Abstract—This paper describes former and modern types of the excitation systems. The results of the study performed are presented in order to assess the behavior of synchronous generator with different types of excitation systems. An overview and comprehensive analysis of the behavior of different excitation systems is presented. Analysis is made using PSCAD software.

I. INTRODUCTION

Excitation systems are one of the most important parts of the synchronous generators. Excitation system of the generator comprise from machines, devices and appliances that are intended to provide direct current to the generator field winding and this current regulation. Additionally, excitation systems are also responsible for control and protection functions of the power system. As an important control unit of synchronous generator, the excitation system and its dynamic performance has a direct impact on generators' stability and reliability [1].

When the behavior of the synchronous machines is to be simulated accurately in power system stability case, it is essential that the excitation systems of the synchronous machines be modeled in sufficient details. The desired models must be suitable for representing the actual excitation equipment performance for both large and small perturbations as well. Models of different excitation systems to be used for system stability studies are presented in corresponding IEEE document [2].

Broad description, characteristics and modeling features of the excitation systems, dynamic performance criteria and definitions of related terms useful in the identification and specification of the excitation systems requirements are widely discussed and described [3], [4].

Following sections describes common types of the excitation systems, their monitoring, protection and control functions, also relative advantages and disadvantages are briefly discussed and compared. Case study includes short presentation of the power system model used, summary of the excitation systems and power system stabilizer tests, and the Grid Code verification results.

II. EXCITATION SYSTEMS

A. Types of the Excitation Systems

Presently there are different types of the excitation systems used worldwide.

Form the excitation power gain point of view excitation systems could be divided in following groups:

- Independent. Exciter is not connected to the grid thus excitation parameters do not have direct connection with grid parameters. The part of turbine mechanical power is used for the excitation.
- Dependent. Exciter utilizes the part of generator power or is connected to the grid.

Accordingly to the excitation source used excitation systems are classified as following:

- DC systems
- AC systems
- Static systems

**DC excitation systems** utilize direct current generators. In such systems direct current is provided to the rotor of the synchronous generator through the slip rings. The exciter may be placed on the same shaft with power generator or is separately driven by a motor. Exciter may be self-excited or with separate excitation, with permanent magnet generator applied.

**AC excitation systems** utilize AC machines for generator excitation. Exciter is typically placed on the same shaft with the turbine. AC is rectified by controlled or non-controlled rectifiers, to provide DC to the generator field winding. Also AC excitation systems may differ by output control method and source of excitation for the exciter.

Presently stationary and rotating AC rectifier systems are in use. In stationary rectifiers the DC output is fed to the field winding of the generator through the slip rings. On the contrary, in rotating rectifiers there is no need in slip rings and brushes and DC is directly fed to the generator field as the armature of the exciter and rectifiers rotate with the generator field. Such systems are known as brushless systems and were developed to avoid the problems with brushes when extremely high field currents of large generators are applied.

In **static (ST) excitation systems** all the elements are stationary. Such systems directly provide synchronous generator field winding with excitation current by means of slip rings. Rectifiers in ST systems gain the power from generator through auxiliary windings or a step-down transformer.

In such systems generator itself is power source what means than the generator is self-excited. As the generator is not able to produce any voltage without excitation voltage, the generator must have auxiliary power source to provide field current and energize the generator. Station batteries are usually for the purpose of additional power sources and the process is named field flashing.

B. Excitation Systems Monitoring, Control and Protective Functions

Modern excitation systems include number of monitoring, protection, control and limiting functions, which helps to fulfill the necessary requirements. Each excitation system
may include some or all functions, it is important to have range of functions that is sufficient for the whole system maintenance on the desired level.

Main functions of the excitation systems are following:
- AC and DC regulators
- Excitation system stabilizers
- Power system stabilizers
- Voltage sensing and load compensators
- Under- and overexcitation limiters
- Volts-per-hertz limiters

Brief description of the control and protection functions:

**AC voltage regulator** main function is to preserve and maintain generator stator voltage. Its additional function is the generator excitation voltage control.

**DC voltage regulator** holds generator excitation voltage on the constant level and is typically manually controlled. Regulator is mainly used during tests, startups and to cover the AC regulator outages. In this mode of operation the field voltage is regulated.

**Excitation systems stabilizing circuits** are used to improve the dynamic performance of the excitation system. As DC and AC excitation systems have elements with significant time constants and it is important to have feedback compensation. The result is minimization of the phase shift caused by elements time constants, what contributes towards generator stable operation such as before the synchronization or after load rejection.

**Power system stabilizer (PSS)** uses special stabilizing signals for excitation system control and power system dynamic performance improvement. Major input signals that PSS usually utilizes are shaft speed, frequency and power. Main function of the stabilizer is the rotor oscillations damping through excitation control. To gain damping stabilizer have to produce appropriate electric torque component.

**Load compensation** is used to control voltage at a point that is external or internal to the generator. Compensator has adjustable impedance to simulate electrical distance between the generator terminals and the point at which the voltage is being controlled. Accordingly to the results achieved voltage drop is calculated and generator terminal voltage regulated.

Voltage regulation at the point that is external to the generator is commonly used to provide proper sharing of the reactive power between generators bussed together.

Voltage regulation at the point that is internal to the generator is used to compensate the voltage drop on the step-up transformers.

**Underexcitation limiter (UEL)** is used to prevent generator excitation decrease to the limit at which generator stability is lost. Limiter input signal is generator voltage and current or active and reactive power. The limits are determined by signal exceeding the reference level.

**Overexcitation limiter (OEL)** major function is to prevent generator overheating due to long term excitation overcurrent. OEL recognizes overcurrent and after the delay reduce excitation to the certain value. There are two ways of time delay: fixed time and inverse time delay. Fixed time limiter operates when excitation current exceeds reference value during preset time. Inverse time limiter operates with the delay that matches field thermal condition.

**Volt-per-hertz limiter** is responsible for generators and step-up transformers protection from excessive magnetic flux due to low frequency or overvoltage. Excessive magnetic flux may cause generator or transformers serious overheating and damage. Magnetic flux is proportional to the ratio of volt per unit to hertz per unit. Generator protection is applied when V/Hz regulator exceeds preset value during specified time.

**Exciter field suppression** is one of the serious problems of synchronous generators tripping. Because of high inductivity during generator tripping extremely high voltage appears in the field winding. Presently special circuit breakers are used in which electric arc is chopped on many smaller electrical arcs and gets extinguished. Typical de-energizing time is 0.5 to 1 s. In static excitation systems rectifiers are switched to the inverter mode in consequence of what power accumulated in the field winding is guided to the exciter or transformer [5].

### C. Excitation Systems Advantages and Disadvantages

Different excitation systems have their relative advantages and disadvantages, main of them are presented in the Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DC</th>
<th>AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excitation supply</td>
<td>Small transformer</td>
<td>Small transformer</td>
</tr>
<tr>
<td>Length of machine</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Response time</td>
<td>Slow</td>
<td>Medium</td>
</tr>
<tr>
<td>Components requiring maintenace</td>
<td>Sliprings and commutator</td>
<td>Sliprings</td>
</tr>
<tr>
<td>De-excitation</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Additionally, it must be mentioned that DC systems are less dependent on voltage oscillations, but their control signals has smaller amplification and response time during transients is slow. AC systems benefits in comparison with DC are extended range of excitation current and voltage and higher signals amplification. Brushless exciters advantage is high reliability in using with large generators because of absence the slip rings and brushes.

Static exciter merits are response time and sizes of the system. Amplification opportunity and excitation current and voltage are much higher than in DC and AC systems. Sometimes ST exciters are even provided with addition field current limiter, because of extremely high ceiling voltage.

The main disadvantage of ST systems is that power source is main generator and it is self-excited indeed. That requires additional power source to initially provide the field current and energize the generator.

### III. Modeling of the Excitation Systems

Excitation systems mathematical models are important for technical requirements estimation, additional control and protection circuits’ configuration and coordination also for the whole system stability research and development.

It is essential that the excitation system of the synchronous generator is modeled in sufficient details, to get accurately simulated power system stability case. Delayed protective and
control features that come into play in long-term system performance, e.g. UEL and OEL, are not presented.

IV. CASE STUDY

A. Excitation System Modeling

The modeled power system is basically one generator and an infinite bus system. The model includes typical power system main electrical equipment, such as generator, power transformer, high-voltage lines, measuring devices, electrical network load.

The synchronous generator data used in this study is somewhat modified actual generator data. Apparent power of the generator was 230 MW with output voltage 15.75 kV. Generator main parameters under observation are rotor speed \((Tm)\), mechanical torque \((Tm)\), excitation voltage \((E)\), excitation current \((I)\), terminal voltage \((U)\) and current \((I)\). Transformer is 250 MVA, 15.75 kV / 347 kV, delta/wye.

Electrical lines are 50 km long OHL; base load is 2.00 MW. Voltage of the transformer is 250 MVA, 15.75 kV / 347 kV, delta/wye.

Excitation system ceiling voltage \(U_{\text{MAXE}}\) is the maximum voltage \(U_{\text{NE}}\) is higher than nominal excitation voltage \(U_{\text{NE}}\), as shown in (1)

\[
k_e = \frac{U_{\text{MAXE}}}{U_{\text{NE}}}, \quad (1)
\]

Excitation response ratio equation is shown in (2)

\[
k_r = 0.632 \frac{U_{\text{MAXE}} - U_{\text{NE}}}{U_{\text{NE}} \cdot t}, \quad (2)
\]

where \(t\) is the time of excitation rise from nominal excitation up to (3)

\[
0.632(U_{\text{MAXE}} - U_{\text{NE}}). \quad (3)
\]

Excitation response ratio measuring unit is \(\frac{U_{\text{MAXE}}}{U_{\text{NE}}}\), which shows how many nominal voltage values excitation system is able to achieve during 1 second.

In this paper models of three most common excitation systems are simulated, tested and represented: DC excitation system – DC1A, AC excitation system – AC1A and static excitation system – ST1A. The parameters selected for different excitation system are based on IEEE material [2].

DC1A, AC1A and ST1A systems excitation voltages during the applied short-circuit are presented in the Fig. 1, Fig. 2 and Fig. 3, respectively.

DC excitation system forcing ratio accordingly to the Fig. 1 and (2) is 1.34, as shown in (4)

\[
k_e = \frac{U_{\text{MAXE}}}{U_{\text{NE}}} = \frac{3.18}{2.37} = 1.34. \quad (4)
\]

Using (2), excitation response ratio is calculated and equals 0.43.

AC excitation system forcing ratio accordingly to (1) is 1.3 and excitation response ratio accordingly to (2) is 0.51

**Fig. 1.** DC1A excitation voltage during three-phase short-circuit.

**Fig. 2.** AC1A excitation voltage during three-phase short-circuit.

**Fig. 3.** ST1A excitation voltage during three-phase short-circuit.

ST excitation system forcing ratio is 3.2 as in (1) and response ratio 13.96 as in (2) (Fig. 3).

These tests clearly show that static excitation system response ratio and forcing ratio are much higher than AC and
DC systems. Presented turbo generators DC and AC excitation systems $\tilde{\eta}$ exceeds 2 and $\tilde{\eta}$ achieves over 2 nominal voltage values during 1 second.

To provide higher forcing and response ratios the static excitation systems, where $\tilde{\eta}$ and $\tilde{\eta}$ reaches 4 and 40 accordingly, are used.

Another point of interest is the time, which is needed for excitation system to reach the ceiling voltage. DC and AC systems behavior is quite similar. Both systems require approximately 1.5 seconds, as seen in Fig. 1 and Fig. 2. On the opposite static excitation system needs 0.015 seconds, as seen in Fig. 3.

Fig. 3. ST1A excitation voltage during three-phase short-circuit.

C. Excitation Systems Response to a Short-circuit in the Power System

This test was performed in order to show different excitation systems reaction on network perturbations.

Short-circuit appears on 15th second, duration of the whole test is 30 seconds to give the system time for the stabilization after short-circuit disappearance. Short-circuit time is chosen 0.15 s, 0.18 s, 0.22 s and 0.24 s, as these are the typical short-circuit lengths in power network. Fig. 4, Fig. 5 and Fig. 6 shows excitation voltage changes of different excitation systems during different short-circuit time.

Fig. 4. DC1A system excitation voltage during different short-circuit time.

Fig. 5. AC1A system excitation voltage during different short-circuit time.

Fig. 6. ST1A system excitation voltage during different short-circuit time.

In general, it must be stated, that the shorter is the short-circuit length, the quicker system become stable. Test shows that with the provided settings all systems become unstable when the short-circuit duration is longer than 0.22 seconds. In addition, it is seen from Fig. 4 to Fig. 6 that in system with static exciter oscillations are damped quicker than with DC or AC systems. The phenomenon is caused by ST system much higher forcing and response ratios.

Oscillations in systems with DC and AC exciters are damping similarly with a slight advantage of AC system. It is seen in Fig. 4 – Fig. 6 that in case of short-circuit duration of 0.22 seconds DC and AC systems excitation voltage became stable on approximately 28th - 30th seconds and ST system on 20th second accordingly. In addition, Fig. 7, Fig. 8 and Fig. 9 shows perturbations of static excitation system ST1A generator terminal voltage, active and reactive power.
Fig. 7. Synchronous generator RMS terminal voltage during different short-circuit time (ST1A system utilization).

Fig. 8. Active power during different short-circuit time (ST1A system utilization).

Fig. 9. Reactive power during different short-circuit time (ST1A system utilization).

It could be seen how parameters of the power system are changing during different short-circuit time: with a gradual increase of short-circuit time the amplitude of the oscillations are getting greater until the stability is lost, e.g., when short-circuit time equals 0.24 s.

D. Static Excitation System Test with Power System Stabilizer

Power system stabilizers (PSS) are used to enhance damping of power system oscillations through excitation control. In this paper, the result of power system stabilizer PSS1A [2] utilized with excitation system ST1A are introduced.

Main object of the test is to show the difference of system stabilization after short-circuit with PSS and without it.

Fig. 10 shows active power oscillations caused by the short-circuit appearance. It is clearly seen, that excitation system with stabilizer recovers quicker, oscillation peaks are lower already on the second fluctuation and totally disappears on 2nd second after disturbance commitment. System without stabilizer also gets stabilized, but a bit later, approximately on 4th second after short-circuit appearance.

More demonstratively the benefit of PSS utilization is shown in Fig. 11. In case of using PSS system recovers and becomes stable on 3rd second after disturbance disappearance. When the PSS is not in use stability is lost.

E. Verification of the Excitation System Conformity

Accordingly to the Grid Code of Estonia [6], series of measurements and tests must be conducted, before excitation system unit utilization positive resolution is obtained.

The steady state is determined by measuring the dynamic characteristics. Power generator is operated in no-load conditions and terminal voltage is changed explosively on 10%. Terminal voltage is changed from 95% to 105% and 105% to 95% of the rated voltage.

In both cases the generator output voltage change must correspond following requirements:

• There should not be oscillations in output voltage;
• Terminal voltage 90% rise time must be 0.2-0.3 seconds for ST systems.

In the Fig. 12 is shown excitation system ST1A no-load verification test. Terminal voltage is changed on 11.06 second from test start from 95 % to 105 % and on 16.5 second is changed back from 105 % to 95 % of rated voltage.

Nominal output voltage of the generator is 15.75 kV, in this case 95% is equal to 14.96 kV and 105% is equal to 16.54 kV. Accordingly to the Grid Code regulations 90% of both values must be reached during 0.2-0.3 seconds if static excitation system is utilized.
The difference between 105% and 95% of rated voltage is 1.58 kV. It means that 90% of this value, equal to 1.42 kV, rise or reduction must be obtained in the period of 0.2 to 0.3 seconds. The test shows, that in case of 10% voltage
reduction needed value is acquired during 0.21 seconds and in case of voltage rise during 0.22 seconds.

V. CONCLUSIONS

One of the most important elements of the power systems are synchronous generators and their excitation systems. These provide consumers with electrical power and to the great extent guarantee power system reliability, security and stability.

In this paper the most common excitation systems of the synchronous generators and their behavior features are thoroughly described and modeled in PSCAD.

The aim of the work was to investigate and show different excitation systems properties, define their parameters, estimate their advantages and disadvantages, model, simulate and test power systems in different conditions. In the study case most important test are presented and described.

Three main excitation systems are modeled and analyzed: DC, AC and static. During the tests the real, most important parameters of the excitation systems, such as forcing ration and response ratio were defined and compared. The parameters correspond to the theoretical ones.

Additionally power system stabilizer impact on the excitation system stability was inspected.

On the whole it could be seen, that the results are reliable and satisfactory. However the models presented are reduced and do not include all the elements and loops of any particular system, as a consequence additional research must be carried out.

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REFERENCES