

Search Space Calculation to Improve Parameter Estimation of Excitation Control Systems

Cálculo del Espacio de Búsqueda para Mejorar la Estimación de Parámetros de los Sistemas de Control de Excitación

Andrés J. Saavedra-Montes¹
Carlos A. Ramos-Paja²
Juan R. Camarillo-Peñaranda³

1 Departamento de Energía Eléctrica y Automática,
Facultad de Minas, Universidad Nacional de Colombia,
Medellín-Colombia
ajsaaaved@unal.edu.co

2 Departamento de Energía Eléctrica y Automática,
Facultad de Minas, Universidad Nacional de Colombia,
Medellín-Colombia
caramosp@unal.edu.co

3 Departamento de Energía Eléctrica y Automática,
Facultad de Minas, Universidad Nacional de Colombia,
Medellín-Colombia
jrcamarillop@unal.edu.co

Abstract

A method to calculate the search space for each parameter in an excitation control system is presented in this paper. The calculated search space is intended to reduce the number of parameter solution sets that can be found by an estimation algorithm, reducing its processing time. The method considers a synchronous generator time constant range between 4s and 10s, an excitation control system performance index, a controller design technique, and the excitation control system model structure. When the obtained search space is used to estimate the parameters, less processing time is used by the algorithm. Also the estimated parameters are closer to the reference ones.

Keywords

Excitation system, parameter estimation, search space.

Resumen

En este artículo se presenta un método para calcular el espacio de búsqueda de cada parámetro del modelo de un sistema de control de excitación. Con el espacio de búsqueda calculado se pretende reducir el número de conjuntos de parámetros solución que pueden ser encontrados por el algoritmo de estimación, reduciendo su tiempo de procesamiento. El método considera un rango de la constante de tiempo del generador sincrónico entre 4s y 10s, un índice de desempeño del sistema de control de excitación, una técnica de diseño de controladores y la estructura del modelo del sistema de control de excitación. Cuando se usa el espacio de búsqueda obtenido para estimar los parámetros, el algoritmo toma menos tiempo de procesamiento y los parámetros estimados son cercanos a los parámetros de referencia.

Palabras clave

Sistema de excitación; estimación de parámetros; espacio de búsqueda.

1. INTRODUCTION

Excitation control system (ECS) models are used to develop several power system analyses. The main influence over the results of power system stability studies is developed by the excitation control system models, which include the synchronous generator, the excitation system (EXS), and the supplementary control models. For that reason, accurate models of the excitation control system are required.

Modeling excitation control system consists of selecting a standard model, carrying out an experiment to acquire data, estimating the parameters of the model and validating the parameters and the selected model. In the parameter estimation stage it is necessary to choose an estimation algorithm and define a search space for each parameter of the ECS model. Normally the search space for each parameter is selected based on the experience of engineers that estimate the parameters, however there are not typical values for parameters in excitation systems due the several per unit system that can change the per unit value of a parameter depending on the selected per unit system. On the other hand, when there is not experience, the search space is selected larger than necessary. Large search space generates more solution parameter sets and also larger processing time than necessary.

When the parameters of an EXS will be estimated, it is necessary to know a range where the parameters could be in order to reduce the iterations of the estimation algorithm and therefore the search time developed by the estimation algorithm. This paper proposes a method to establish a parameter search space based on the time constant of the synchronous generator, a controller design technique, performance criteria for ECS, and its model structure.

2. METHODOLOGY

The range of values for each parameter of the excitation control system model is established. First the structure of the model that represents the excitation system has to be selected, and ECS

standard requirements have to be stated and associated with the model. Then, a typical or well-known controller design technique has to be used to get the parameters in a symbolic way. Finally, with the parameters equation, the range of the generator time constant, and the range of the damping ratio, the minimum and maximum range could be established.

2.1 Performance Criteria for Excitation Control System and Synchronous Generator Time Constant Range

In the IEEE 421.2-1990 performance indexes are presented in two tables (IEEE, 1990). In the first one, the accepted value of indexes that characterize a good feedback control system performance, and in the second one, the range of ECS small signal dynamics performance.

In this work, a damping ratio ρ between 0.6 and 1 is considered. This range is accepted as a good performance index in excitation control systems (IEEE, 1990). In addition, such a controller is designed to ensure a closed loop settling time ts_{CL} equal to the half of the open loop one ts_{OL} , improving the system dynamics (IEEE, 1990), therefore, if the settling time measurement corresponds to the 2% band as given in (1) (Mandal, 2006), where τ corresponds to the time constant of the system, the settling time of the ECS is given by (2). Consequently, the relation between the damping ratio ρ and the natural frequency ω_n is given by (3).

$$ts = 3,9 \cdot \tau; \tau = 1/\rho \cdot \omega_n \quad (1)$$

$$ts_{CL} = ts_{OL}/2 = 3,9 \cdot T'do/2 \quad (2)$$

$$\rho \cdot \omega_n = 2/T'do \quad (3)$$

The analysis considers synchronous generators with direct-axis transient time constant $T'do$ between 4s and 10s where the synchronous generators normally used by utilities are represented.

2.2 Excitation Control System Model and Control Design Technique

To obtain the range of the parameters, it is necessary to know the ECS model and select some control design technique. Two ECSs are discussed: the first one is a static excitation system in a single loop, and the second one is an ECS with a rotating exciter in a double loop.

2.2.1 Excitation control system with a single loop

The static excitation system, which can be considered as a modern excitation system, is represented by the model in Fig. 1. In this case the AVR is a PI controller. The static exciter is represented by a K gain, and its time constant is neglected because is several times shorter than the main dynamic of the system. The generator is represented by a first order system taking into account offline operation. Considering the gain of the exciter K in the AVR gain, the closed loop transfer function V_T/V_{REF} of the diagram observed in Fig. 1 is given by (4):

$$\frac{V_T}{V_{REF}} = \frac{K_{PA} \cdot s + K_{IA}}{T' do \cdot s^2 + (K_{PA} + 1) \cdot s + K_{IA}} \quad (4)$$

Using the zero-pole assignment technique (Mandal, 2006), the equations to obtain the search space of the parameters are given in (5) and (6):

$$(1/T' do) \cdot (1 + K_{PA}) = 2 \cdot \rho \cdot \omega_n \Rightarrow K_{PA} = 3 \quad (5)$$

$$(1/T' do) \cdot K_{IA} = \omega_n^2 \Rightarrow K_{IA} = 4 / (\rho^2 \cdot T' do) \quad (6)$$

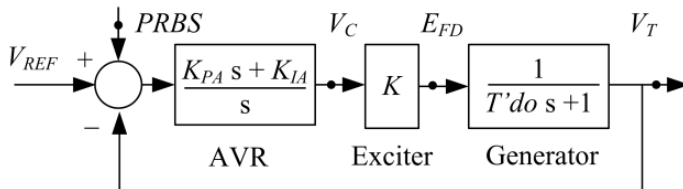


Fig. 1. Model structure of a modern ECS. Source: Authors

From (5) and (6), the range of $T'do$ between 4 s and 10 s, and the accepted range of ρ between 0.6 and 1, the search space of each parameter is established and presented in Table 1. In this particular case $K_{PA} = 3$; however, the method is intended to establish a search space of the parameter more than design the controller, for that reason a search space around K_{PA} value is established in Table 1.

Table 1. Parameter range of a modern ECS. Source: Authors

	K_{PA}	K_{IA}	$T'do$ (s)
Minimum	0,00	0,40	4,00
Maximum	6,00	2,77	10,00

2.2.2 Excitation control system with a double loop

Rotating exciters are present in dc and ac excitation systems (IEEE, 2006). A general block diagram of a rotating excitation system is presented in Fig. 2. There are two control loops, the inner loop regulates the field voltage of the generator and includes the field voltage regulator (FVR), which is a PI controller and the rotating exciter, which is represented with a first order system without the magnetic saturation representation. The outer loop regulates the generator terminal voltage, the AVR is a PI controller and the synchronous generator is also represented by a first order system. The time constant of the exciter T_e is usually 3 to 5 times shorter than the generator time constant, therefore $T_e = T'do/x$.

The closed loop transfer function of the inner loop is given by (7). Again, the zero-pole assignment technique is used to obtain (8) and (9) and consequently the feasible search space of the inner loop parameters.

$$\frac{E_{FD}}{V_R} = \frac{K_{PA} \cdot s + K_{IA}}{(T'do/x) \cdot s^2 + (K_{PA} + 1) \cdot s + K_{IA}} \quad (7)$$

$$(x/T'do) \cdot (1 + K_{PA}) = 2 \cdot \rho \cdot \omega_n \Rightarrow K_{PA} = 3 \quad (8)$$

$$(x/T'do) \cdot K_{IA} = \omega_n^2 \Rightarrow K_{IA} = (4 \cdot x) / (\rho^2 \cdot T'do) \quad (9)$$

To establish the search space of the outer loop, the closed loop transfer function of the inner loop and the generator transfer

function are assumed to be a first order system. This approximation is used to design controllers in double loop systems (Saa-vedra-Montes et al., 2012b). However in this case, this approximation is used only to establish the parameters search space of the outer loop. The closed loop transfer function of the outer loop is given by (10), and (11) and (12) are the equations derived from the zero-pole assignment technique.

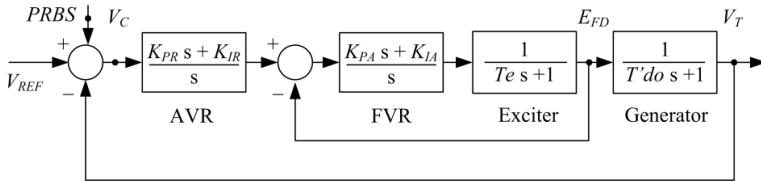


Fig. 2. Model structure of an ECS with a rotating exciter in a double loop. Source: Authors

$$\frac{V_T}{V_{REF}} = \frac{K_{PR} \cdot s + K_{IR}}{T'do \cdot s^2 + (K_{PR} + 1) \cdot s + K_{IR}} \tag{10}$$

$$(1/T'do) \cdot (1 + K_{PR}) = 2 \cdot \rho \cdot \omega_n \Rightarrow K_{PR} = 3 \tag{11}$$

$$(1/T'do) \cdot K_{IR} = \omega_n^2 \Rightarrow K_{IR} = 4/(\rho^2 \cdot T'do) \tag{12}$$

From (8), (9), (11), (12), and the direct axis time constant and damping ratio ranges, the parameters search space for an ECS with double loop is established and presented in Table 2. The exciter time constant is considered three times faster than generator time constant. For both loops, proportional gains are equal to 3; therefore a search space around this value is defined.

Table 2. Parameter range of an ECS with double loop. Source: Authors

	K_{PA}	K_{IA}	$T_e (s)$	K_{PR}	K_{IR}	$T'do(s)$
Minimum	0,00	1,20	1,33	0,00	0,4	4
Maximum	6,00	8,33	3,33	6,00	2,77	10

3. RESULTS AND DISCUSSION

To show the usefulness of selecting a parameter search space for the parameter estimation stage, an identification experiment is

simulated over the two ECS models presented in Section 2. Then, the registered data are used to estimate the parameters, first with an arbitrary search space for each parameter, and then with the recommended parameter search space presented in Tables 1 and 2.

3.1 Simulation of an Identification Experiment in a Modern ECS

To simulate the experiment, it is necessary to assume some parameters values in the ECS presented in Fig. 1. The generator has a direct axis time constant $T'do = 5$ s. The parameters of the AVR are the proportional gain $K_{PA} = 2$, and the integral gain $K_{IA} = 1.6$. The settling time of the ECS registered from the step response, presented in Fig. 3, is $ts_{CL} = 14.3$ s.

In Fig. 3 the closed and open loop step responses of a modern ECS are presented. The settling time for closed loop ts_{CL} , and open loop, ts_{OL} are measured taking into account the 2% band. The ts_{CL} is used to design a pseudo random binary sequence (PRBS) to excite the system dynamics during the identification experiment (Saavedra-Montes et al., 2012a). The PRBS design parameters, the time of the experiment, and the sampling period values are presented in Table 3. The PRBS is applied in the summing junction of Fig. 1, and PRBS, V_C , E_{FD} , and V_T signals were registered during the experiment simulation and are presented in Fig. 4. In order to allow a better visualization of the signals, only the interval time corresponding to one PRBS period are shown, i.e. the time of the experiment reported in Table 3 is 315.315 s, which corresponds to two PRBS periods, but only 157.6575 s are presented in Fig. 4.

3.2 Simulation of an Identification Experiment in an ECS with a Rotating Exciter

Some parameter values are assumed to simulate the ECS shown in Fig. 2. The direct axis time constant of the generator $T'do = 9$ s, the rotating exciter time constant $T_e = 2.5$ s; the parameters of the FRV are the proportional gain $K_{PR} = 5$, and the

integral gain $K_{IR} = 3.5$; the parameters of the AVR are the proportional gain $K_{PA} = 2.1$, the integral gain $K_{IA} = 0.65$. The settling time of the ECS with a rotating exciter is $t_{sCL} = 26.5s$. This settling time is used to design a perturbation signal that was applied in the first summing junction of the block diagram in Fig. 2 during an identification experiment. The experiment is simulated and PRBS, V_C , E_{FD} , and V_T signals were registered. The PRBS design parameters, the time of the experiment, and the sampling period are listed in Table 4.

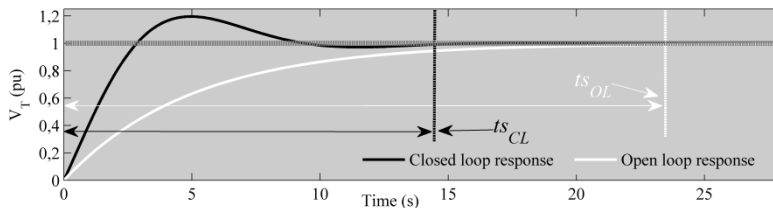


Fig. 3. Step response of a modern ECS. Source: Authors

Table 3. PRBS parameters, experiment time, and sampling period for the single loop ECS. Source: Authors

t_{sCL} (s)	N	T_{SW} (s)	M	T_{exp} (s)	T_m (s)
14,3	6	25,025	63	315,315	0,1

Table 4. PRSBS parameters, experiment time, and sampling period for the double loop ECS. Source: Authors

t_{sCL} (s)	N	T_{SW} (s)	M	T_{exp} (s)	T_m (s)
26,5	6	46,375	63	584,325	0,1

3.3 Parameter Estimation of the Excitation Control Systems

In Fig. 4 the registered signals during the identification experiment over the ECS with single loop are presented. However, only the PRBS and the V_T signals were used to estimate the parameters. Although in a previous work (Saavedra-Montes et al., 2011), E_{FD} has been used as output signal to estimate the excitation system parameters, in this case V_T is considered as output signal and therefore the direct axis time constant of the generator is also estimated. Methodologies that do not require internal signals of the ECS, e.g. V_C or E_{FD} , can be applied in excitation system with-

out access to those signals, extending the application range of the methodology. Once EXS input and output signals were registered, they were separated in estimation and validation data. Because the signals were registered from simulated experiments, i.e. without noise, only mean centering was developed to remove the dc components. The Levenverg Marquardt implementation of the nonlinear least square estimation algorithm was used to estimate the parameters.

In Table 5 the results to estimate the parameters of the ECS with a single loop using two different search spaces are shown. The first search space is an arbitrary one, where the minimum value for each parameter was 0, the maximum value was 1000, and the initial value was 1. The second search space was the one obtained in Section 2 and presented in Table 1. Table 5 includes the estimated parameters, the Error (%) between the estimated and the reference parameters, which was calculated with (13). Table 5 also includes the number of iterations, the processing time taken by the algorithm to estimate the parameters, and the normalized sum of squared errors (NSSE), which is an index error calculated with (14), where n is the number of data. The index is calculated between the estimated output signal and the output signal registered during the simulation of the identification experiment. The comparison of the signals is shown in Fig. 5.

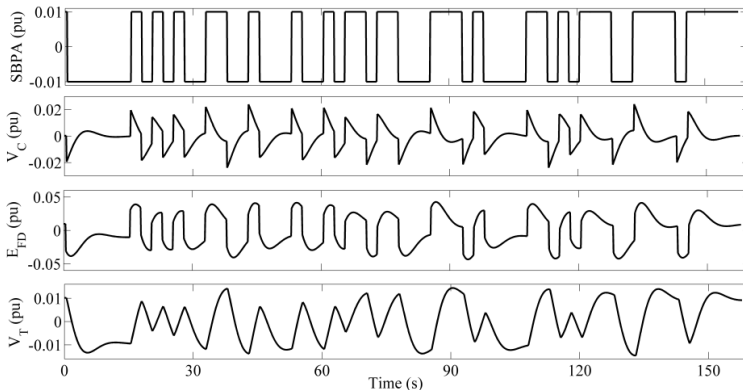


Fig. 4. Signals from the identification experiments for the ECS with single loop.
Source: Authors

$$\text{Error}(\%) = \frac{|\text{Estimated value} - \text{Reference value}|}{\text{Reference value}} \cdot 100 [\%] \quad (13)$$

$$\text{NSSE}(\%) = 100 \cdot \left(\sum_{i=1}^n (V_{Ti} - \widehat{V}_{Ti})^2 \right) / \left(\sum_{i=1}^n V_{Ti}^2 \right) [\%] \quad (14)$$

From results presented in Table 5, it is possible to see an improvement in the processing time when the search space established with the method proposed here is used; however the errors in the estimated parameters for both sets of parameters are very close. The Error (%) is always below 5.62%. The NSSE (%) was 1.442% for both set of parameters.

In Table 6 the parameter estimation results of the ECS with double loop using two different search spaces are shown. Again, in the first search space, the minimum value of each parameter was 0, the maximum value was 1000, and the initial value was 1. The second search space was presented in Table 2. When the search space obtained with the method proposed here, improvements in the processing time and the estimated parameter Error (%) are quite evident; however, when the estimated output signal and the output signal registered during the simulation of the identification experiment are compared, there is only a small difference between the NSSE (%). This situation illustrates the problem that arises when an arbitrary search space is used, because there are more parameter solution sets that can be found by the algorithm. Some parameter solution sets are far from the reference parameters. The consequences of that inaccuracy will be appear when the models are used with nonlinearities, and the internal signals of the ECS are different, generating a misunderstood behavior of the ECS.

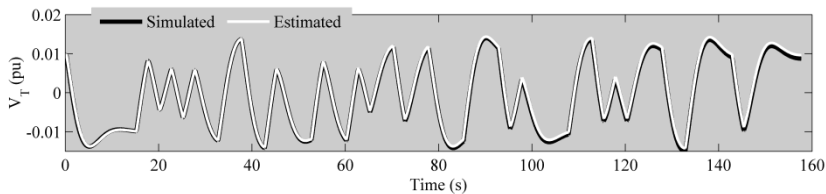


Fig. 5. Validation of a modern ECS model. Source: Authors

Table 5. Parameters of an ECS with single loop estimated with different search spaces. Source: Authors

	Search space values			Parameter values			P. T. (s)	NSSE (%)
	<i>Min</i>	<i>Max</i>	<i>Initial</i>	<i>Ref.</i>	<i>Est.</i>	<i>Error %</i>		
K_{PA}	0	1000	1	20,0	18,878	5,61	64,02	1,442
K_{IA}	0	1000	1	16,0	15,420	3,62		
$T'do (s)$	0	1000	1	50,0	47,823	4,35		
K_{PA}	0	6,00	3,000	20,0	18,906	5,47	54,53	1,442
K_{IA}	0,400	2,77	1,585	16,0	15,432	3,55		
$T'do (s)$	4,000	10,00	7,000	50,0	47,880	4,24		

Table 6. Parameters of an ECS with double loop estimated with different search spaces. Source: Authors.

	Search space values			Parameter values			P.T (s)	NSSE (%)
	<i>Min</i>	<i>Max</i>	<i>Initial</i>	<i>Ref.</i>	<i>Est.</i>	<i>Error %</i>		
K_{PA}	0	1000	1	50,0	26,168	47,66	820,31	1,008
K_{IA}	0	1000	1	35,0	0,5184	85,18		
$Te (s)$	0	1000	1	25,0	17,095	31,62		
K_{PR}	0	1000	1	21,0	26,909	28,13		
K_{IR}	0	1000	1	0,50	0,6389	27,78		
$T'do (s)$	0	1000	1	90,0	81,342	9,65	360,42	1,003
K_{PA}	0	6,000	3,000	50,0	47,050	5,90		
K_{IA}	1,200	8,333	4,766	35,0	37,615	7,47		
$Te (s)$	1,333	3,333	2,333	25,0	24,453	2,18		
K_{PR}	0	6,000	3,000	21,0	18,702	10,94		
K_{IR}	0,400	2,777	1,585	0,50	0,6219	24,38		
$T'do (s)$	4,000	10,000	7,000	90,0	82,664	8,15		

4. CONCLUSION

A method to obtain the search space for each parameter in an ECS was presented in this paper. The search space is intended to reduce the number of parameter solution sets that can be found by the estimation algorithm, reducing its processing time. The method considers a synchronous generator time constant range, ECS performance indexes, a controller design technique and the ECS model structure. The most relevant advantage to choose the search space with the proposed method appears in ECS with two loops, where the internal signals of the ECS are not available. The

average Error (%) of all estimated parameters when the search space was calculated with the method proposed here was 9.83%.

5. ACKNOWLEDGMENT

The authors acknowledge the doctoral scholarship 095-2005 from the Departamento Administrativo de Ciencia, Tecnología e Innovación (Colciencias), and the support by the Universidad Nacional de Colombia under the research projects IDENT-EXGEN and SMART-ALEN.

6. REFERENCES

- IEEE. (1990). IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems. IEEE Std 421.2-1990, 1–45.
- IEEE. (2006). IEEE Recommended Practice for Excitation System Models for Power System Stability Studies. IEEE Std 421.5-2005 (Revision of IEEE Std 421.5-1992), 1–85.
- Mandal, A. K. (2006). Introduction to control engineering modeling, analysis and design. New Age International.
- Saavedra-Montes, A. J., Ramirez-Scarpetta, J. M., & Malik, O. P. (2011). Methodology to estimate parameters of an excitation system based on experimental conditions. *Electric Power Systems Research*, 81(1), 170–176.
- Saavedra-Montes, A. J., Ramirez-Scarpetta, J. M., Ramos-Paja, C. A., & Malik, O. P. (2012a). Identification of excitation systems with the generator online. *Electric Power Systems Research*, 87, 1–9.
- Saavedra-Montes, A. J., Ramos-Paja, C. A., Orozco-Gutierrez, M. L., Cifuentes, W. A., Ramirez-Scarpetta, J. M. (2012b). Calculation of excitation system controllers to fulfill IEEE standard performance indexes. *Electric Power Systems Research*, 89, 196–203.