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COMPARISON OF DIFFERENT METHODS FOR EXCITATION OF SYNCHRONOUS MACHINES

Abstract: The energy turnaround in Germany leads to new operating conditions for small and medium synchronous generators. Since the electricity generation through renewable energy sources, such as wind or photovoltaic, is highly volatile, generators have to run up from standstill into rated operation within several minutes. Hence, it is necessary to compensate a lack of electricity generation caused by wrong weather forecasts. Usually, gas turbine systems provide this possibility. The generator is used as a starter engine due to the connection to a frequency inverter. The excitation current is often provided by static excitation systems. Thus, it is possible to start from standstill and run up the drive until the gas turbine is able to generate a positive torque. A new excitation concept, based on an induction machine with a 3-phase rotor winding, is able to provide an excitation current at 0 rpm and eliminates the need for brushes. To verify the applicability for power systems, both systems are compared under different aspects. The control of the excitation current at different speeds and the possibility to settle shaft oscillations after electrical faults are aspects researched in the paper at hand. A power system simulation is performed with a synchronous machine connected to a grid. Both excitation systems are modeled by equivalent circuit diagrams in Matlab Simscape.

Keywords: *AC machines, Brushless machines, Electromagnetic transients, Excitation system, Power system simulation*

1. Introduction

The increasing amount of highly volatile energy generation, such as wind power stations and solar plants, leads to new operating conditions for fossil-fueled power plants [1]. Since it is possible that the amount of active power fed by renewable energy sources changes within several minutes, the amount of conventional fed energy has to compensate for those fluctuations. Some gas power plants operate in turning operation for up to 70% of time per year [2], since it is not possible to start them from standstill in a short time.

Common generators are direct current excited synchronous machines. Therefore, it is possible to regulate the amount of reactive power by adjusting the DC excitation. There are mainly two set-ups to feed the field winding of a synchronous generator with direct current [3], [4]:

1. Brushless excitation systems
2. Static excitation systems

Brushless exciters are synchronous machines with a rotating multi-phase winding mounted to the shaft and a stationary DC coil. The multi-phase winding is connected to a rotating rectifier and the rectifier is connected to the generator's field coil. The energy conversion with synchronous machines and therefore with common brushless exciters works only while the system is rotating, since there is no electromagnetic induction in the multi-phase winding at 0 rpm. Compared with common brushless excitation systems, static excitation systems use controlled rectifiers connected via slip rings and brushes to the generator's field coil. Thus, it is possible to provide an excitation current at standstill. This system requires a higher amount of maintenance work.

In order to start a turbine generator or a synchronous condenser within a few minutes from standstill without using auxiliary drives, the synchronous machine can be used as motor for the start up by using it as inverter drive. There is a wide range of inverter topologies which are appropriate for the use with synchronous machines [5].

Typical brushless excitation systems are not able to provide an excitation current at 0 rpm. Thus, it is not possible to start a generator from standstill, unless it is equipped with a static excitation system.

A third excitation system uses an induction machine as inductive energy transfer system to generate a direct current without using brushes. This system is typically used for very large drive applications, such as multi-megawatt compressor drives in liquid natural gas (LNG) plants.

Fig. 1 shows the brushless excitation systems (green) typically used for large drives.

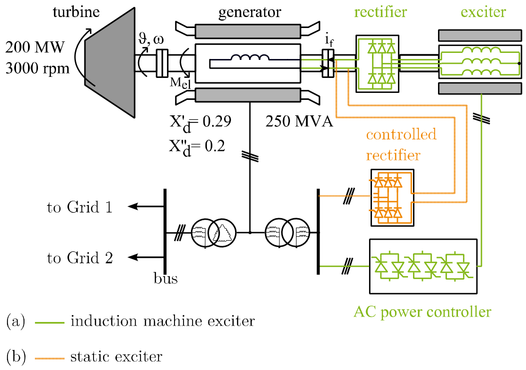

Fig. 1. Schematic drawing of an induction machine based excitation system (a) and a static excitation system (b) for turbine generators

The induction machine stator winding is connected to an AC power controller. The rotary field, generated by the 3-phase stator winding of the exciter, turns in the opposite direction of the rotating direction of the shaft. Thus, the operational slip of the induction machine is at s = 1 during standstill and at s = 5 during rated operation. This system is brushless and it is able to feed the generator's field coil with a DC current at standstill. Its effects on the generator performance are unknown, since it is only used as an excitation system for large drives. Those drives do not have to regulate reactive power or have to stabilize the grid during faults.

Fig. 1 also shows a typical static excitation system (orange dashed). It consists of a controlled 6-pulse rectifier, which is directly connected to the rotating field coil by using brushes and slip rings. The static excitation system has the advantage of being able to feed the field coil with a negative field voltage to reduce the field current in the case of an overexcitation. It has the disadvantage that it depends on using brushes and may cause shaft voltages [6], [7].

2. System under investigation

Switching operations in the grid or grid faults can cause oscillating shaft torques, which can damage the power system and lead to mechanical failures. Thus, the excitation system has to attenuate those resonances between the rotating system and the grid. In order to verify the applicability of the induction machine exciter (IM exciter) for turbine generators, a detailed power system simulation is performed. The control performance of the IM exciter is compared with a static excitation system. The detailed equivalent circuit of the static excitation system is modeled and the controls are taken from the ST1A standard excitation system [8]. Both excitation systems are equipped with the same power system stabilizer (PSS1A) [8]. The stabilizer modifies the input signal of the voltage controller in order to suppress shaft oscillations in consequence of grid faults or resonance excitation. It uses the shaft acceleration as input signal.

The simulation is performed by using a typical benchmark model. As depicted in Fig. 2, the generator is connected to 2 equivalent grids. Hence, they have the same short circuit capacity (SCC) of 1500 MVA. Furthermore, both lines have a length of 50 km with the same values for resistance and reactance.

Both excitation systems are fed by the on-site power. The on-site power is supplied by a transformer connected to the generator's terminals. Thus, both systems get affected by voltage drops on the transmission line.

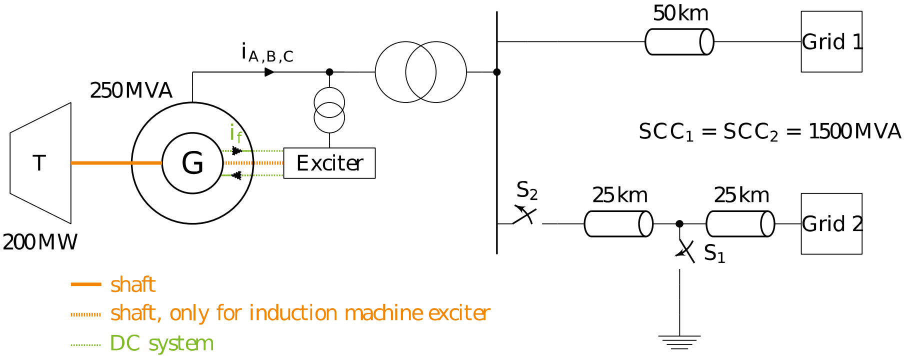

Fig. 2. Simulation model for the performance analysis of the excitation systems

Two scenarios are chosen to prove the applicability of the IM exciter for power generation systems. First, a 185 ms 3-phase fault is simulated in the middle of one transmission line. At the beginning of the simulation the system runs at rated operation and at the time of t = 0 s the switch S_1 is closed. After 185 ms the fault is cleared by opening the switch S_2. Following it is assumed that the fault is cleared and the switch S_2 recloses successfully.

Secondly, the 3-phase fault is simulated once again. The switch S_1 is closed similar to the successful reclosing simulation. After 185 ms the switch S_2 opens and the generator gets separated from the 3-phase fault.

37 periods or 740 ms after S_2 was opened, it closes again. In this case the generator is connected to the 3-phase fault once again. This second simulation is called unsuccessful reclosing. The reclosing fault is cleared after additional 185 ms.

For both scenarios it is assumed that the turbine torque keeps constant to simplify the comparison. The fast travel mode of the turbine valves may be activated at real power plants due to the fault, in order to reduce the overspeed of the shaft [9].

3. Simulation and results

3.1 Successful reclosing

Fig. 3 shows the most important generator values during the 3-phase fault on the transmission line. The values are expressed in the per unit system, which brings benefit to the comparability of the presented figures.

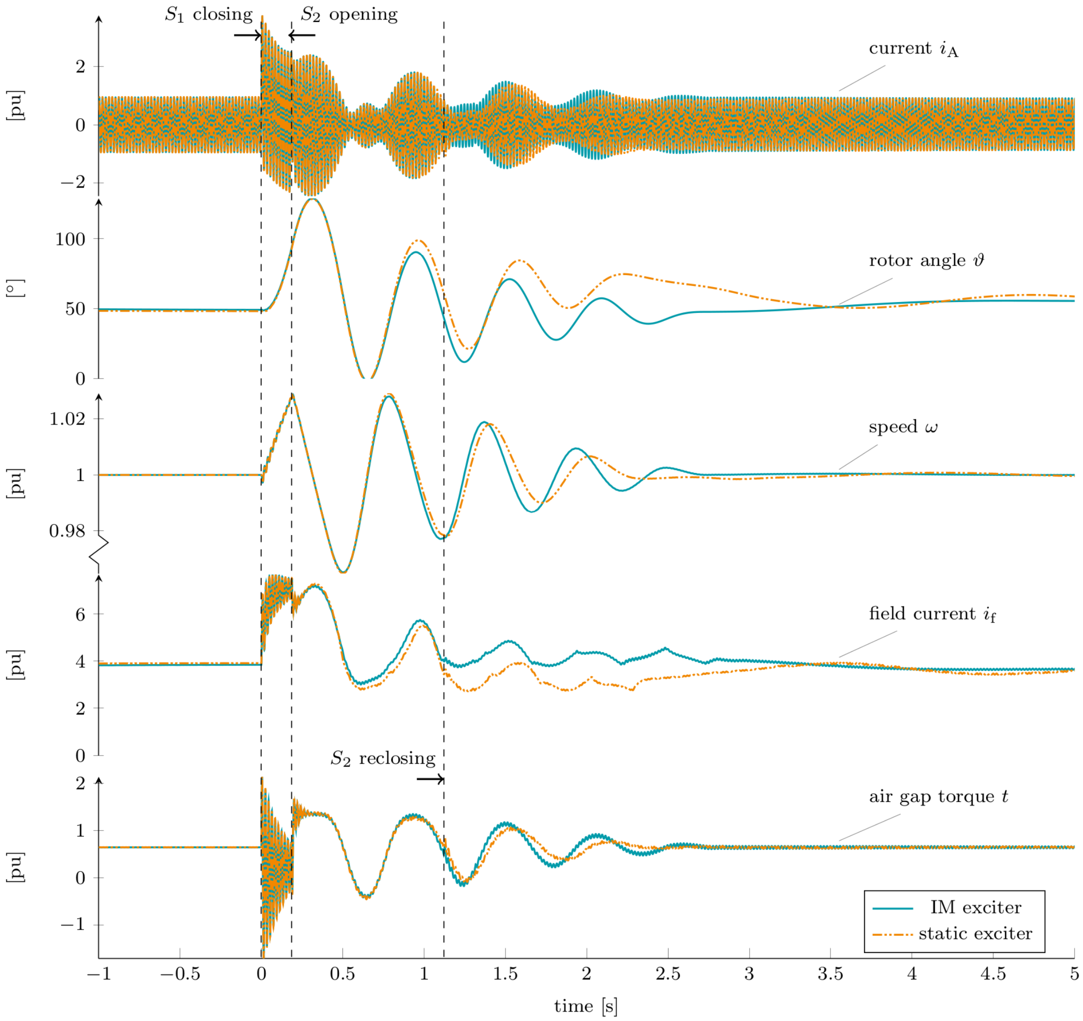

Fig. 3. Most important generator values for both excitation systems during the successful reclosing simulation

The generator operates under rated conditions at 3000 rpm. At the time of $t = 0$ s the switch S_1 is closed. The sudden short circuit leads to high transient generator currents. Since the turbine torque is constant during the whole simulation, the generator starts to accelerate. Both excitation systems have no visible influence on the transient values during the short circuit. Generator currents and the air gap torque have the same behavior.

After 185 ms the switch S_2 opens and the generator returns into rated operation. The recovery time for the rotor angle ϑ and the speed ω is similar.

The generator field current i_{f} shows a big difference. By using the IM exciter, the field current is about 1.5-2 pu greater than the field current with the static excitation system. The static excitation system offers the possibility to reverse the field voltage. The negative field voltage values lead to lower field current values after fault clearance. Thus, the oscillating air gap torque of the generator has lower amplitudes after fault clearance. Nevertheless, both excitation systems return the generator into rated operation within a time period of 3 seconds. The generator stator currents have the same maxima for both excitation systems.

3.2 Unsuccessful reclosing

Fig. 4 shows the most important generator values for the unsuccessful reclosing simulation. The generator runs at rated operation and at the time of $t = 0$ s the switch S_1 is closed. 185 ms after S_1 is closed, the switch S_2 opens.

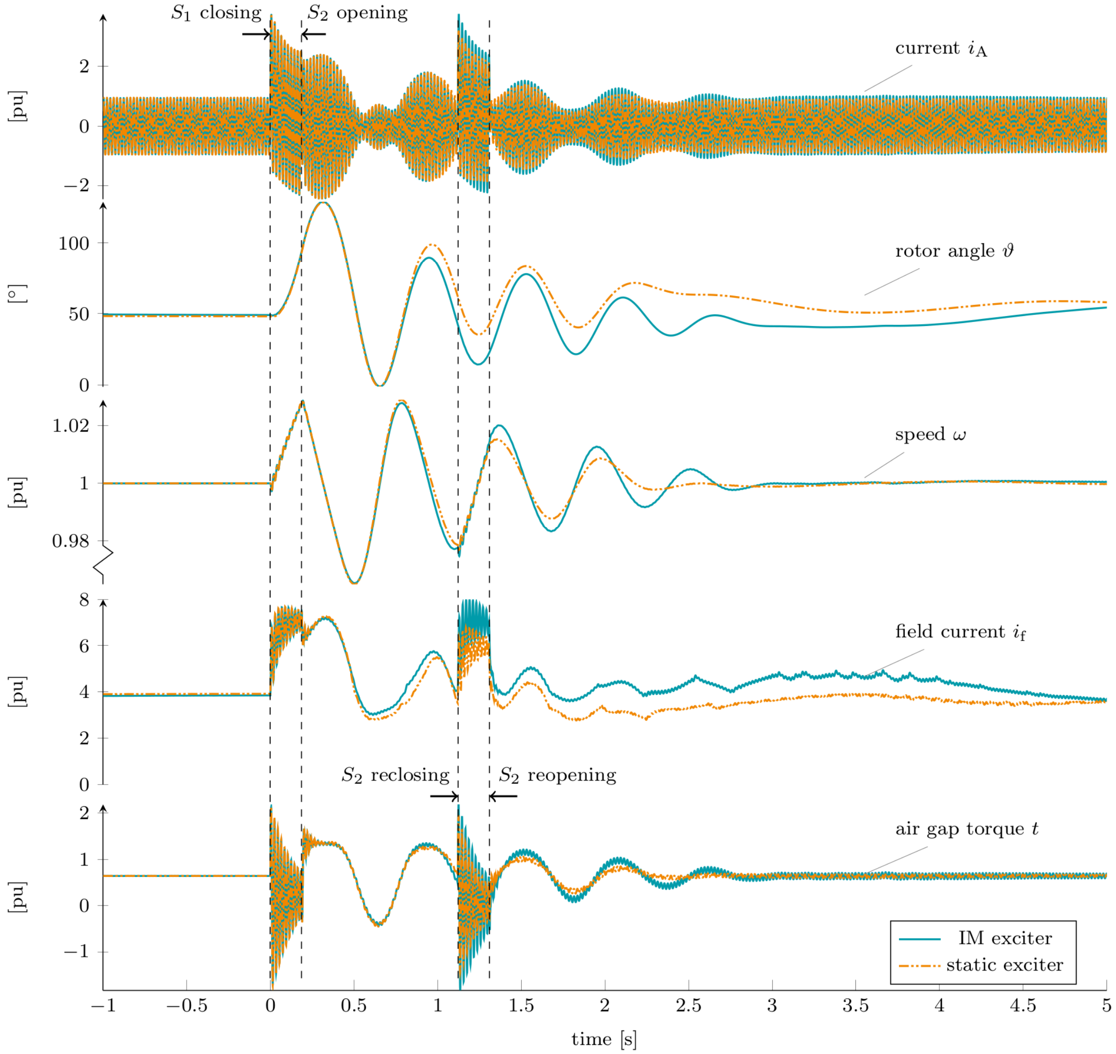

Fig. 4. Most important generator values for both excitation systems during the unsuccessful reclosing simulation

Compared to Fig. 3, all values are equivalent until the switch S_2 closes 37 time periods after the first fault clearance. S_1 is kept still closed during the whole simulation. Hence, the generator gets connected to the 3-phase fault once again.

The rotor angle ϑ and speed ω show higher oscillation amplitudes for the IM exciter. By using the speed ω as reference, the static excitation system is 500 ms faster in suppressing the oscillations. By using the rotor angle ϑ as reference value, both systems are at rated operation after 5 seconds.

As noticed during the successful reclosing simulation, the IM exciter leads to higher field current values after the first fault clearance. The generator's field current is at 3.5 pu with the static excitation system and at 4 pu with the IM exciter while S_2 is reclosing at the time of $t = 1.12$ s. Hence, the maximum value of the field current during the second fault is at 6.75 pu for the static excitation system and at 8 pu by using the IM exciter. The same effect is visible at the terminal currents.

Nevertheless, both excitation systems help to return the generator into rated operation. There are visible differences, but both systems can totally suppress the shaft oscillations within 3 s after the second fault clearance.

4. Conclusions

The IM exciter shows good regulation characteristics for the presented simulations. A disadvantage, which comes with all brushless excitation systems, is the lack of possibility to feed the field coil with negative field voltage values. Thus, the field current i_f has higher values. This has a negative influence on the generator's air gap torque values and current amplitudes after an unsuccessful reclosing event. The settling times are comparable to the static excitation system ST1A.

In order to build brushless excitation systems for turbine generators with the possibility to generate a field current at standstill, the IM exciter is an efficient way to combine fast regulation characteristics and the advantages of classical brushless excitation systems, where less servicing is required.

5. References

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