# Influences of Excitation Systems on the Dynamic Voltage Behavior of Power Systems

H. Zimmer, M. W. Asmah, J. Hanson

***Abstract*—Keeping the voltage within certain boundaries is one of the main tasks for operation of electric power systems. During dynamic processes the voltage regulation is mainly carried out by the excitation systems of the large synchronous generators in the system. Different types of excitation systems are installed and have been classified within IEEE Std. 421.5. This paper investigates how different parameters of three excitation system types influence voltage stability during a generator outage and three-phase short-circuit incidents within the IEEE 39 bus benchmark system. Furthermore, it is investigated whether the share of different excitation system types within the power system influences voltage stability.**

***Keywords- Power system control; Automatic voltage control; Power grids; Power quality; Power system dynamics; Power system stability; Synchronous generators***

## I. INTRODUCTION

Keeping the voltages within certain boundaries in electrical HV transmission systems is achieved using the Automatic Voltage Regulation (AVR) of large synchronous generators in the grid together with the transformer tap changers and additional equipment (e.g. MSCDNs or SVCs). The excitation systems of synchronous generators, in contrary to transformer tap changers, are able to also influence the voltage behavior during dynamic incidents. The AVR controls the terminal voltage of the synchronous generator by influencing the DC voltage fed to the rotor, the so called excitation. Different types of controlled excitation systems can be found for large synchronous generators and have been classified within IEEE Std. 421.5 (see [1]) for dynamic investigations. Within this paper the dynamic behavior of three different excitation systems for different control parameters is investigated during a generator outage and a three-phase short circuit. In addition it is shown how different shares of excitation system types influence the dynamic voltage behavior of a power system.

As specified by [1], the following excitation system types have been chosen for the investigations:

- DC excitation : DC1A
- AC excitation : AC5A
- Static excitation : ST1A

The DC1A excitation system model is representing an AVR using a DC machine with exciter field rheostat to supply DC voltage to the rotor of a synchronous generator. Its regulator contains of a lead-lag-filter in series to a regulator amplifier represented by a PT1-element with gain $K_A$ and time constant $T_A$.

The AC5A excitation system model is representing an AVR using an AC machine together with a rotating rectifier to supply DC voltage to the rotor of a synchronous generator. It is a very general model to represent the behavior of brushless AC exciters. The regulator amplifier is modeled as PT1-element with gain $K_A$ and time constant $T_A$ together with a filtered feedback loop.

The ST1A excitation system model is representing an AVR using a stationary rectifier to supply DC voltage to the rotor of a synchronous generator. Usually, it is used to represent full bridge rectifier systems and able to produce high initial responses. The exciter time constants are very low and are neglected within the model. The regulator is represented by a series compensation, stabilizing feedback loop and regulator amplifier with gain $K_A$ and time constant $T_A$. However, the regulator stabilization can also be achieved by tuning the series compensator and, thus, the feedback loop is not necessarily part of the model.

A detailed description of the behavior of the different types of excitation systems along with a description of the different model blocks can be found in [2], [3] and [4].

## II. SIMULATION MODEL

The power system model used is the IEEE 39 bus benchmark system, a generic power system recommended for dynamic investigations as indicated in [5]. The power system has been implemented in DIgSILENT PowerFactory v.15.1. The implementation of the IEEE 39 bus system and modifications made to the system are described in [6]. Figure 1 shows a single-line diagram of the power system model.

J. Hanson, Head of Department and H. Zimmer, Research Associate are with the Department of Electrical Power Supply Systems with Integration of Renewable Energies, Technische Universität Darmstadt, Darmstadt, Germany (e-mail of corresponding author: henning.zimmer@e5.tu-darmstadt.de).
M. W. Asmah, Research Associate is with the Institute of Energy Systems, Energy Efficiency and Energy Economics, Technische Universität Dortmund, Dortmund, Germany (e-mail: marilyn-winifred.asmah@tu-dortmund.de).

Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015

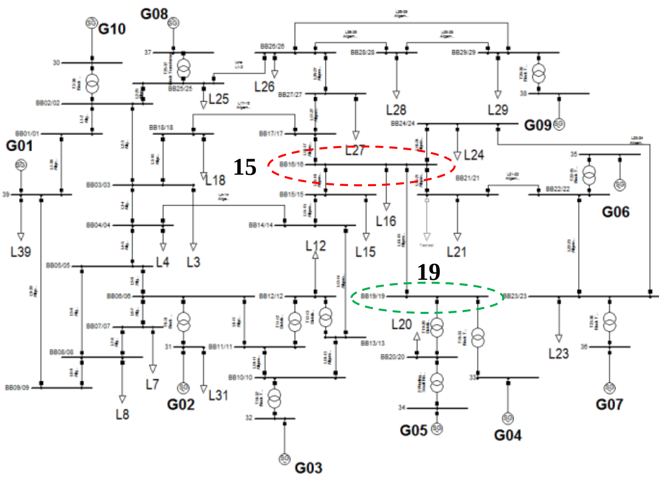


Figure 1 Single-line diagram of the IEEE 39 bus system (red circle around busbar 15, green circle around busbar 19)

## *A. Implementation of Synchronous Generators*

Synchronous generators are implemented as power plant models with steam turbine governor and excitation system. The steam turbine governor is modeled using the PowerFactory default steam turbine governor model TGOV1 (see [7]) with its default parameter set as given in TABLE I. The droop constant is set to 5 % and damping effects are neglected.

TABLE I. PARAMETER SET OF THE TGOV1 TURBINE GOVERNOR MODEL

| **Parameter** | **Value** |
|---|---|
| Governor Time Constant $T_1$ in s | 0,2 |
| Turbine Derivative Time Constant $T_2$ in s | 1 |
| Turbine Delay Time Constant $T_3$ in s | 2 |
| Minimum Gate Limit $V_{min}$ | 0 |
| Maximum Gate Limit $V_{max}$ | 1 |

## *B. Implementation of Exciation Systems*

The excitation systems have been modeled according to [1] using the following parameter sets:

TABLE II. PARAMETER SET OF THE DC1A EXCITATION SYSTEM MODEL

| **Parameter** | **Value** |
|---|---|
| Controller Gain $K_A$ in p.u. | 200 |
| Controller Time Constant $T_A$ in s | 0,005 |
| Filter Derivative Time Constant $T_C$ in s | 3,1 |
| Filter Delay Time Constant $T_B$ in s | 40 |
| Exciter Constant $K_E$ in p.u. | 0,5 |
| Exciter Time Constant $T_E$ in s | 0,05 |
| Stabilization Path Gain $K_F$ in p.u. | 0,01 |
| Stabilization Path Time Constant $T_F$ in s | 0,3 |
| Controller Minimum Output $V_{R,min}$ in p.u. | -5 |
| Controller Maximum Output $V_{R,max}$ in p.u. | 9 |

TABLE III. PARAMETER SET OF THE AC5A EXCITATION SYSTEM MODEL

| **Parameter** | **Value** |
|---|---|
| Controller Gain $K_A$ in p.u. | 200 |
| Controller Time Constant $T_A$ in s | 0,03 |
| Exciter Constant $K_E$ in p.u. | 0,5 |
| Exciter Time Constant $T_E$ in s | 1 |
| Stabilization Path Gain $K_F$ in p.u. | 0,2 |
| Stabilization Path 1st Time Constant $T_{F1}$ in s | 3 |
| Stabilization Path 2nd Time Constant $T_{F2}$ in s | 1 |
| Stabilization Path 3rd Time Constant $T_{F3}$ in s | 0 |
| Saturation Factor 1 E1 in p.u. | 3,13 |
| Saturation Factor 2 $S_{E1}$ in p.u. | 0,1 |
| Saturation Factor 3 E2 in p.u. | 4,18 |
| Saturation Factor 4 $S_{E2}$ in p.u. | 0,5 |
| Controller Minimum Output $V_{R,min}$ in p.u. | -20 |
| Controller Maximum Output $V_{R,max}$ in p.u. | 20 |

TABLE IV. PARAMETER SET OF THE ST1A EXCITATION SYSTEM MODEL

| **Parameter** | **Value** |
|---|---|
| Controller Gain $K_A$ in p.u. | 100 |
| Controller Time Constant $T_A$ in s | 0,05 |
| Filter 1st Delay Time Constant $T_B$ in s | 30 |
| Filter 1st Derivative Time Constant $T_C$ in s | 0,1 |
| Filter 2nd Delay Time Constant $T_{B1}$ in s | 0,5 |
| Filter 2nd Derivative Time Constant $T_{C2}$ in s | 1 |
| Current Limiter Factory $K_C$ in p.u. | 0,01 |
| Stabilization Path Gain $K_F$ in p.u. | 0,01 |
| Stabilization Path Time Constant $T_F$ in s | 1,2 |
| Current Input Factor $K_{IR}$ in p.u. | 1 |
| Controller Minimum Output $V_{R,min}$ in p.u. | -5 |
| Controller Maximum Output $V_{R,max}$ in p.u. | 5 |

## III. Parameter Investigations

To closly investigate the dynamic behavior of the excitation systems, the influences of the controller gain $K_A$ and the controller time constant $T_A$ have been simulated. These investigations show how tuning the regulator itself would affect the excitation system behavior. All generators of the IEEE 39 bus system are equipped with the same excitation system. For each parameter investigation a three-phase short circuit with duration of 150 ms at busbar 19 and a sudden outage of generator G08 are simulated.

### *A. Influences of Controller Gain $K_A$ and Controller Time Constant $T_A$ for an outage of G08*

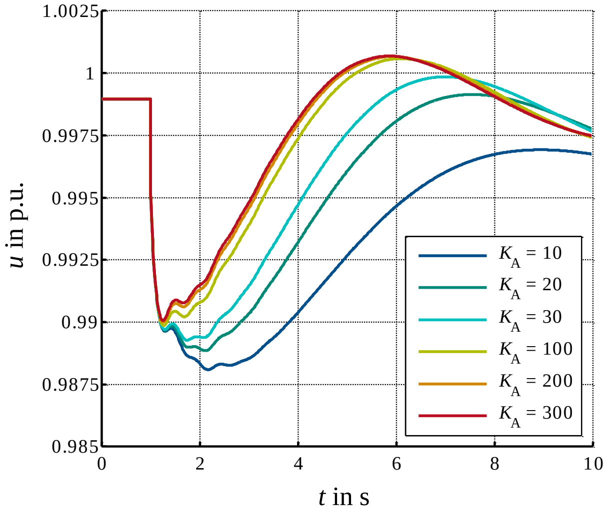


Figure 2 Voltage at busbar 15 for different values of $K_A$; G08 outage; all Generators equipped with AC5A AVR

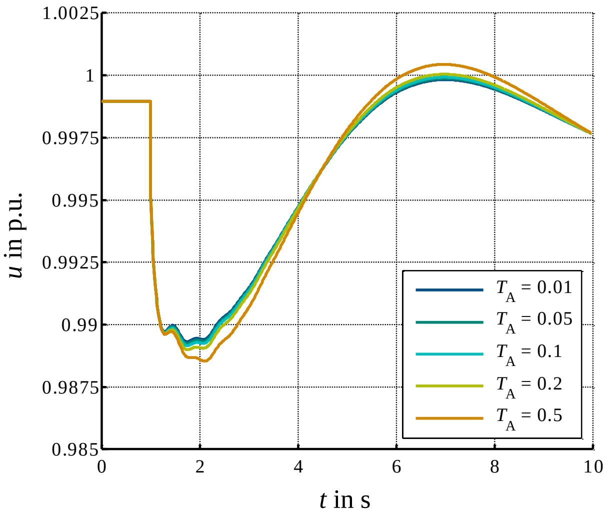


Figure 3 Voltage at busbar 15 for different values of $T_A$ in s; outage of G08; all Generators equipped with AC5A AVR

As can be seen in Figure 2, for the AC5A exciter having a controller gain of $K_A > 100$ is desirable for generator outage incidents, since otherwise the voltage drop will be significantly high and long. However, higher values of $K_A$ lead to positive voltage overshoots not significantly increasing after $K_A > 100$.

In Figure 3 it can be seen, that a controller time constant $T_A$ smaller than 0,2 s is desirable for generator outages since it leads to lower positive and negative voltage overshoots. However, the potential for waveform improvments by lowering the controller time constant $T_A$ to a minimum is very low.

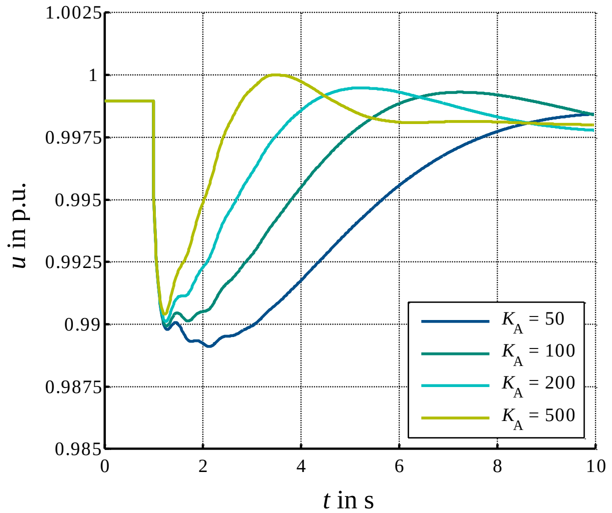


Figure 4 Voltage at busbar 15 for different values of $K_A$; G08 outage; all Generators equipped with DC1A AVR

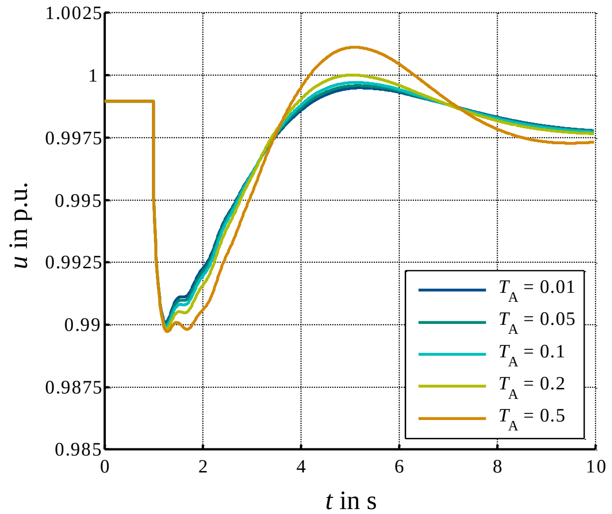


Figure 5 Voltage at busbar 15 for different values of $T_A$ in s; G08 outage; all Generators equipped with DC1A AVR

For the DC1A excitation system Figure 4 shows that in case of a generator outage a high controller gain $K_A > 200$ leads to a quicker reaction of the AVR and a smaller voltage drop than for low values of $K_A$. However, when approaching values of more than 500 it shows a significant positive voltage overshoot that should be avoided. As already observed for the cases with AC5A excitation, the controller time constant should be lower or equal to 0,2 s otherwise high negative and positive voltage overshoots are experienced during generator outage as can be seen in Figure 5.

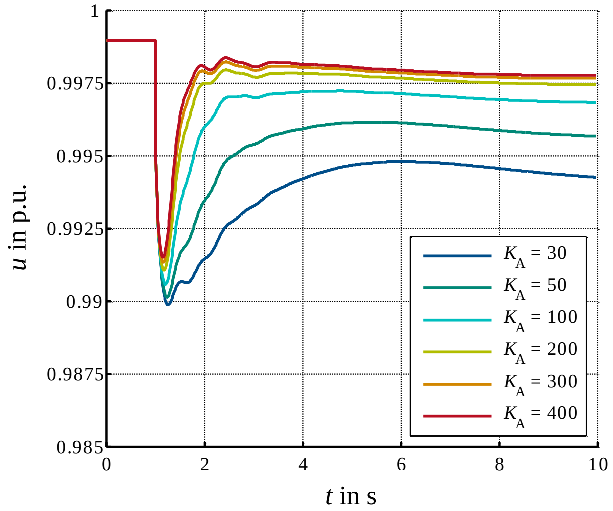


Figure 6 Voltage at busbar 15 for different values of $K_A$; G08 outage; all Generators equipped with ST1A AVR

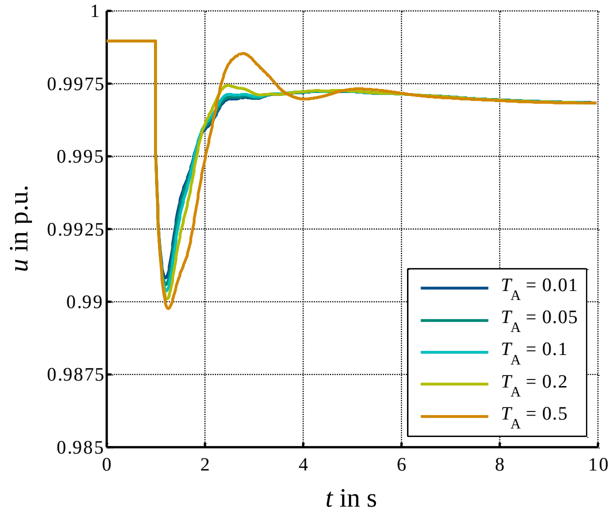


Figure 7 Voltage at busbar 15 for different values of $T_A$ in s; G08 outage; all Generators equipped with ST1A AVR

As can be seen in Figure 6, the ST1A excitation system during generator outage produces significantly lower stationary voltages for low values of $K_A < 200$. Therefore a value of $K_A > 200$ would be recommended. High values (e.g. $K_A = 400$) do not improve or worsen the exciter behavior. As well as for the DC1A and AC5A excitation system a controller time constant $T_A < 0{,}2$ s is recommended since otherwise positive and negative voltage overshoots are to be expected. These overshoots are getting significantly higher for values of $T_A \geq 0{,}5$ s.

### *B. Influences of Controller Gain $K_A$ and Controller Time Constant $T_A$ for a three-phase short-circuit at busbar 19*

For a three-phase short circuit incident and AC5A excitation systems high values of $K_A$ improve system behavior as can be seen in Figure 8.

Figure 9 shows that the controller time constant almost has no influence on the short circuit behavior. Together with the investigations for a generator outage it can be said, that for an AC5A excitation system values of $K_A$ in the range of 200 to 300 and $T_A < 0{,}2$ s would be recommended for overall good behavior.

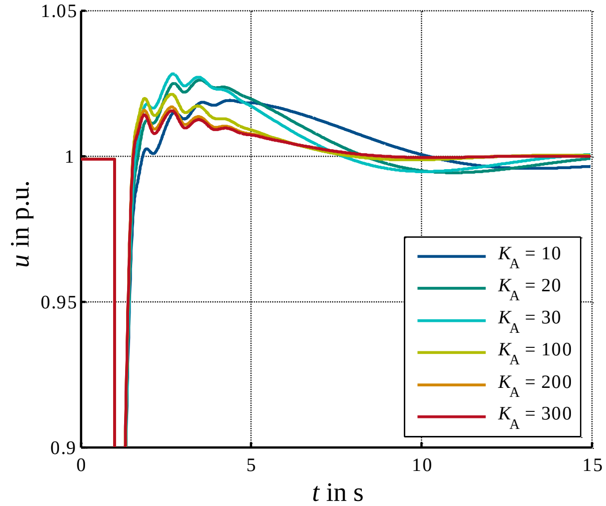


Figure 8 Voltage at busbar 15 for different values of $K_A$; 3-phase short circuit at busbar 19; all Generators equipped with AC5A AVR

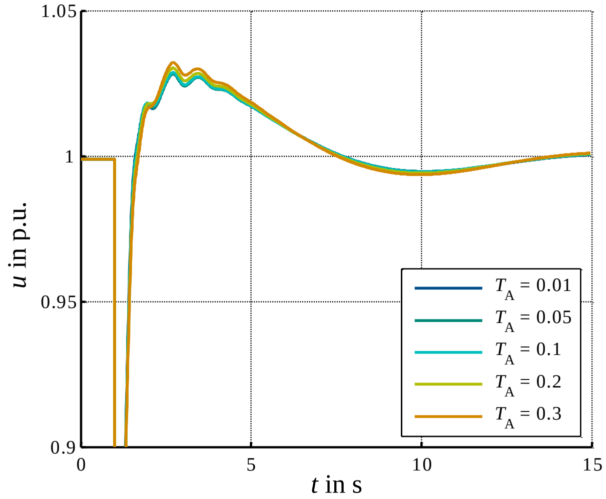


Figure 9 Voltage at busbar 15 for different values of $T_A$ in s; 3-phase short circuit at busbar 19; all Generators equipped with AC5A AVR

Figure 10 shows that high values of $K_A$ lead to very rapid and high voltage overshoots for DC1A excitation systems after the three-phase fault is cleared. However, the time until a stationary voltage value is reached is lower for high values of $K_A$. Thus, good values for short circuit behavior would be in the range of about 100 to 200, which would also be a good range for generator outage behavior. As well as for the AC5A exciter small values of $T_A < 0{,}2$ s are recommended for the DC1A excitation system as well.

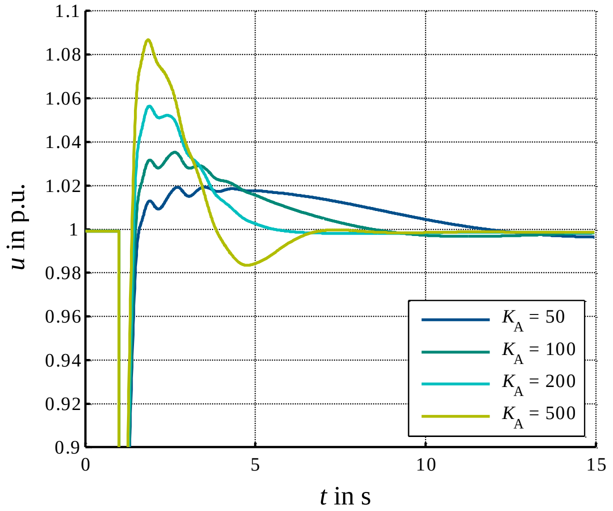


Figure 10 Voltage at busbar 15 for different values of $K_A$; 3-phase short circuit at busbar 19; all Generators equipped with DC1A AVR

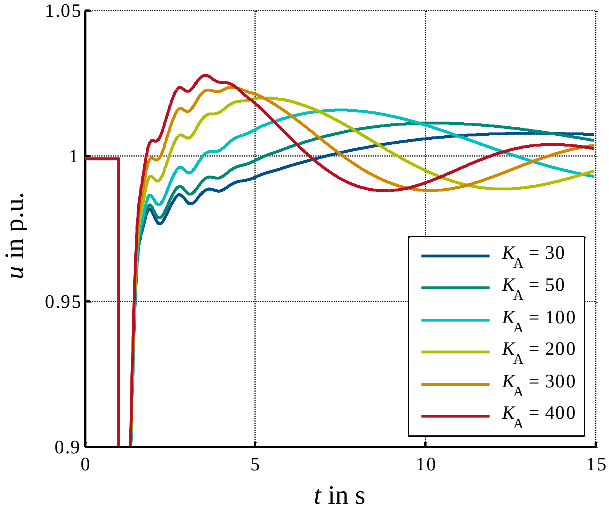


Figure 12 Voltage at busbar 15 for different values of $K_A$; 3-phase short circuit at busbar 19; all Generators equipped with ST1A AVR

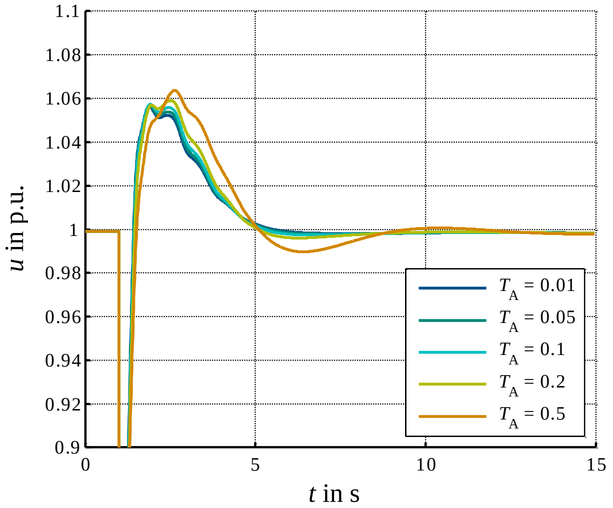


Figure 11 Voltage at busbar 15 for different values of $T_A$; 3-phase short circuit at busbar 19; all Generators equipped with DC1A AVR

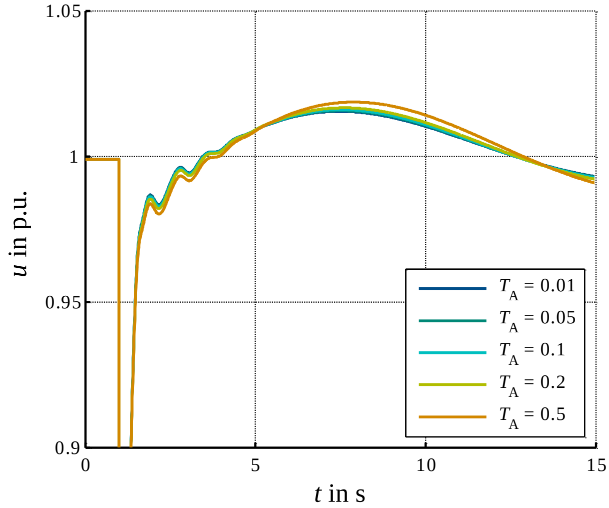


Figure 13 Voltage at busbar 15 for different values of $T_A$; 3-phase short circuit at busbar 19; all Generators equipped with ST1A AVR

The behavior of ST1A exciation systems during three-phase short circuitis is quick with high overshoots for high values of $K_A$ (see Figure 12). Together with the results from the generator outage investigation a good range for $K_A$ would be 100 to 200. $T_A$ as well as for the other excitation systems leads to better behavior for small values. In general values of $T_A < 0{,}2$ s would be recommended.

## IV. Investigation of a Combination of Different Excitation Systems

In power systems a variety of different excitation systems is installed rather than one single excitation system. Thus, to study the influence of the different shares of excitation system types, the following scenarios 1 to 3 have been defined.

For each scenario the voltage over time at busbar 15 of the IEEE 39 bus system is investigated for a sudden outage of generator G08. In addition, basic parameter sets have been implemented for the excitation systems as described in section II.

**Scenario 1 – One Excitation System Type**: This is the basic scenario in which all generators are operated with one single excitation system type, AC5A, DC1A or ST1A.

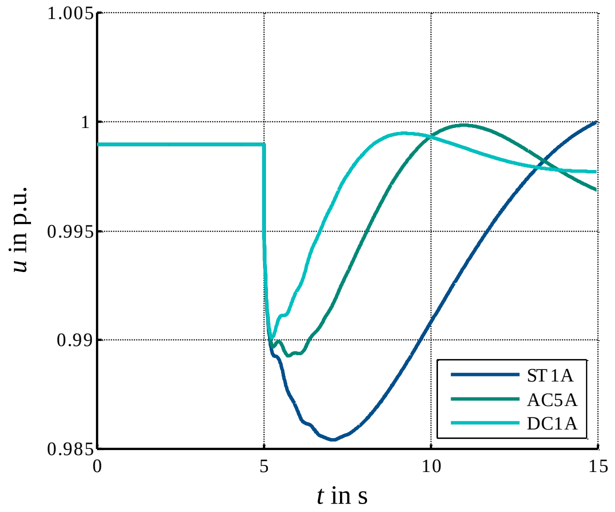


Figure 14 Voltage of busbar 15 over time for Scenario 1

As can be seen in Figure 14, the different excitation systems show quite a different behavior when they are operating alone. The voltage of busbar 15 for the ST1A excitation system shows the highest negative overshoot.

**Scenario 2 – 70:30 Excitation Mix**: For this scenario the ST1A excitation system is representing close to 70% of the active power supply (G01 to G07) while AC5A or DC1A respectively are representing 30% (G08 to G10) of all excitation systems.

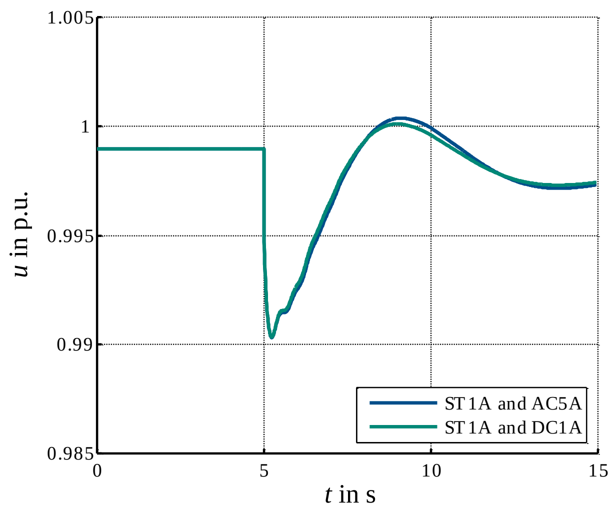


Figure 15 Voltage of busbar 15 over time for Scenario 2

When the generators in the system are operated with a 70:30 ratio of different excitation systems, it can be seen, that the voltage curve is almost equal for either a mix of 70% ST1A and 30% AC5A or 70% ST1A and 30% AC5A.

**Scenario 3 – 50:50 Excitation Mix**: In this scenario the AC5A excitation system is implemented in G01 to G05 while ST1A or DC1A exciters are implemented in G06 to G10.

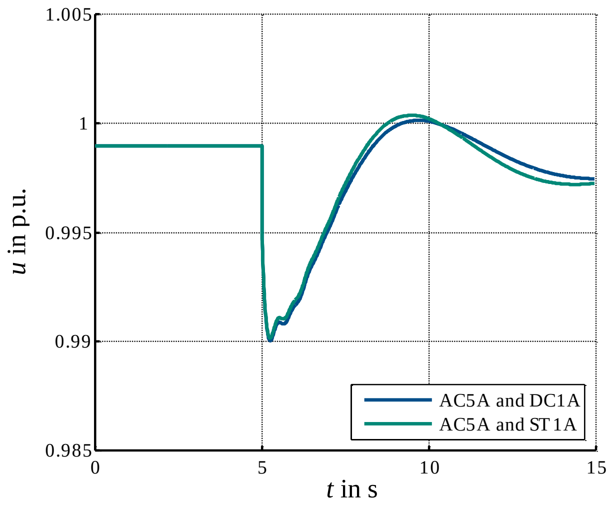


Figure 16 Voltage of busbar 15 over time for Scenario 3

As well as for scenario 2 also for a 50:50 ratio of excitation system types the voltage behavior at busbar 15 is very similar for AC5A and DC1A or AC5A and ST1A, even though the different systems on their own show very different behavior.

## V. Verification Using the IEEE Nine Bus System

The results of the investigations for different shares of excitation system types lead to the conclusion that for a mix of exciation systems regardless of its composition the system will show very similar voltage behavior, if the composition is not dominated by a single excitation system. To verify these results, the voltage behavior of the IEEE Nine Bus System is investigated using different compositions of excitation systems.

### *A. IEEE Nine Bus System*

The IEEE Nine Bus System was introduced by [7] and its representation in PowerFactory is shown in Figure 17. It contains of three Generators, eight busses and three Loads. Load A is connected to bus 5, load B is connected to bus 6 and load C is connected to bus 8. The results of the load flow as starting point for dynamic investigations are shown in TABLE V.

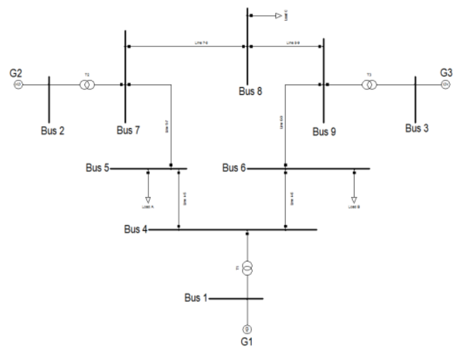


Figure 17 Single-line diagram of the IEEE Nine Bus System

TABLE V. LOAD FLOW RESULTS FOR OF THE IEEE NINE BUS SYSTEM

| | P in MW | Q in Mvar |
|---|---|---|
| **G1** | 71,6 | 27 |
| **G2** | 163 | 6,7 |
| **G3** | 85 | -10,9 |
| **Load A** | 125 | 50 |
| **Load B** | 90 | 30 |
| **Load C** | 100 | 35 |

The regulator setup that is implemented contains of an excitation system of either type ST1A, AC5A or DC1A and a turbine governor of type TGOV1 for each generator as specified in section II.

### *B. Short-Circuit Investigation with Different Excitation System Compositions*

To investigate the dynamic voltage behavior of the IEEE Nine Bus System, a three-phase short-circuit with duration of $t_{sc}$ = 150 ms is introduced at busbar 6 at simulation time $t$ = 1 s and the voltage behavior at the central busbar 8 is observed. This is done for all three generators having the same excitation system installed and for different compositions of exciation systems. A simulation of a generator outage is not performed since with only three generators in the system the two remaining generators after an outage are not a sufficient setup for excitation system compositions.

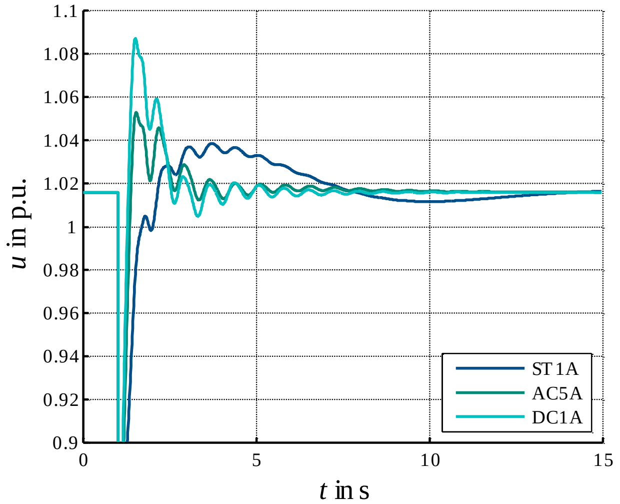


Figure 18 Voltage at busbar 8 for short-circuit at busbar 6; all generators equipped with the same excitation system

The voltage over time at busbar 8 for a three-phase short-circuit at busbar 6 and for all generators equipped with the same excitation system can be seen in Figure 18. As shown, the voltage behavior in peak value and settling time differs greatly depending on the excitation system all generators are equipped with.

When the short-circuit investigation is performed for different compositions of excitation systems, a different behavior can be seen. Figure 19 shows that regardless of the mix of excitation systems in the system, the voltage behavior at busbar 8 is very similar.

Differences between the curves are related to the excitation system mix getting more homogeneous. For example for the excitation system mix where G1 and G2 are equipped with an ST1A and G3 is equipped with a DC1A excitation system, the voltage curve at busbar 8 is shifting more towards the voltage obtained for all generators equipped with ST1A.

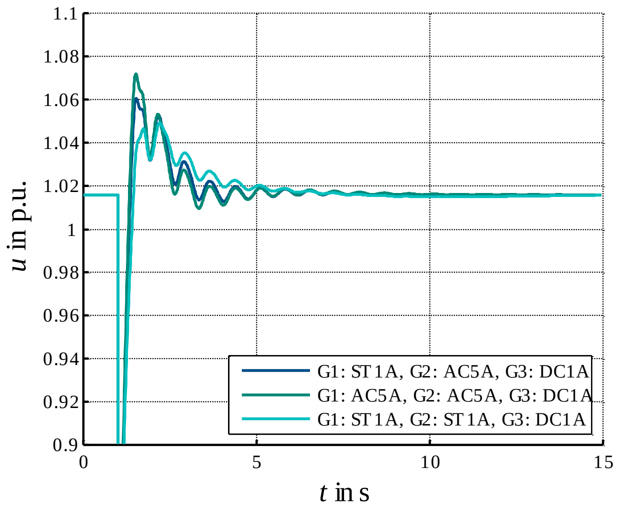


Figure 19 Voltage at busbar 8 for short-circuit at busbar 6; different compositions of excitation systems

The IEEE Nine Bus System is a simple benchmark model. However, the previous results obtained within the IEEE 39 Bus System, that an inhomogeneous mix of excitation systems regardless of its composition will lead to similar voltage behavior at a central busbar are shown also to be true for the IEEE Nine Bus System.

## VI. CONCLUSIONS AND OUTLOOK

Using the IEEE 39 bus benchmark system it has been shown that for a generator outage and a three-phase short circuit low values of the controller time constants $T_A < 0{,}2$ s are desirable for the three excitation system types investigated. In addition it has been shown that for large generator outages high values of the controller gain around $K_A > 200$ show better behavior, while the controller gain should be kept within a region of 100 to 300 depending on the AVR to produce acceptable behavior during three-phase short-circuit faults. Further investigations may focus on excitation system behavior for additional parameters (e.g. compensation or stabilizing loops).

The simulations of different excitation system shares have shown that whenever a mix of different excitation system types is installed within a power system model the excitation system types surprisingly are almost not of importance for dynamic voltage behavior at a central busbar. This was also verified within the IEEE Nine Bus Benchmark System. Of course, verification within a real power system model is desirable.

## VII. REFERENCES


[1] IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, IEEE Std. 421.5-2005, Apr. 2006.

[2] P. Kundur, *Power System Stability and Control*, pp. 315 - 333, New York: McGraw-Hill, 1994.

[3] J. J. Grainger, W. D. Stevenson, *Power System Analysis*, New York: McGraw-Hill, 1994.

[4] J. Machowski, J. W. Bialek, J. R. Bumby, Power System Dynamics: Stability and Control, 2nd edn., pp. 462 – 470, New York: John Wiley & Sons, 2008.

[5] M. A. Pai, *Energy Function Analysis for Power System Stability*, Appendix A, Boston: Kluwer Academic Publishers, 1989.

[6] H. Zimmer, G. Papaioannou, J. Hanson, "Influence of the Mix of Conventional Power Plants and Different Shares of Renewable Energies on Frequency Stability", Electrimacs 2014, Valencia, Spain, 19-22 May 2014.

[7] IEEE PES Power System Dynamic Performance Committee, *Dynamic Models for Turbine-Governors in Power System Studies*, Technical Report PES-TR1, IEEE, 2013.

[8] P.M. Anderson and A.A. Fouad, *Power System Control and Stability*, Ames: The Iowa State University Press, 1977.

[9] A. Glaninge - Katschnig, F. Nowak, M. Bächele, J. Taborda, "New Digital Excitation System Models in addition to IEEE.421.5 2005", *Power and Energy Society General Meeting*, Minneapolis, USA, 25-29 Jul. 2010.

[10] C. W. Taylor, *Power System Voltage Stability*, New York: McGraw-Hill, 1994.

[11] C.-J. Wu, Y-S. Chuang, "A Practical Experience about Dynamic Performance and Stability Improvement of Synchronous Generators", *Journal of Marine Science and Technology*, Vol. 11, No. 3, pp. 164-173, 2003.