Simulation of Generator Transients with Asymmetry of Stator Phase Circuits

Igor Alferov, Nikolay Mitrofanov and Gleb Glazyrin

ABSTRACT

Transient processes of a synchronous machine operating on a load with a delta connection circuit are considered. A method is proposed for numerical simulation of transient processes of a synchronous machine with the possibility of taking into account the asymmetry of the stator winding. The model was verified by comparing the results of the calculation of generator transients with an asymmetrical stator winding, obtained using the developed model and using the MATLAB Simulink tools.

INTRODUCTION

Existing software packages for modeling transient processes in electric power systems, such as MATLAB Simulink [1], PSCAD, Mustang, are used to describe electromagnetic processes in a synchronous machine of the Park—Gorev equation [2] and, accordingly, cannot be used to calculate processes in a damaged synchronous machine. A machine with different parameters of phase windings. VF Sivokobilenko [3] (calculation of a synchronous machine with the rotor of the machine taking into account multi-circuit circuits) and S. A. Kharitonov [4] (description of electromagnetic transients in systems for generating electric energy for autonomous objects) are actively involved in practical methods for calculating transients of a synchronous machine.

As a result of the study, a system of differential equations describing transients of a three-phase synchronous machine with regard to individual active resistances and windings inductances is derived. Also, a comparison was made of...
the simulation results of the transient processes of a synchronous machine made
using the library SimPowerSystems, which is part of the MATLAB Simulink
environment, with the results obtained using the proposed method.

INITIAL EQUATIONS THAT CHARACTERIZE THE OPERATION OF
A SYNCHRONOUS MACHINE

Consider a synchronous machine with three-phase windings, an excitation
circuit, as well as one longitudinal and one transverse damping windings.

Denote by \( u_\eta \) (\( \eta = a, b, c \)) and \( u_f \) – instantaneous voltages on the phase
windings and the excitation winding, respectively; \( i_\eta \) and \( i_f \) – instantaneous
currents; \( \psi_\eta \) and \( \psi_f \) – resulting winding flux couplings; \( R_\eta \) and \( R_f \) – active
resistance of the phase windings and the excitation winding. Then the differential
equilibrium equations and voltage drops in the contours of a synchronous
machine will have the form [1]:

\[
\begin{align*}
\frac{d\psi_\eta}{dt} & = -\frac{u_\eta}{R_\eta} - \frac{\psi_\eta}{R_\eta} \quad (\eta = a, b, c); \\
u_f & = \frac{d\psi_f}{dt} + R_f i_f.
\end{align*}
\]

In addition, the system of differential equations (1) should be supplemented
with equilibrium equations of electromotive force (EMF) and voltage drops in the
damper circuits:

\[
\begin{align*}
0 & = -\frac{d\psi_{yd}}{dt} - R_{yd} i_{yd}; \\
0 & = -\frac{d\psi_{yq}}{dt} - R_{yq} i_{yq},
\end{align*}
\]

where \( \psi_{yd} \) and \( \psi_{yq} \) – the resulting flux linkage of the longitudinal and
transverse damping windings, respectively, \( R_{yd} \) and \( R_{yq} \) – their active
resistance, \( i_{yd} \) and \( i_{yq} \) – instantaneous values of currents in the damper circuits.
The proposed method for calculating transients is based on the joint solution of equations (1) and (2), supplemented by expressions of voltage drops on the load resistance. This approach makes it possible to simulate a synchronous machine with different parameters of phase windings by describing electromagnetic processes in each phase by a separate differential equation.

The simplest resulting differential system of equations is obtained in the case of connecting a star-shaped load with a neutral wire without resistance [6]: it suffices to replace \( u_\eta \) on \( L_{ng,\eta} \left( \frac{di_\eta}{dt} \right) + R_{ng,\eta} i_\eta \) in equation (1).

**DERIVATION OF A SYSTEM OF DIFFERENTIAL EQUATIONS FOR A GENERATOR OPERATING ON AN AUTONOMOUS LOAD WITH A DELTA CONNECTION SCHEME**

As a matter of fact, the power distribution schemes of power plants provide for the operation of generators with insulated neutral (without neutral wire). As a rule, the generator is connected to the winding of a step-up transformer connected in a “delta”. For accurate calculation of transients in such schemes, it is necessary to simulate both the generator and the transformer, which greatly complicates the mathematical calculations. The paper considers the case of generator operation for an autonomous load, connected according to the “triangle” scheme, figure 1. The calculation is based on the algorithm proposed by [5].

When calculating the operating modes of a generator operating on an autonomous active-inductive load connected in a “triangle” scheme, the following transformations should be taken into account, in which \( u_k \) \((k = ab, bc, ca)\) – instantaneous values of linear voltages at the terminals of the synchronous machine; \( i_k \) – instantaneous linear current values:

\[
\begin{align*}
u_{ab} & = u_a - u_b; \\
u_{bc} & = u_b - u_c; \\
u_{ca} & = u_c - u_a;
\end{align*}
\]

\[
\begin{align*}
i_a & = i_{ab} - i_{ca}; \\
i_b & = i_{bc} - i_{ab}; \\
i_c & = i_{ca} - i_{bc}.
\end{align*}
\]
Then the equilibrium EMF and voltage drops in the contours of a synchronous machine (1) will be defined as:

\[
\begin{align*}
    u_{ab} &= -\frac{d\psi_{ab}}{dt} = \left( R_{g,a} i_a - R_{g,b} i_b \right) ; \\
    u_{bc} &= -\frac{d\psi_{bc}}{dt} = \left( R_{g,b} i_b - R_{g,c} i_c \right) ; \\
    u_{ca} &= -\frac{d\psi_{ca}}{dt} = \left( R_{g,c} i_c - R_{g,a} i_a \right) , \\
\end{align*}
\]

(5)

where $R_{g,\eta}$ ($\eta = a, b, c$) – active resistance of the phase winding circuit, $u_k$ ($k = ab, bc, ca$) – instantaneous values of linear voltages at the terminals of the synchronous machine, $\psi_{ij} = \psi_i - \psi_j$.

When calculating the operating modes of a generator operating on an autonomous active-inductive load connected in a "triangle" scheme, the system of differential equations takes the form:

Figure 1. Load connection diagram.
\[
\begin{align*}
\frac{d\psi_{ab}}{dt} &= -L_{n,ab} \frac{di_{ab}}{dt} - \left( R_{g,a} + R_{g,b} + R_{n,ab} \right) i_{ab} - R_{g,a} i_{ca} - R_{g,b} i_{bc} ; \\
\frac{d\psi_{bc}}{dt} &= -L_{n,bo} \frac{di_{bc}}{dt} - \left( R_{g,b} + R_{g,e} + R_{n,bc} \right) i_{bc} - R_{g,b} i_{ab} - R_{g,e} i_{ca} ; \\
\frac{d\psi_{ca}}{dt} &= -L_{n,co} \frac{di_{ca}}{dt} - \left( R_{g,e} + R_{g,a} + R_{n,ca} \right) i_{ca} - R_{g,e} i_{bc} - R_{g,a} i_{ab} ; \\
\frac{d\psi_f}{dt} &= u_f - R_f i_f ; \\
\frac{d\psi_{yd}}{dt} &= -R_{yd} i_{yd} ; \\
\frac{d\psi_{yq}}{dt} &= -R_{yq} i_{yq} ,
\end{align*}
\]

(6)

where \( R_{n,k} \) – load resistance \((k = ab, bc, ca)\), \( L_{n,k} \) – load inductance.

Entering the assumption of linearity of the relationship between the windings flux couplings and the currents flowing in them, as well as performing some transformations of the system (6), we obtain the following system of equations in a matrix form:

\[
\begin{bmatrix}
L_{ab} & M_{ab,e} & M_{ca,e} & M_{abf} & M_{abyd} & M_{abyq} \\
M_{ab,e} & L_{bc} & M_{bc,e} & M_{bcf} & M_{bcyd} & M_{bcyq} \\
M_{ca,e} & M_{bc,e} & L_{ca} & M_{caf} & M_{cayd} & M_{cayq} \\
M_{abf} & M_{bcf} & M_{caf} & L_f & M_{fyd} & 0 \\
M_{abyd} & M_{bcyd} & M_{cayd} & M_{fyd} & L_yd & 0 \\
M_{abyq} & M_{bcyq} & M_{cayq} & 0 & 0 & L_yq
\end{bmatrix}
\begin{bmatrix}
\frac{di_{ab}}{dt} \\
\frac{di_{bc}}{dt} \\
\frac{di_{ca}}{dt} \\
\frac{di_f}{dt} \\
\frac{di_{yd}}{dt} \\
\frac{di_{yq}}{dt}
\end{bmatrix}
= \begin{bmatrix} -\frac{\partial\psi_{ab}}{\partial \gamma} \omega - u_{\Sigma ab} \\
-\frac{\partial\psi_{bc}}{\partial \gamma} \omega - u_{\Sigma bc} \\
-\frac{\partial\psi_{ca}}{\partial \gamma} \omega - u_{\Sigma ca} \\
-\frac{\partial\psi_f}{\partial \gamma} \omega - R_f i_f + u_f \\
-\frac{\partial\psi_{yd}}{\partial \gamma} \omega - R_{yd} i_{yd} \\
-\frac{\partial\psi_{yq}}{\partial \gamma} \omega - R_{yq} i_{yq} \end{bmatrix},
\]

(7)

where \( L_{k,\Sigma} \) \((k = ab, bc, ca)\) – own total inductances of the circuits, \( M_{k,e} \) – equivalent mutual inductances of the circuits, \( u_{\Sigma k} \) – instantaneous values of
voltage drops on active resistances of circuits, \( M_{sf}, M_{bd}, M_{bq} \) \((k = ab, bc, ca)\) – mutual inductance values of the excitation winding, longitudinal and transverse damping windings.

**VERIFICATION OF THE IMPLEMENTED MODEL**

As an example, for the comparison of models, calculations of transient processes of the TVV-200-2 generator with the full symmetry of the phase windings are performed.

The generator operation is considered in several modes: in a normal steady state under load, in idle mode and a three-phase short circuit on the generator terminals.

The results of calculations of a three-phase short circuit at the generator outputs during a three-phase short circuit at the generator terminals and its operation in the load mode using simulation by a numerical method and in the Simulink environment are shown in Figures 2 and 3.

![Figure 2](image)

Figure 2. The results of calculations by a numerical simulation with a three-phase short circuit at the outputs of the generator and its operation in the load mode.
From a comparison of the results obtained with a three-phase short circuit at the generator terminals, it can be seen that in the numerical simulation method, the amplitude value of the shock short-circuit current $i_y = 38.4$ kA. When simulating a generator in MATLAB Simulink $i_y = 40.9$ kA.

The results of the comparison of the computational method and the model in the MATLAB Simulink environment obtained during the study with the symmetric phase circuits of the stator and without taking into account the saturation of the magnetic system showed the reliability of the proposed numerical simulation method. The implemented mathematical model makes it possible to consider the effect of the unbalance of the phase circuits of the stator and the saturation of the magnetic system in the simulation of a synchronous machine. In the future, the method will allow using the results of calculations of transient processes of a synchronous machine for analyzing the work and creating new algorithms for relay protection of generators of power plants.

REFERENCES