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Impact of Exciter Gain on the Transient Stability of an IEEE 9-bus System

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Abstract—The voltage at the terminals of a generator is regulated using an Automatic Voltage Regulator (AVR) and thus, this is an important component of a generation plant. Fast acting exciters are used in power systems to mitigate against non-oscillatory rotor angle instability. There is also need to understand the impact of the excitation system gain on transient stability. This paper investigates transient stability of the modified IEEE 3-generator 9-Bus system with different excitation system gains.

Load flow analysis is first done to ascertain the system steady state conditions. Thereafter, a three-phase fault is introduced on one of the transmission lines for 0.1 seconds and the generators' rotor angles analyzed. For better understanding of the role of the AVR, the simulations were first run with the generators on manual excitation control and later with AVR control.

The rotor angle stability was analyzed for the increased AVR exciter gain in the reference generator G1 and critical generator G2. The simulations were done using DIgSILENT PowerFactory. The results show the AVR introduces negative damping and large values of exciter gain constant lead to instability**.**

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Keywords— AVR, Exciter Gain, Transient Stability, rotor angle, speed deviation

I. INTRODUCTION

For electrical power to reach the final consumer, it moves through three systems namely, generation, transmission and distribution. The electrical power generation is dominated by the synchronous generators. However, there has been a deregulation of the power system to encourage efficiency and power connectivity. With the increase in interconnectivity, power systems have become largely meshed with different loads connected far and between. With the meshed grid, a fault in one section can affect the whole network adversely. Therefore, there is need to evaluate the transient stability when designing and assessing the operational security of a power system. This evaluation is vital to ensure that the system works continuously, even in the event of a fault [1]. Transient stability is the ability of the power system to remain stable after being subjected to a major disturbance. A fault in the system may cause the generators to lose synchronism, a catastrophic event, which would deteriorate the system stability and may lead to a cascading blackout. The large disturbance may be due to loss of load, generator or transmission line, large change in load or significant shift in the generator rotor angle. The disturbance may result in lower system voltages, reduced power transfer and increase in the power angle. If the system deterioration is unchecked, the generators will lose synchronism, leading to transient instability.

One of the ways to enhance the system stability is the application of excitation systems. Excitation systems supply exciter voltage to the synchronous generators. In addition, they control the field voltage and the field current in the armature windings. These controllers ensure that the reactive power limits of the generators are not exceeded. The excitation system comprises of transducers, controllers, exciters and limiters. Each of these components has parameters and depending on the selection, will affect the damping and synchronizing torque in the system, which in turn will affect the system stability.

Transient stability analysis of the power system has been studied extensively by many researchers and it has been shown that the AVR introduces negative damping in single machine infinite bus and multi machine systems as well. Sorrentos et al [2] evaluated the effect of control of generators and turbines on the system transient stability using excitation systems and speed governor and deduced that the transient stability of the system depended on the type of control system. Esmeraldo concluded in [3] that the introduction of the AVR and the governor had a positive impact on system stability of the multi machine system as compared to the system without regulators. The sole contribution of the exciter to the stability of the system was not considered in the above studies. The study in [4] deduced the effect of excitation power on the AVR of synchronous generators and was found to improve the transient stability of the Single Machine Infinite Bus. The dynamics of a multi machine system were not included in this case. Avik et al [5] studied the effects of the AVR in state space on the system stability and deduced that dynamic instability was introduced by the excitation. However, they recommended additional tuning of the regulator in order to achieve dynamic stability.

The introduction of exciter systems affects the dynamics of the different generators within a system, which contributes or degrades the system stability. Therefore, the impact of the excitation parameters should be studied to understand their

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influence on the system stability. The tuning of parameters of the AVR is a great potential for research in transient stability studies of multi machine systems. This is because tuning of the excitation gain parameter is able to influence the level of damping torque by the AVR, hence influencing the non-oscillatory system damping. The exciter gain is determined by the voltage deviation from the reference voltage.

In this study, the effect of the exciter gain parameter of the AVR on transient stability is evaluated. The paper is organized as follows. Section II gives a brief description of the AVR and its parameters. Section III presents the methodology whereas the simulation results and discussion are in section IV. The conclusions and recommendations for further work are given in section V.

II. AVR MODEL

A. *Elements of an excitation system*

The requirements of the excitation systems consider both the synchronous generator and the power system [6]. In the generator, the AVR is to adjust the field current in the windings automatically so that the terminal voltages are maintained. It should also be capable of rapid response to enhance transient stability in case of a fault.

The exciter provides DC power to the field winding of the synchronous generator. This is the power stage of the excitation system. The regulator processes and amplifies the input control signals to a level that they can be controlled. These functions are the regulating and stabilizing stages of the excitation system. The voltage transducer and load compensator detects the generator terminal voltage, rectifies and filters the signal into the DC component and compares it to the reference terminal voltage. The load compensator could be required to hold constant voltage at some point from the generator. The limiters and the protective circuits ensure that the capability limits of the exciter and generator are not exceeded.

B. *Types of the Excitation System*

The systems can be classified according to the power source used for excitation. These include DC excitation, AC excitation and static excitation systems [6].

DC excitation systems utilize the DC generator for power and provide power to the rotor of the synchronous generator through slip rings. The set of brushes are located 90 degrees apart, on the d axis and the other on the q axis. The AC excitation systems utilize alternators as the main sources of power. The exciter is on the same shaft as the turbine generator. The AC output of the rectifier is transformed to produce a field current that is needed for the field windings of the generator. The Static exciter supplies excitation current directly to the field windings through the slip rings. The AC excitation system was used in this research based on the model from the modified IEEE 9-bus system data. The figure 1 below shows the diagram of AVR IEEET1 with the transfer functions of the different components.

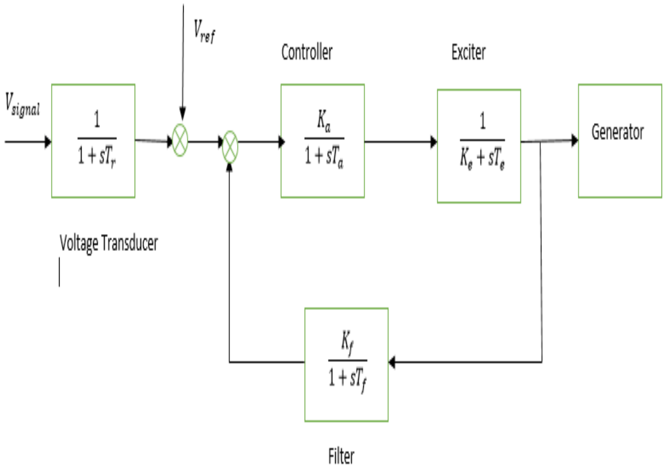

Fig. 1 Typical block diagram of an AVR

The voltage transducer has a time constant T_r in which the generator terminal voltage can be compared with the voltage reference. The difference between the voltages (error signal) is then transferred to the controller as input. The signal is enhanced by the gain K_a and transferred to the exciter. The exciter gain K_e propagates the signal, to affect the damping torque introduced in the power system. The filter stabilizes the signal through the stabilization gain K_f.

C. *Excitation System Performance*

The performance of the excitation system depends on the power system. Since the power system is nonlinear, it is critical to study the performance in large signal stability and small signal stability [6].

Large signal performance measures include excitation system ceiling voltage. It is indicative of the field supply capability of the system; high ceiling voltages tend to improve the system stability. The ceiling voltages is determined at rotating speed for the rotating exciters. The ceiling current may be based on the excitation thermal capacity during large perturbations. The excitation system voltage response time will affect the performance. An excitation system with a voltage response of 0.1 seconds or less indicates a high response and expeditious system.

D. *Mathematical modelling of the AVR*

From Fig. 1, the AVR receives terminal voltage from the generator. The generator terminal voltage can be expressed in complex terms

$$E_t = e_d + je_q \qquad (1)$$

Therefore, $$E_t^2 = e_d^2 + e_q^2 \qquad (2)$$

Applying a small disturbance, the new terminal voltage is written as

$$(E_{to} + \Delta E_t)^2 = (e_{d0} + \Delta e_d)^2 + \left(e_{q0} + \Delta e_q\right)^2 \qquad (3)$$

Neglecting the second order terms involving perturbed values, the above equation reduces to

$$E_{t0}\Delta E_t = e_{d0}\Delta e_d + e_{q0}\Delta e_q \quad . \qquad (4)$$

Therefore, $\Delta E_t = \frac{e_{d0}}{E_{to}}\Delta e_d + \frac{e_{q0}}{E_{to}}\Delta e_q$ (5)

Where the disturbance components are represented by

$$\Delta e_d = -R_a\Delta i_d + L_i\Delta i_q - \Delta\Psi_{aq} \qquad (6)$$

$$\Delta e_q = -R_a\Delta i_q - L_i\Delta i_d + \Delta\Psi_{ad} \qquad (7)$$

Where Δe_q *and* Δe_d are the disturbance components in the d and q axis respectively, R_a *and* L_i are the resistance and inductance of the generator armature windings respectively, $\Delta i_q, \Delta i_d$ *and* $\Delta\Psi_{aq}, \Delta\Psi_{ad}$ are the small changes in the armature current and flux on the d and q axis components respectively.

The above expressions of Δe_q *and* Δe_d yield into

$$\Delta E_t = K_5\Delta\delta + K_6\Delta\Psi_{fd} \qquad (8)$$

Where,

$$K_5 = \frac{e_{d0}}{E_{t0}}\left[-R_a m_1 + L_l n_1 + L_{aqs} n_1\right] + \frac{e_{q0}}{E_{to}}[-R_a n_1 - L_l m_1 - L'_{ads} m_1] \qquad (9)$$

$$K_6 = \frac{e_{d0}}{E_{t0}}\left[-R_a m_2 + L_l n_2 + L_{aqs} n_2\right] + \frac{e_{q0}}{E_{to}}\left[-R_a n_2 - L_l m_2 + L'_{ads}\left(\frac{1}{L_{fd}} - m_2\right)\right] \qquad (10)$$

The change in the field flux that is as a result of the AVR is given by

$$\Delta\Psi_{fd} = \frac{K_3}{1+sT_3}\left[-K_4\Delta\delta - \frac{G_{ex}(s)}{1+sT_R}\left(K_5\Delta\delta + K_6\Delta\Psi_{fd}\right)\right] \qquad (11)$$

Where K_3 *and* K_4 are the gains of the compensators in the excitation system, G_{ex} is the exciter gain and T_R *and* T_3 are the time responses of the transducer and the filter respectively.

By grouping the terms of $\Delta\Psi_{fd}$ together and rearranging, we obtain:

$$\Delta\Psi_{fd} = \frac{-K_3[K_4(1+sT_R)+K_5G_{ex}(s)]}{s^2T_3T_R+s(T_3+T_R)+1+K_3K_6G_{ex}(s)}\Delta\delta \qquad (12)$$

The change in the air gap torque due to change in field flux linkage is

$$\Delta T_e = K_2\Delta\Psi_{fd} \qquad (13)$$

Where K_2 is a constant of the air gap torque.

It should be noted that the constants K_2, K_3, K_4 *and* K_6 are usually positive. The constant K_5 may have either positive or negative values. Therefore the effect of the AVR on the synchronizing and damping torque of the system is affected byK_5 *and* $G_{ex}(s)$.

From figure 2, the voltage change from the output of the transducer is given by

$$\Delta v_1 = \frac{1}{1+\rho T_R}\Delta E_t. \qquad (14)$$

Rearranging the equations gives

$$\rho\Delta v_1 = \frac{1}{T_R}(\Delta E_t - \Delta v_1) \qquad (15)$$

Substituting the above equation with (8), gives

$$\rho\Delta v_1 = \frac{K_5}{T_R}\Delta\delta + \frac{K_6}{T_R}\Delta\Psi_{fd} - \frac{1}{T_R}\Delta v_1 \qquad (16)$$

Considering the exciter block as a constant $G_{ex}(s)$, the output of the exciter is

$$E_{fd} = G_{ex}\left(V_{ref} - v_1\right). \qquad (17)$$

From (17) a large gain will lead to a higher excitation field voltage and the change in flux will increase. From (12), when the G_{ex} is small and the constant K_5 is positive, a positive damping torque component is introduced in the power system. Negative damping will be introduced if the conditions are reversed.

III. METHODOLOGY

A. *System under study*

The modified IEEE 9-Bus system shown in Fig. 2 was used as the case study [7].

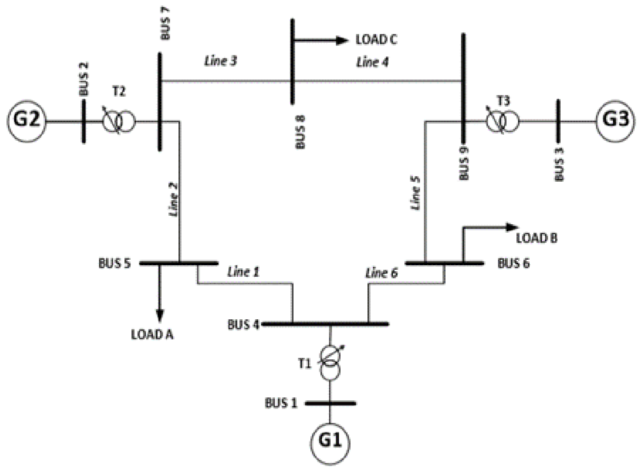

Fig. 2 IEEE 9 Bus system

The system data are given in the appendix. Bus1 is the slack/swing bus and is maintained at 1.04∠0° pu whereas buses 2 and 3 are PV buses maintained at 163MW and 1.025pu, 85MW and 1.025pu, respectively. The real power output of the generators are 71.6MW, 163MW, and 85MW for G1, G2, and G3, respectively and the active and reactive power consumed by the loads A, B and C is 125MW, 90MW, 100MW and 50MVAr, 30MVAr, 35MVAr respectively.

B. *Load Flow Analysis*

The analysis of transient stability requires the information about the system in steady state condition, which includes the pre-fault values. Key among the requirements is the voltage magnitude and phase angle at each bus bar, the transmission line power flow and losses, the generator bus power flow among others. Using load flow analysis, the pre fault conditions are obtained using Newton Raphson method.

C. *Test Scenarios*

A three-phase fault was introduced at 1 second on transmission line 5-7, which has the highest power transfer in the system. The fault was located at a distance 30% along the line from bus 7, near G2, which is dispatching the highest power in the system. The fault was cleared after 100 milliseconds by opening the circuit breakers at both ends of the line. The simulations were run in different scenarios in order to understand the effect of the excitation on the synchronous machine dynamics and study the transient changes in the machines with the change in the excitation gain. Time domain simulations were run for three excitation control scenarios: (i) manual (without AVR) (ii) AVR with exciter gains given in the modified system data (iii) AVR with G1, G2, and G3 exciter gains increased to 3. The analysis of the excitation systems was done for the reference generator G1 and the critical generator G2. For each scenario, the rotor angle response of each generator was analyzed. The Critical Clearing Time (CCT) of the generator most affected by the disturbance was noted.

IV. SIMULATION RESULTS

A. *Synchronous generators under manual excitation control*

The analysis of the rotor angle and the speed deviation was taken accordingly.

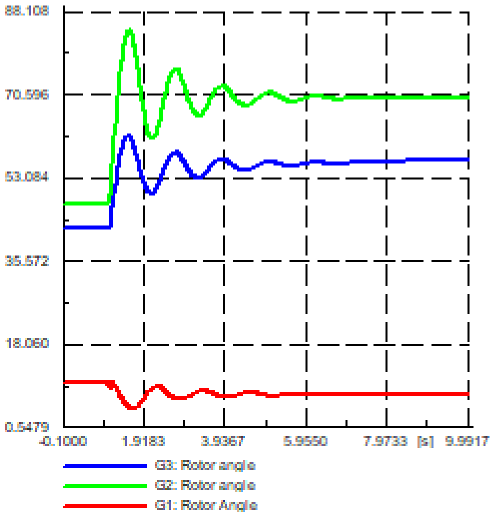

Fig. 3 Rotor angle response - manual excitation control

Fig. 3 shows the increase of rotor angles for the three generators after fault initiation at 1 second. The rotor angle of the generators increases after the fault occurs. There is an overshoot which varies for each generator but the settling time is achieved at 7.5 seconds; all the three generators remain stable. The overshoot is different for the three generators because they are located at different distances from the fault. Generator G2, which is the closest to the fault, records the highest overshoot whereas G1 which is the furthest from the fault remains relatively stable in terms of the overshoot and the settling time. In addition, the pre-fault rotor angle for G1 is small and hence, it is impacted less by the fault.

B. *Synchronous generators with AVR*

This scenario involves the simulation of the system with the AVR installed in each synchronous generator. The rotor angle and speed deviation responses are observed.

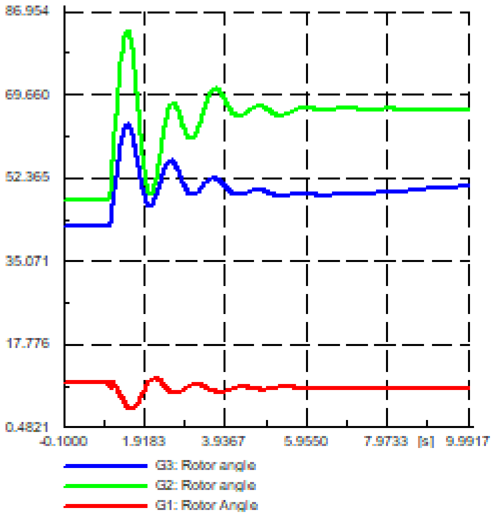

Fig. 4 Rotor angle response-AVR control

The Fig. 4 shows that the overshoot and the rise time of the rotor angle reduces during the fault. The settling time is achieved at 5.8 seconds. The rotor angle oscillations largely affect the generators G2 and G3 whereas G1 remains relatively stable.

C. *Comparison of the rotor angle response for different excitation systems.*

In this scenario, the AVR exciter gain in G1 is increased as the parameters of the other machines are held constant. The simulated results are as shown below

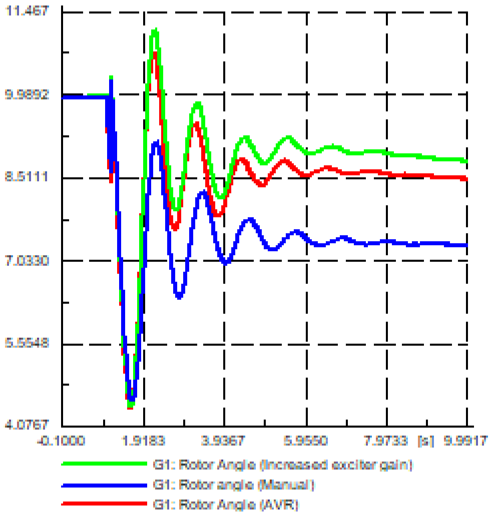

Fig. 5 Rotor angle response-Comparison of excitation in G1

The Fig. 5 represents the system response for the rotor angle for different excitation systems in G1. The overshoot in the rotor angle is greater in the AVR excitation as compared to the manual excitation. With increasing exciter gain to 3, the oscillations increase as well.

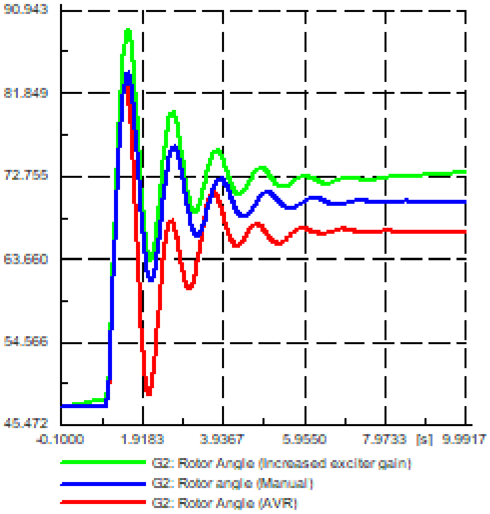

Fig. 6 Rotor angle response- Comparison of excitation in G2

The Fig. 6 represent the comparison of the system response in different excitation systems for the generator G2. Its exciter gain is increased to 3 while keeping the others constant. The overshoot in angular oscillation increases as the AVR exciter gain increases. This indicates that the system takes longer to attain stability with increasing exciter gain.

From the figures 5 and 6, the AVR, will introduce negative damping and higher overshoot as compared to the system under manual excitation. The overshoot in the oscillations increase with increasing exciter gain and the system takes long to achieve stability. For the scenario, where the AVR gain of all the generators was maintained at the given system value, the AVR introduced negative damping of the oscillations and the settling time was reduced. As a result, the system stability was improved.

Thus, a low AVR gain results into shorter settling time to the power system, which enhances stability whereas a high AVR gain increases the oscillatory overshoot, which reduces stability. A high AVR gain on the critical generator or the reference generator adversely affects the stability of the system.

V. CONCLUSION AND FURTHER RECOMMENDATIONS

In this paper, the impact of the exciter gain constant on the transient stability of the system has been studied. The time domain simulations of the systems with manual excitation and the AVR have been studied and compared.

In this study, it has been deduced that the magnitude of the exciter gain constant can affect the level of damping torque the AVR supplies to the power system, thus affecting the stability. It has also been shown that the AVR reduces the damping thus, negatively affecting the transient stability of the system.

A low exciter gain improves transient stability whereas a high gain reduces the stability. If the high gain is applied in the critical generator or the reference generator, the system losses stability immediately after the fault.

. However, with the variation of the exciter gain, other excitation parameters are affected as well, which could affect the response time, overshoot and settling time of the system stability. Thus, there is need to research further on the aspects of negative gain in the excitation systems and the evaluation of the upgrade of the excitation system parameters to enhance transient stability.

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APPENDIX

Modified IEEE 9-bus system data

The network values in per unit form are to the common base of 250MVA and 230kV to the high voltage of the transformer.

Generator Data

Type	**G1**	**G2**	**G3**
Nominal Power (MVA)	512	270	125
Nominal Voltage (L-L)	24	18	15.5
X_d (pu)	1.7	1.7	1.22
X'_d (pu)	0.27	0.256	0.174
X''_d (pu)	0.2	0.185	0.134
T'_{do} (s)	3.8	4.8	8.97
T''_{do} (s)	0.01	0.01	0.033
X_q (pu)	1.65	1.62	1.16
X'_q (pu)	0.47	0.245	0.25
X''_q (pu)	0.2	0.185	0.134
T'_{qo} (s)	0.48	0.5	0.5
T''_{q0} (s)	0.0007	0.0007	0.07
R_a (pu)	0.004	0.0016	0.004
X_L (pu)	0.16	0.155	0.0078
H (s)	2.6312	4.1296	4.768

Load Data

Item	**Load**	**Active Power (MW)**	**Reactive power (MVar)**
1	A	125	50
2	B	90	30
3	C	100	35

System Operating Conditions

Item	**Parameter**	**G1**	**G2**	**G3**
1	Active Power (MW)	71.6	163	85
2	Reactive Power (MVar)	27	6.7	-10.9
3	Voltage (pu)	1.04	1.025	1.025
4	Power angle (°)	0	9.3	4.7

Transmission line data (The lines are assumed to be 1km long)

Item	**Line Section**	**Resistance (Ω/km)**	**Reactance (Ω/km)**	**Susceptance (µ/km)**
1	4-5	5.29	44.965	332.7
2	4-6	8.993	48.668	298.69
3	5-7	16.928	85.169	578.45
4	7-8	4.4965	38.088	281.66
5	8-9	6.2951	53.3232	395.08
6	6-9	20.631	89.93	676.75

Transformer data

Item	**Parameter**	**T_1**	**T_2**	**T_3**
1	Rated MVA	250	200	150
2	Rated kV	16.5/230	18/230	13.8/230
3	Positive sequence reactance (pu)	0.144	0.125	0.0879
4	Positive sequence resistance (pu)	0	0	0

Exciter Data

Type	**G1 (IEEET1)**	**G2 (IEEET1)**	**G3 (IEEET1)**
Rated Power (MVA)	512	270	125
T_r (s)	0.000	0.000	0.060
K_a (pu)	200	30	25
T_a (s)	0.395	0.400	0.200
V_{Rmax} (pu)	3.840	4.590	1.000
V_{Rmin} (pu)	-3.840	-4.590	-1.000
K_e (pu)	1.000	-0.020	-0.0601
T_e (s)	0.000	0.560	0.6758
K_f (pu)	0.0635	0.050	0.108
T_f (s)	1.000	1.300	0.350
E_1 (pu)	2.880	2.5875	2.4975
SE (E_1)	0.000	0.7298	0.0949
E_2 (pu)	3.840	3.450	3.330
SE (E_2)	0.000	1.3496	0.37026