International Review on Modelling and Simulations (I.RE.MO.S.), Vol. 4, N. 2
April 2011

Tuning of Over and Under Excitation System Limiters of Synchronous Generator and Studying of its Effects on Power System Voltage Stability

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Abstract – *Excitation system of synchronous generator can help to an effective voltage control and power system stability support. In fact, for the stability improvement, this excitation system should be able to apply proper input voltage to the generator field winding. In this paper limiters and protective circuits of generator excitation system are explained. Two important types of these limiters are over and under excitation ones. The over-excitation limiter protects the generator against over-temperature caused by high field current for long time. Under-excitation limiter prevents the decrease of generator field current to the values lower than the stability margin or the thermal limit of end side of the stator core. Various models of the over and under excitation limiters have been presented in the literature. Tuning these limiters can be performed in different ways by considering the generator's capability curves. The limiter models and their parameters tuning affect voltage stability straightly. In this research, after implementation the proper model for our case study, the tuning of limiters is obtained by analyzing well known voltage stability methods. Some simulations have been done in Matlab/Simulink to analyze the effect of the selected model and tuned limiters on voltage stability both in single and multi-machines system. Also the dynamic parameters of a real system (Bistun power plant) are used as the case study. The results issued from this study are also discussed and validate the simulations.*

***Keywords**: Excitation System, Voltage Stability, Synchronous Generator, Over Excitation Limiter, Under Excitation Limiter*

I. Introduction

The main task of excitation system is to provide the direct current of field winding in the synchronous machine as well as control and protection task by voltage excitation controlling (excitation current result), which is important in proper function of a system. In order to ensure maximum usage of the excitation system, the system must be compatible in loading the proper and comprehensive short-term capabilities of the generator and with no deviance permitted limits, provide the system requirements [1].

Therefore, this paper studies the effect of over and under excitation limiters tuning of synchronous generator excitation control system in power system. This article shows that how the tuning of these limiters causes voltage instability in power system. Bistun power plant parameters are used as a case study. In the second part the over and under excitation limiters have been clarified. In the third part, the effect of over and under excitation limiters tuning on voltage stability has been studied by simulating the single and two-machines systems.

In the fourth part, the effect of over and under excitation limiters tuning on voltage stability has been perused using dynamic parameters of a generator in Bistun power plant of Kermanshah, Iran and in the fifth part the results of study are presented.

II. Over and Under Excitation Limiters

Limiters in control system, guarantee the generator function according to its physical limits. These limiters are determined by generator capability chart and other conditions affecting its functions. The most important limiters used in excitation system are: under excitation current limiter, Stator current limiter, voltage to frequency limiter, over excitation current limiter. Generator capability curve shows the power delivery ability by generator and turbine, according to the standard conditions and natural limits considered for generator and turbine. Siemens (115/41 TLRI) generator capability curve is shown in Fig. 1.

Manuscript received and revised March 2011, accepted April 2011

II.1. Over Excitation Limiter

The purpose of over-excitation limiter is to protect the generator against over-temperature caused by high field current for long time. The generator excitation windings are designed so that they work continuously in nominal load conditions. According to the ANSI c 50/13 standard (1977), thermal permitted overload of cylindrical rotor generator's excitation winding is calculated by standard curve. Designing the limiter is done with the help of points passing through curve and actually over excitation limiter is coordinated with excitation heat capability. There is a sample of this coordination in Fig. 2 [1], [7], and [5].

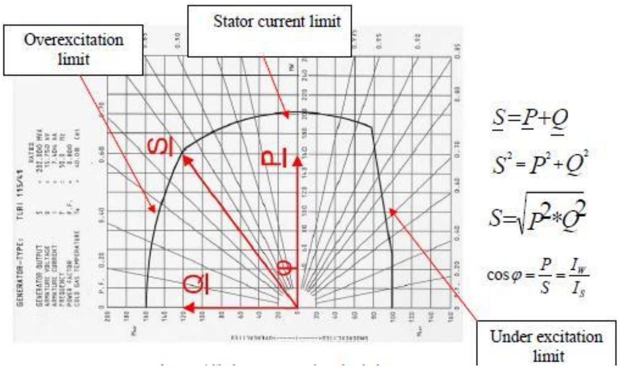

Fig. 1. Siemens (115/41 TLRI) generator capability curve

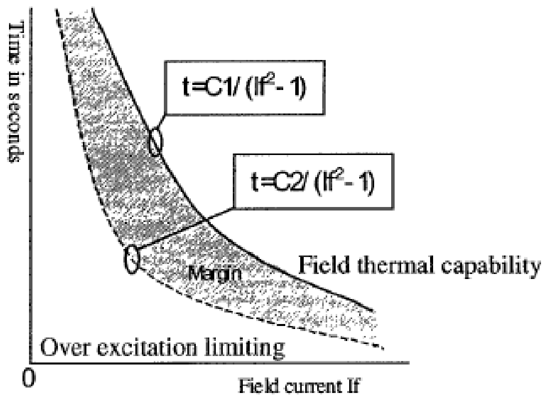

Fig. 2. Coordination of over excitation limiter with excitation heat capability

This limiter usually works when voltage reduces because of short-circuit fault in generator output excitation system and its voltage controller increase the excitation current to recovery this voltage reduction [1],[11].

II.2. Under Excitation Limiter

The aim of under excitation limiter is to prevent the decrease of generator field current to the values lower than the stability margin or the thermal limit of end side of the stator core. This limiter's control signal is provided by a combination of voltage and current or active and reactive power. Tuning is done based on system stability observation or stator core heating limit. Moreover, limiter function should be coordinated with protective function that controls generator no-excitation. When it is time to tune under excitation limiter, the limiter controls total excitation system until the signal reaches to the below of its tuning limit. Figure 3 shows the way in which limiter with small signal stability limit and no-excitation relay coordinate with each other.

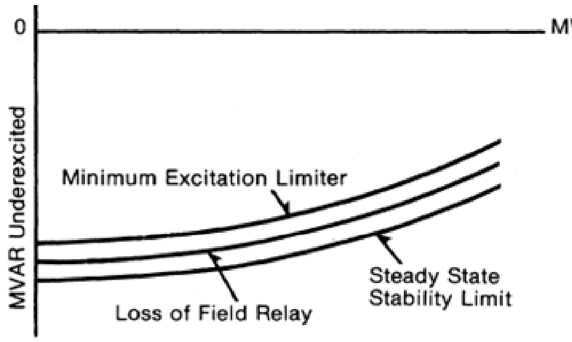

Fig. 3. The way in which limiter with small signal stability limit and no-excitation relay coordinate with each other

III. Effect of Over and Under Excitation Limiter Tuning on Voltage Stability

In the first part, a single machine system without any additional control devices such as PSS has been studied. In this part by the use of relevant research on analysis of effect of tuning on stability issue, p-v and p-Q curves are used as a tool for analysis. In this part and next, the effect of limiter tuning on voltage stability will be analyzed in detailed modeling of limiters and simulating different systems. The proper model is selected between various models presented for limiters in different articles and has been implemented. The criterion of model selection for limiter is to cover most generator capacity limitation in over and under excitation parts. For simulating, initial typical values are required for all parameters which are available in resources in selective models.

In presented simulation done in Matlab/Simulink, intended parameters for tuning are as follows: for over-excitation limiter, the upper limit is the mentioned parameter which is the most amount of limit current in i_{fd}-t coordinates which is displayed by i_{flm}, and the other parameter for the under excitation limiter is its radius in p-q coordinates which is shown by k_r. in Fig. 4, the implemented model in Matlab/Simulink for over excitation limiter is shown. In Fig. 5, performance condition for over excitation limiter and intended parameter for tuning is displayed. Figure 6 shows the implemented model in Matlab/Simulink for under excitation limiter and Fig. 7 brows performance condition for under excitation limiter and intended parameter for tuning.

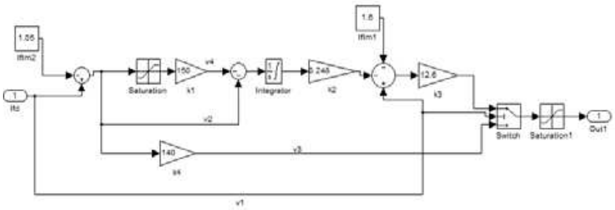

Fig. 4. Implemented model in Matlab/Simulink for over excitation limiter

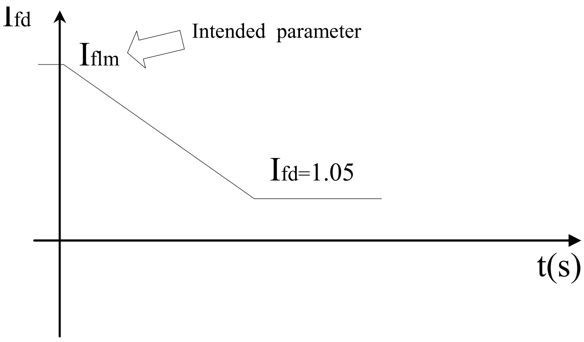

Fig. 5. Performance condition for over excitation limiter and intended parameter for tuning

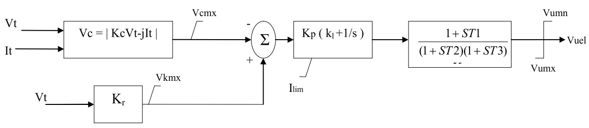

Fig. 6. Implemented model in Matlab/Simulink for under excitation limiter

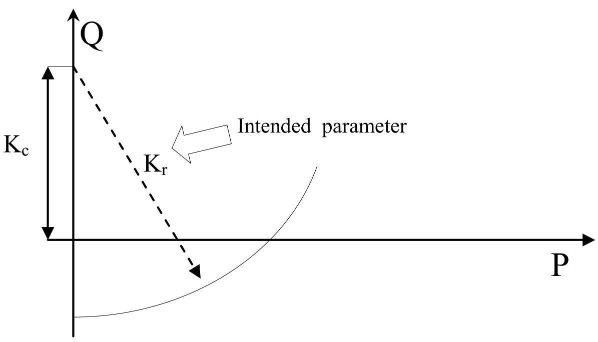

Fig. 7. Performance condition for over excitation limiter and intended parameter for tuning

III.1. Single Machine System

System studied in this part includes a generator, a circuit breaker and a transformer with a transmission line that is modeled by π model and two sets of loads (RLC and Capacitive) which have been shown in Fig. 8.

III.1.1. Over Excitation Limiter Analysis

The power system in Fig. 8 may work in two states: 1-normal working conditions that AVR tunes terminal voltage in proper amount, 2- Field current (I_f) is limited to protect additional heat of field winding.

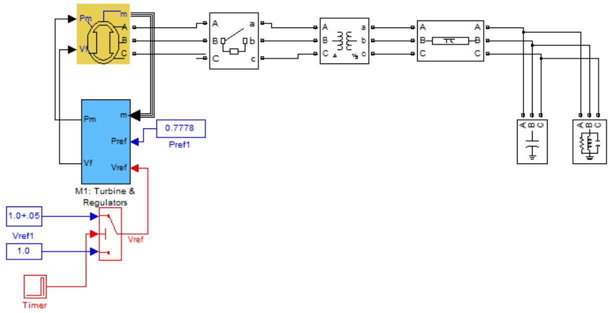

Fig. 8. Single machine system implemented in Matlab/Simulink

In this case, the *E* internal voltage is stable and there isn't any voltage tuning. These two cases are shown in Fig. 9. In this figure, it is necessary to change the active power in fixed-reactive power bus to reach p-v curve [8].

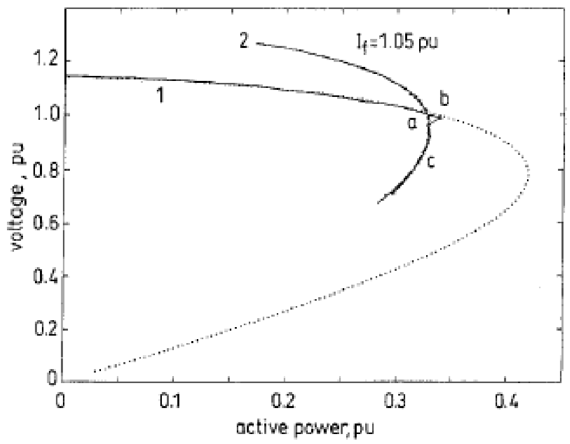

Fig. 9. Two states for generator

Curve number 1 is a p-v curve in normal working condition that AVR tunes terminal voltage in proper amount, and the curve number 2 is related to the case in which the limiter is active. As it is clear in both curves, increasing the active power to a certain extent, the system voltage drops and eventually will be instable. The amount of the active power in this action depends on whether is there any over excitation limiter in the system and the other point is how the over excitation limiter parameter tuning (I_{flm}) is done. In order to tune the parameter in over excitation limiter, I_{flm} should be changed and simulation should be done in different cases.

The amount of active power defining instability boundary is specified in different amount of I_{flm}. The results are expressed as figure and tables for proper analysis. Generator exterior power is 400MVA and assumes the load power is stable. At first I_{flm} has been initiated 1.4 and simulation has been done. When the simulation was started, the circuit breaker will be closed after 3 seconds and load will be connected to the system. For powers of 220,240,200,260 MW for load, the amount of output generator voltage is the same as Fig. 10.

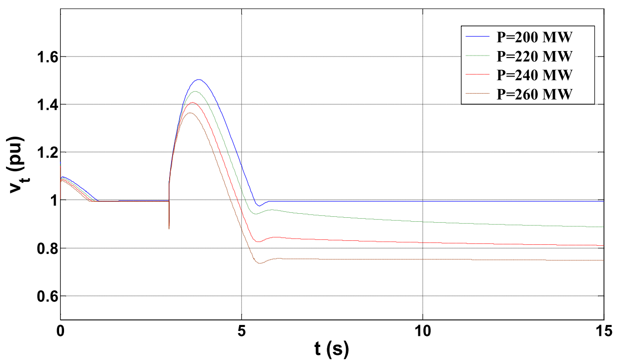

Fig. 10. The amount of output generator voltage for various active power

In simulation with active power at 270 MW, the system reaches instability point and the result wouldn't be converged. Therefore, instability boundary for over excitation limiter at I_{flm}=1.4 is equal to 270 MW. The results are gathered in Table I.

TABLE I
SIMULATION RESULTS FOR ACTIVE POWER & I_{FLM}=1.4

active power	200	220	240	250	260	270
I_{flm}	1.4	1.4	1.4	1.4	1.4	1.4
amount of voltage	0.98	0.89	0.82	0.79	0.72	instability

Amount of instability boundary changes would be specified by changing amount of I_{flm}. In new case increase the I_{flm} about 5% and change the active power. The results are given in Table II.

TABLE II
SIMULATION RESULTS FOR ACTIVE POWER & IFLM=1.45

active power	200	220	240	260	280	300
I_{flm}	1.45	1.45	1.45	1.45	1.45	1.45
amount of voltage	0.98	0.89	0.82	0.76	0.70	instability

Increasing I_{flm} results in increasing the amount of active power which could be transmitted in stability state and the instability boundary reaches to 300MW. Now, amount of I_{flm} reaches to 1.35 and simulation is repeated. The results are shown in Table III.

Reducing I_{flm} leads to decreasing the amount of instability boundary to 250MW. In Tables I, II and III, voltage amount means the value of generator's output voltage. Effect of tuning of over excitation limiter parameter on stability (P-V curve) is summarized in Fig. 11 according to what was analyzed. In all these discussions, the main factor to be considered is the amount of steady state.

TABLE III
SIMULATION RESULTS FOR ACTIVE POWER & IFLM=1.35

active power	200	210	220	230	240	250
I_{flm}	1.35	1.35	1.35	1.35	1.35	1.35
Amount of voltage	0.98	0.93	0.89	0.85	0.82	instability

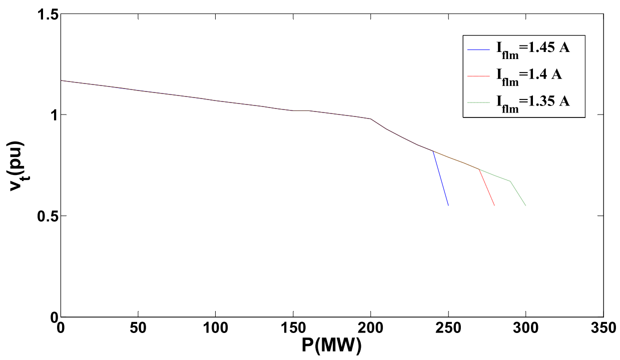

Fig. 11. Effect of tuning of over excitation limiter parameter on stability (P-V curve)

III.1.2. Under Excitation Limiter Analysis

P-Q chart is used to analyze the stability and its boundary – according to the under excitation limiter selective model-. Figure 12 shows the stability boundary of an under excitation limiter in P-Q coordinates [6],[10].

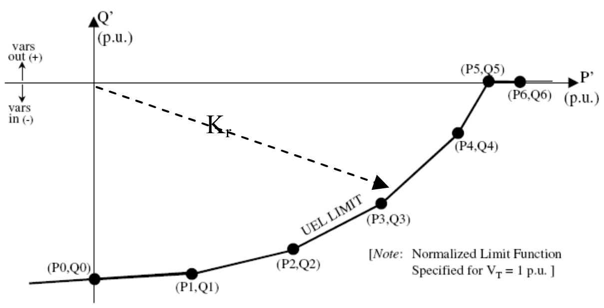

Fig. 12. The stability boundary of a under excitation limiter in P-Q coordinates

The more limiter's radius, the more area will be covered. k_r is the limiter's radius in the model and it is expected that changes in its value causes some changes in system stability.

In Figure 8, system's parameters have been tuned and simulation is done. The purpose is to identify the (p,q) points placing in or out of stability area or on boundary by different k_r. In simulation, at first k_r is equal to 4 and active power is 200MW. Changing the capacitive load's reactive power and increasing it with constant k_r, the simulation of area will be given.

Simulation results (amount of output voltage, output active power (p_{eo}), generator output reactive power (Q_{eo})) at k_r=4 are given in two states (stable and unstable) in Figures 13, 14, 15 and then they are listed in Table IV.

According to the Table IV and Figures 13, 14, 15 at k_r=4 and constant active power 200MW for load, the amount of reactive power equals to 200 MVAr for capacitive load has been determined as a boundary that destabilize the system. Because of the amount of voltage parameters, output active and reactive power get down to zero.

TABLE IV
SIMULATION RESULTS (FOR ACTIVE POWER 200 MW)

reactive power for load	20	60	100	150	190	200
k_r	4	4	4	4	4	4
Q_{eo}	0.25	0.33	0.45	0.60	0.73	0.00
p_{eo}	0.55	0.57	0.60	0.63	0.66	0.00

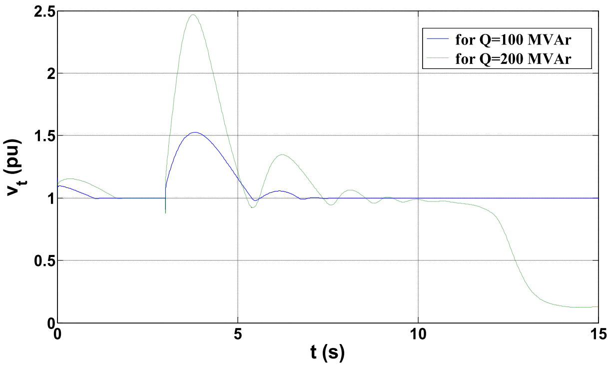

Fig. 13. Amount of output voltage in two states (stable and unstable)

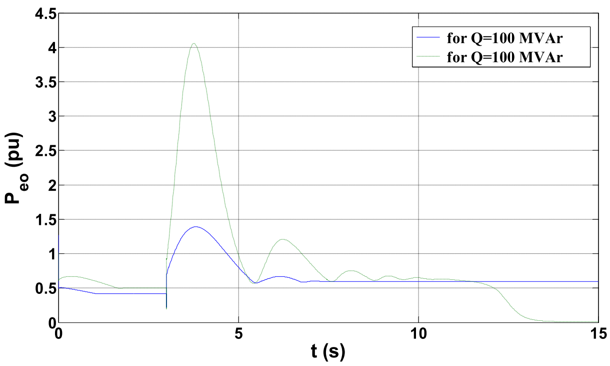

Fig. 14. Output active power (P_{eo}) in two states (stable and unstable)

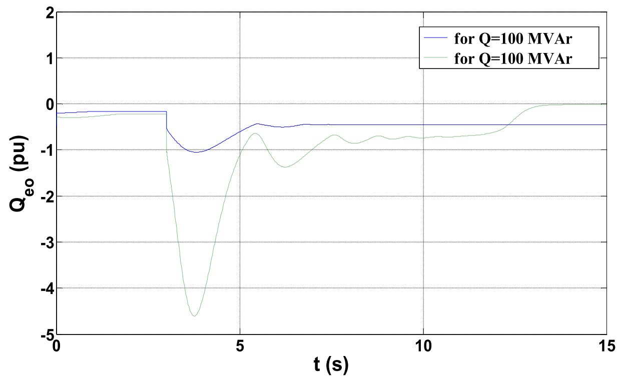

Fig. 15. Output reactive power (Qeo) in two states (stable and unstable)

Increasing active power to 250MW, leads to increasing the reactive power's instability to 170 MVAr. Boundary points reminisced in Figure 12 obtained like this and it is possible to obtain other points. Table V shows results of new state (250MW active power).

TABLE V
SIMULATION RESULTS (FOR ACTIVE POWER 250 MW)

reactive power for load	160	170	180
k_r	4	4	4
Q_{eo}	0.60	0.00	0.00
p_{eo}	0.80	0.00	0.00

Changing the amount of limiter radius (k_r), its role in the stability range will be obtained, like simulation in beginning, the amount of parameters considered, doing the simulation by k_r=6 until reaching to boundary points in new state. In 200MW active power, amount of 200 MVAr reactive power bordered on stability boundary means the stability area is increased.

It is also observed in simulation at k_r=6, 250MW of active power, 170 MVAr capacitive load, the system is stable and this point added to stability area. Thus the role of under excitation limiter radius parameter (k_r) is specified in changing stability area by above simulation.

The point (P=200, Q=200) with k_r=6 is stable and with k_r=4 is unstable. The point (P=250, Q=170) with k_r=6 is stable and with k_r=4 is unstable.

III.2. Two Machines System

The system given in Figure 16 has 2 generators and 2 excitation systems that in one of them (generator1) the implemented models are used. In this part, through changing parameters of over and under excitation limiter in generator1, the stability condition is studied.

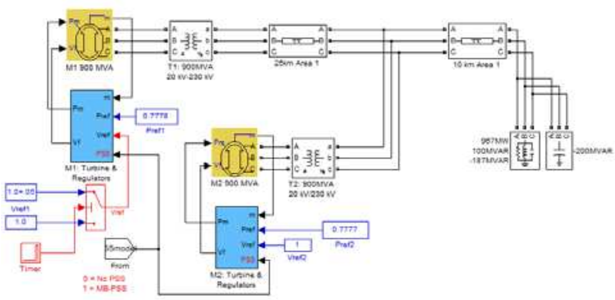

Fig. 16. Two machines system

III.2.1. Over Excitation Limiter's Function Analysis

According to what was explained in the single machine system, in this part the result of simulation is compared by changing the amount of I_{flm}.

In these parts if I_{flm} has such value that by considering required power, the system fails to keep the voltage in the proper range, the voltage drops and if this loss is severe the system will be collapsed. In the first part by considering nominal power system and at I_{flm}=2.8, output voltage of generator1 is in appropriate area without stable drop. I_{flm} has gradually been brought down in generator1 and output voltage of generator1 and its stability state is observed. Simulation results for different I_{flm} are given in Figure 17. The results show that at

I_{flm}=2.5, system is still stable and voltage decreases negligibly (about 3%). This shows that the excitation system continues to provide desired current to maintain the voltage in desired area and system stability.

In next part, I_{flm}=2.2 will be considered and simulation will be repeated. It can be seen that the output voltage of generator1 has a 10% downfall which means by this amount for I_{flm}, excitation winding current limits in certain extent and output voltage can't reach to 1p.u. However, the system is still stable, but results in Figure 17 show that at I_{flm}=2, excitation winding cannot provide required current and system has severe decrease in voltage and get unstable. According to the previous clarified subject, from amount of 2 and lower due to severe drop of voltage and lack of required current by winding, system excitation will be unstable.

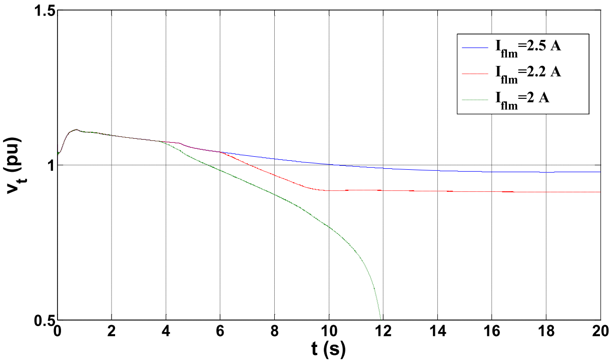

Fig. 17. Simulation results for, I_{flm}=2.5, I_{flm}=2.2, I_{flm}=2

III.2.2. Under Excitation Limiter's Function Analysis

Returned to Figure 16 one more time and do a new analysis. In this part changing under excitation limiter's radius, result of simulation is compared as Figure 18.

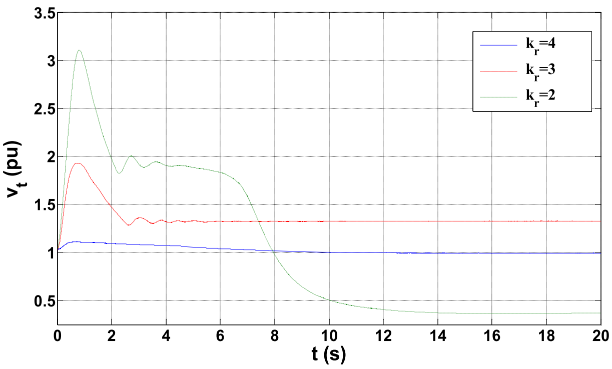

Fig. 18. Amount of outage voltage for k_r=2, k_r=3, k_r=4

In the first simulation with k_r=4, it is observed that voltage and frequency are in their nominal area and system continues it's function in stable state. In next part k_r is reduced to 3 and simulation has been repeated. With reduced radius, generator1 can't completely receive reactive power produced in system and this issue caused increasing of voltage in generator1 and somehow in generator2. but, in spite of additional voltage, the system permanently continues to work. In step 3, limiter's radius kr is reduced to 2 and simulation is being repeated. According to Figure 18, according to low limiter's radius, system's additional voltage rises and after transient state gets unstable.

IV. Case Study: Bistun Power Plant

In this section, simulation of limiter models has been done by generator's real parameter in Bistun power plant (Kermanshah, Iran), and the results are analyzed. Bistun power plant is located in the west of IRAN with 3 units, each of them has 400 MVA nominal power with *PF*=0.8 [3], [4].

IV.1. Limiter Models Simulation in Bistun

The Bistun power plant has been simulated which is shown in Figure 19. In this system, parameters of the generators and excitation system are placed according to power plant dynamic information obtained. In generator1, over and under excitation limiter are used in this report but not about generator2.

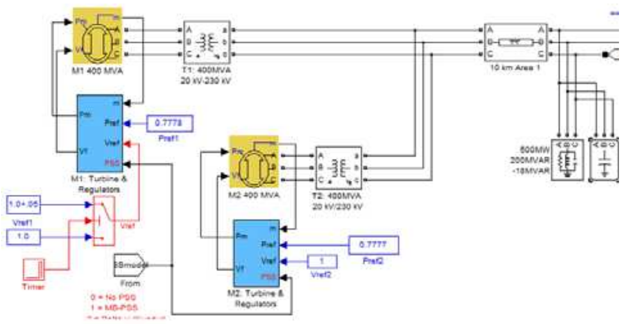

Fig. 19. Simulated system of Bistun power plant

IV.1.1. Over Excitation Limiter Analysis

Regarding to what is in excitation system of Bistun power plant, parameter's conditions are investigated. Amount of output voltage of generator1 on which limiter models are placed is shown in simulation results, first simulation was done with I_{flm}=2.5 and second one was performed using I_{flm}=1.5 and results are the same as Figure 20.

In steady state, noticing to proper upper limit of excitation in I_{flm}=2.5, required current is provided and voltage is in proper area for both two generators (about 1 p.u.). When upper limit in generator1 is reduced to I_{flm}=1.5, decreasing of output voltage in generator1 takes place and it reaches to 0.8 p.u. but output voltage of generator2 is stable. Considering the over excitation limiter restricts the field current level of generator1, flux is not enough for keeping voltage in 1 p.u. level, and due to the issue that there is not the same in generator2, output is in desirable range.

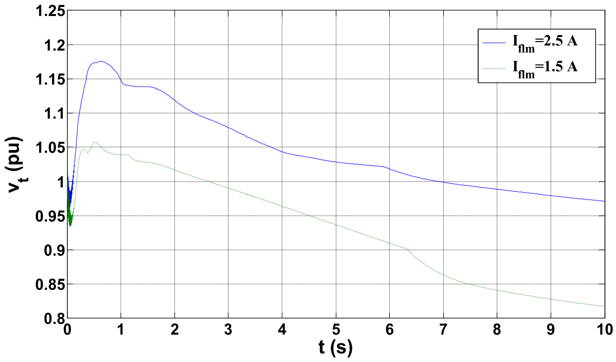

Fig. 20. Simulation with I_{flm}=2.5, I_{flm}=1.5

IV.1.2. Under Excitation Limiter Analysis

In this section, first simulation starts with radius of k_r=4. Results show limiter's radius are appropriate for required power of load and reactive power perception is in proper range and the size of output voltage of both generators are in desired area. Now, in this constant load power, reduce the limiter's radius to k_r=3 and simulation is repeated. Results are shown in Figure 21.

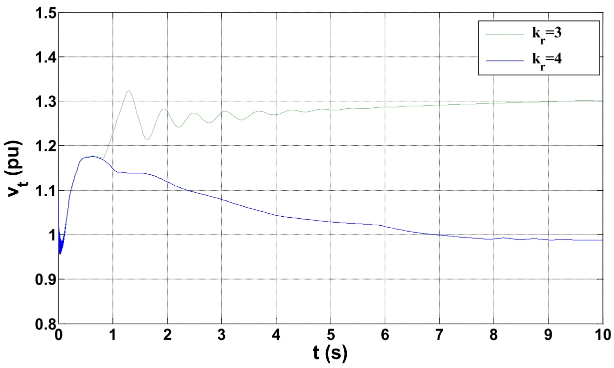

Fig. 21. Outage voltage in simulation with k_r=4, k_r=3

Considering Figure 21, it is obvious that expressed radius is not sufficient for reactive power reception, by generator1 and reducing under excitation limiter's radius; generator will has additional output voltage and voltage range in generator1 output reach to 1.3 p.u. .

Analyzing above simulations, limiter's role in this part (with dynamic parameters and excitation system model of Bistun power plant) is shown.

V. Conclusion

In this paper, the important roles of excitation system limiters of synchronous generator and effect of its parameters tuning on voltage stability in power system have been studied. In fact, tuning these limiters, move system stability bound and their improper tuning can cause instability.

For over excitation limiters, reducing upper limit (I_{flm}), since the excitation current cannot provide required flux for output voltage and produce sufficient reactive power, output voltage of generator drops, and reducing the range of this limiter causes faster reduction of voltage and this action leads to reduction of maximum active power transmission and eventually the system collapses faster.

For under excitation limiter the opposite of above-mentioned result is true. Reducing the radius of synchronous generator function area which means limiting the reactive power obtain, the voltage size in output generator won't fixed properly and by its rise and going out from stability bound, system will have instability in voltage.

Therefore, according to power capability curve in generator, a proper model should be implemented in excitation system for limiters and for its tuning it is necessary to pay attention to generator capability curve for keeping system stable and usage of maximum generator capacity.

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