Study of the transients with the loss of field of the synchronous generator in the industrial electric power station

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Abstract. One of the main trends of industrial power engineering today is the need to improve the reliability of power supply of responsible consumers along with the increase of competitiveness of products by reducing cost. These requirements are ensured by the widespread introduction of distributed generation sources. These include mini combined heat and power unit, gas turbine, gas engine and combined-cycle gas turbine power plants. At the same time, such changes significantly complicate both the power supply system and possible modes of operation. One of the possible emergency modes in such networks is the loss of field of the synchronous generator. The admissibility of such a regime is specified by regulatory documents. In such a case this generator goes into asynchronous mode and consumes reactive power from the network. The aim of this work is to study the operation of a synchronous generator for a certain time in the asynchronous mode as a result of a loss of field and to develop measures to ensure the admissibility of such a mode in a complex looped network. An algorithm has been developed for calculating the electromechanical transients of a synchronous generator, taking into account the loss of machine field. Studies are carried out for various operational modes of an industrial power plant, taking into account the initial load of the generator using the KATRAN software package. The calculation results allow determining the generator load with active power, at which the synchronous generator can operate in the asynchronous mode without excitation.

Keywords: parallel operation, software package, industrial synchronous generator, electromechanical transients, field regulator, separate operation, loss of field, asynchronous operation.

1. Introduction
A large number of works [1-11] are devoted to the study of static, dynamic and resulting stability of synchronous machines. A large number of researches carried on within Russia [12-19] are devoted to issues of operation of distributed generation.

The asynchronous operation of a synchronous generator can proceed in two forms. First the asynchronous operation of a synchronous generator with the field. This mode occurs as a result of a loss of static or dynamic stability and is accompanied by a significant change in the voltage and currents of the machine and is not continuous.

An asynchronous generator operation in case of a field loss is accompanied by the consumption of reactive power from the network and a decrease in the generation of active power into the network. The admissibility of this mode depends on the type of generator and its cooling system. Thus for indirectly cooled turbogenerators asynchronous operation mode is allowed up to 30 minutes. In this case, its generated power should be reduced to 50-70% and the stator current should not exceed 110% of the nominal value. Turbogenerators having direct cooling can operate in asynchronous mode up to 15 minutes with reducing turbine power to 40-55%. In this case, the voltage at the generator terminals should not decrease by more than 30% of the nominal value. Otherwise, the damping power will be small and the stability of the operation of synchronous machines in this node may be disturbed.
Therefore the ability of the synchronous generator to operate in the asynchronous mode with loss of the field depends on a large number of factors, including the initial operating mode and the power of the grid.

To analyze this mode, a corresponding mathematical model had been developed, taking into account the flux degradation in the field winding. The model was applied in the algorithm for calculating the electromechanical transients with parallel and separate operation with the power grid. The KATRAN software complex [14–19] developed at the department of Electric Power Supply of Industrial Enterprises of Nosov Magnitogorsk State Technical University takes into account the algorithm and makes it possible to calculate the modes of asynchronous operation and resynchronization with regard to the loss of field of a synchronous machine, and also to evaluate the admissibility of such modes.

Introduction of the field loss in the mathematical model of the generator

A large number of works are devoted to mathematical modeling of synchronous generators. The mathematical model chosen in this case makes it possible to take into account the change in magnetic fluxes and other parameters of a single machine with a short calculation time. This method involves the presentation of individual generators and their regulators by external characteristics and allows to determine the stability of each machine in a particular node, for example, an industrial power plant. Sources of distributed generation in such a node are, as a rule, of different types and have a certain electrical distance relative to each other. Since the development of industrial generation significantly complicates the emergency and operational modes of power supply systems, this approach is justified.

In the chosen mathematical model the generator is not represented directly by the flux linkages, but by the transient (subtransient) emf proportional to the corresponding total flux linkages. To use this approach, the steady state operation mode is first calculated [14–15]. This approach is used to analyze dynamic stability and is described in the works [14–19].

In the case of a long-term transient, subtransient components can be neglected, therefore, the generator mode is calculated using transient electromotive forces $E' = E'q + jE'd$, proportional to the total flux linkage along the direct and quadrature axes, respectively. At each step of the calculation, the change in the transient e.m.f. is taken into account along with the change in the stator response flow and the field winding.

Thus the stator reaction flow is determined by the stator current which can be obtained from the calculation of the transient mode at each step of the transient process and determines the total e.m.f. of the machine $E = Eq + jEd$. This flux is taken into account to determine the total flux linkage along both the direct and quadrature axes. In the asynchronous mode the stator response will be driven by both synchronous and asynchronous power. When taking into account asynchronous powers it is conditionally assumed that one of the axes is connected with the real axis, the other with the imaginary.

Another flux which determines the transition is the field winding flux. This magnetic flux is determined by the change in the induced e.m.f. of the machine $Eq$. First of all it is influenced by the action of automatic excitation control and field forcing. Obviously with the field loss of a synchronous generator a gradual decrease in the induced e.m.f. to zero is observed. And the generator goes from synchronous mode to asynchronous.

Fig. 1 shows the algorithm for calculating the transients taking into account the loss of field of a synchronous generator. It presents the definition of the initial values of the e.m.f. and their change over time.
Figure 1. Algorithm for calculating generator parameters
In the asynchronous mode, the voltage level in the network plays a big role. If it is high enough then the magnitude of the damping power is sufficient to create the braking torque of the generator in question. In this case, the generator works stably and the swings of other machines are not observed. In accordance with the voltage level at the terminals of the stator winding the asynchronous active $P_a$ and reactive $Q_a$ power and the increment of the corresponding transient e.m.f. are determined. After determining the new value of the transient e.m.f. the new value of the rotor angle is determined in accordance with the numerical solution of the rotor motion equation and the new mode is calculated with the new parameters.

![Diagram of Power Supply System](https://example.com/diagram)

**Figure 2.** The power supply system

The developed algorithm can be used for numerical integration methods. In this case, the calculation is carried out by a combination of sequential reduction method for calculating steady-state modes and the method of successive intervals for calculating the electromechanical transients.

2. Implementation of the mathematical model in the “katran” software package

The modes were calculated using the KATRAN software package, developed at the department of Electric Power Supply of Industrial Enterprises of Nosov Magnitogorsk State Technical University. In the event of a field loss the generator from the over-excited state goes into the under-excited state and begins to consume reactive power from the network. In this mode, as it is shown in fig. 3, for a generator that has lost its field the angle of load significantly increases in relation to other generators that hadn’t lost field. When conducting research the calculation of the mode is performed in terms of parallel operation with the grid and a generator has a lost the field has been selected. To reduce the percentage of overload the output active power of the generator which fall out of synchronism had been reduced and the recommended value of active power was determined, providing the value of the emergency mode current with an acceptable percentage of overload. As shown by calculations taking into account the current load the most overloaded by the stator current with the loss of field is the generator $G-2$. At the initial load with active power of 100% and loss of field an 26% overload on the stator current is...
observed as a result of a change in the consumed reactive power. Elimination of overload is achieved by reducing the active power by 17%. The calculations allow us to analyze the operation of the synchronous generator in the asynchronous mode with loss of field. Since in such a mode the machine consumes asynchronous reactive power and produces active power it is possible to control only active power through a speed controller to ensure the permissible current of the stator winding of the generator.

![Figure 3. Change in the generator’s rotor angle with loss of field](image)

3. Conclusion
The electromechanical transient mode of asynchronous operation with loss of field of a synchronous generator in an industrial power plant in terms of parallel operation with the grid had been considered. A mathematical model of a synchronous generator has been developed which takes into account the change in the transient e.m.f. along the direct and quadrature axes of the machine taking into account the damping powers with a loss of field. This model can be applied for the calculation of transients by numerical integration methods. The model was taken into account when developing an algorithm for calculating the electromechanical transients which forms the basis of the KATRAN software package. Calculations of modes using this software were carried out in relation to an industrial power plant with turbo-generators of various capacities. Recommendations for the loading of generators with the active power in the investigated mode had been developed.

The developed software package can be used to analyze possible emergency and post-emergency conditions as a dispatcher's advisor for operational dispatch personnel of industrial power plants.

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