Simulation of power supply systems with external faults and methods for increase of residual voltage at terminals of power receivers

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Abstract. The article discusses the effect of the remoteness of the place of a three-phase short circuit on the depth of the voltage dip depending on the load on the synchronous generators and synchronous motors. A series of experiments was carried out where the length of the 110 kV overhead power line varies, at the end of which a short circuit occurs, as well as the load distribution coefficient of a synchronous machine with higher than normal field-forcing ratio and the influence of these parameters on the level of residual voltage among large industrial consumers. The efficiency of using synchronous machines with a higher than normal field-forcing ratio of the excitation is estimated, and their stability under a sharp increase in loads, which cause voltage changes during the transition process and cause rotor vibrations, accompanied by magnetic losses due to the occurrence of eddy currents in the rotor core, is considered. The results of simulation presented in the Simulink are a MATLAB-based graphical programming environment for modeling, simulating and analyzing multi-domain dynamical systems.

1. Introduction

When a three-phase fault (TPF) occurs, a voltage drop (VD) occurs and the behavior of high-voltage synchronous electric motor (SEM) largely depends on the settings of the protections in the 110 kV grid. As it is known, when a VD occurs, SEM go into the generator mode, turning, in fact, into sources of electricity. If the protection of 110 kV lines does not have the necessary speed for deep VD, then SEM goes out of synchronism and special measures must be taken to resynchronize them.

Modern devices for fast-automatic transfer switch (FATS) with a transformer substation on an overhead power line (OPL) of 110 kV become ineffective [1-3]. The paper suggests ways to increase the residual voltage by increasing the field-forcing ratio of synchronous machines (SM) excitation, as well as using the energy storage system (ESS) in the excitation system.

2. Circuit diagram and simulation model of a typical industrial customer. simulation results

Although the excitation forcing of SM can not always completely remove the problem of the impact of short-term power outages (STPO) on the quality of electricity, it should be noted the effectiveness of this method for prevention STPO: firstly, it requires almost no additional costs, and secondly, significantly reduces the critical length of line (CLL) [4-6], i.e. that zone within which all faults lead to a decrease in voltage at the main step-down substation (MSDS) below the technologically permissible...
The schematic diagram (Figure 1) shows a diagram where a three-phase fault occurs on a 110 kV OPL in an external power supply system.

Both SEM and synchronous generator (SG) are considered as SM. In accordance with the circuit diagram of the power supply of an industrial customer, a simulation model of a typical unit of the power supply system of an industrial consumer is developed (Figure 2). This model allows researching the effect of the excitation forcing of SM on the depth of VD caused by a three-phase fault in a 110 kV OPL.

The parameters for the simulation model blocks are set as follows: the resistive resistance of the
power supply is 0.04 ohms, the inductive resistance is 0.016 H. The distance to the TPF varies from 1 to 30 km, which covers the power supply system of the city and its environs. For the 110 kV powerline, reference characteristics of the steel-aluminum wire AC 120/19 and the intermediate support PS 110–9 V were used. SM parameters: Unom=10.5 kV, Xd=1.41 pu, Xq=0.47 pu, Xd'=0.21 pu, Xd"=0.101 pu, Rs=0.003 pu The nominal power of the SM in one considered case was 8 MVA, in the other - 16 MVA. The SMs work with a load distribution coefficient Kdl equal to 1. The coefficient takes into account the load distribution on the SM and is defined as the ratio of the load on the SM terminals to its nominal power. Transformer parameters: the rated power of the transformer is 8 MVA in one considered case, 16 MVA in the other, 110 kV primary winding voltage, and dissipation inductance 0.08 pu, secondary voltage 10.5 kV, and dissipation inductance 0.08 pu.

In the case of STPO, voltage recovery in the 10 kV section of the main power supply occurs due to the action of the Loss of Mains (LoM) protection [1; 4].

At the time of TPF, there is a VD on all sections of buses. The LoM turns off the input switch, ensures the start of the FATS and gives the command to turn on the excitation of the SM, the time of the full transfer cycle is 45 - 60 ms [1; 8; 9].

A three-phase fault occurs at a time of 0.1 s, on a 110 kV overhead line 17 km away from industrial customer buses, and the current amplitude is 8 kA. The resulting short circuit causes VD on the buses of the industrial customer in all 3 phases, which is clearly seen in Figure 3.

![Figure 3](image-url)

**Figure 3.** Oscillogram of phase voltages and currents on the buses of an industrial customer without excitation forcing.

The level of residual voltage under these conditions amounted to 61% of the nominal voltage, with an 8 MVA SEM being in operation at an industrial customer.

When switching pathogens to ESS, it is possible to fully use the capabilities of the SM to increase the level of residual voltage. In order to identify the patterns of influence of the field-forcing ration (with independent power supply from the ESS and the power supply of the exciter from its own buses), a series of experiments were carried out with an SG of 8 MVA and the length of the overhead line at which the short circuit occurs. Figure 4 shows a comparison of the graphs of the CLL for the SG.
The comparison of the graphs for the SG with a system powered by its own buses and an independent excitation system from the ESS shows that at the level of the specified minimum allowable residual voltage of 80% of the nominal, the CLL for the SG with an independent excitation system from the ESS is less than for the SG with exciter power system from own buses for 18 kilometers. If we compare the efficiency of the field-forcing ratio of the SG with an independent excitation system from the ESS, then four-time field-forcing provides a twofold decrease in the CLL [2; 10]. Fig. 5 shows the moment of switching on the four-time field-forcing ratio of SEM. When we turn on the four-time field-forcing ratio of SEM in 20 ms, we can reach the residual voltage level of 80% of the nominal. By analogy, SG was also considered.

Figure 4. Residual voltage level change

Figure 5. Oscillogram of phase voltages and currents on the buses of an industrial customer at the time of VD with the next turning on four-time field forcing ratio of SM.
However, due to a sudden increase in load on the SM rotor, vibration appears, which causes a voltage change during the transition process. SEM swings are within acceptable limits and SEM continues to work. Figure 6 shows the oscillograms of the phase currents of the SM and the angular velocity of the rotor rotation. Vibrations of the rotor cause energy losses, of which the magnetic losses due to the occurrence of eddy currents in the rotor core are of the greatest importance.

![Figure 6](image6.png)

**Figure 6.** Phase currents in the SM field winding and the angular velocity of the rotor rotation of the SM during the four-time field-forcing ratio

The rotor vibrations have a damped character, and therefore, after some time, the rotor will take a position corresponding to the angle at which the moment balance is established [11].

SM load distribution coefficient is defined as the ratio of the load at the SM terminals to its nominal power. The examples of the influence of various load distribution coefficient on the exciting ability of SM are presented below.

The following experiment shows the dependence of the degree of residual voltage reduction on the Krl voltage at the installed capacity of SM - 8 MVA, Figure 7, and SM - 16 MVA, Figure 8.

![Figure 7](image7.png)

**Figure 7.** Dependence of the residual voltage on Kdl when installing SM with a capacity of 8 MVA.
Figure 8. Dependence of the residual voltage on Kdl when installing SM with a capacity of 16 MVA.

3. Conclusion

The experimental results allow making the following conclusion: three-phase fault on 110 kV OPL (average line length is 1-10 km) cause VD sufficient to dysfunction most equipment (residual voltage is less than 60%) at any three-phase fault power.

Faults to the supply and outgoing lines of adjacent substations (the total distance to the fault location is 10-20 km) at short-circuit currents from the system of 15 kA and higher cause VD with a depth of up to 40%. This is enough to maintain the health of most unregulated motors with a voltage of 6-10 kV. With a short-circuit current of 30-40 kA, the residual voltage among consumers approaches 80% of the nominal when the short-circuit point is removed from distribution of busbars of 110 kV substation for 20 km or more. However, a four-time field-forcing ration of the SG excitation makes it possible to reduce the CLL of power line to 10 km.

Fault to remote substations with a voltage of 110 kV (which also corresponds to the electrical distance of the short circuit point from the buses of the distribution substation 110 kV that occurred at nearby district and junction substations with a voltage of 220 and 550 kV) causes voltage dips of up to 30% depth even with a very high short-circuit power. Such devices as industrial controllers, instrumentation circuits, thyristor converters of complex units with stiff Undervoltage protection remain sensitive to VD of this depth. These devices, as a rule, ensure the operation of complex units that perform continuous technological processes in automatic mode. The shutdown of such units due to VD causes defective products and the undersupply of expensive products, but due to the possibility to use a four-time field-forcing ratio, these risks can be minimized.

The presence of SG and SEM on 10 kV buses allows increasing the level of residual voltage up to 25% depending on the power of the SM, for SG the level of residual voltage is 10% higher than for SEM. With close faults, when the level of residual voltage is critically low, using circuitry to increase the short-circuit power on 110 kV buses and the SM ability to excitation forces can significantly reduce the CLL to 3 km.

Thus, to sum up we can conclude that the excitation forcing of SM installed in the internal power supply system of industrial consumers, allows increasing the level of residual voltage during VD caused by a three-phase fault in 110 kV supply grids. The higher than the normal field-forcing ratio of SM contributes to a decrease in the CLL and, as a result, leads to a decrease in the number of process...
shutdowns at consumers with a continuous production cycle. When choosing a high-voltage current-limiting protector, designed to increase the level of residual voltage at the MSDS at three-phase fault in 110 kV supply grids, it is necessary to take into account the capabilities of SM in terms of excitation forcing. Switching exciters to ESS allows full use of the capabilities of SM to increase the level of residual voltage.

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