I, Mathematique*, *319*(12), 1317-1322.

20- Pourgholi, M., Majd, V. J., Nabavi, M. T., & Aghamohammadi, M. R. (2007, April). Synchronous Generator's Model Identification Using Hook-Jeeves Optimization Method. In *2007 International Conference on Power Engineering, Energy and Electrical Drives* (pp. 318-323). IEEE.

21- Amini Boroujeni, E., et al.(2008) "Experience with SSFR test for Shahid Rajaee synchronous generator parameters identification using Pattern-Search optimization algorithm." *Iran-rotate Conference*, (pp. 1-10).