Modeling of sudden six-phase and three-phase short circuits of a six-phase turbogenerator

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Abstract. A demand for the highest possible power density in electrical machinery in some applications often requires a change in conventional and well-known three-phase stator winding solution. This paper discusses high-power turbogenerators with a six-phase winding. Mutual inductance between two three-phase windings requires updating of the equations for transient processes modelling. The equivalent circuits and equations for the dq0-reference frame are summarised, sudden six-phase and three-phase winding short circuit processes of the generator under load are modelled.

1. Six-phase turbogenerator application

In electrical energy industry sometimes it is economically efficient to build power units of ultimate power of 1200 MW and even 1800 MW. Volume and mass of such powerful turbogenerators become rather significant for the operation plant. Therefore, it is important to increase the power density of the machine while keeping the volume and mass minimized.

A way to solve this challenge that is used by various turbogenerator manufacturers is to adopt a six-phase stator winding instead of the conventional three-phase winding. The schematic representation of this solution is demonstrated in Figure 1. Two three-phase windings with 30° shift between them provide better winding factor that allows increasing of power density up to 6% [1].

Figure 1. General vector representation of a six-phase synchronous machine and transformation of a static coordinate system into a rotating system dqθ fixed with the rotor. Two three-phase windings ABC and XYZ have a 30° shift between. Rotor in general has excitation winding F in d-axis and damper windings Kd and Kq. Rotor angular speed is \( \omega_r \), and angular position is \( \Theta_r \).
The main drawback of six-phase winding arises from a fact that three-phase windings of the generator magnetically connected through mutual inductance. Firstly, normally both three-phase windings are connected to the same energy system; therefore, the 30° phase shift in voltages must be compensated. It could be solved via the usage of transformers with different groups of winding connection. Secondly, the presence of two three-phase windings brings challenges with steady state and transient regimes analysis for the electrical power system. Although the theory and practice for modeling and analysis of various regimes for a turbogenerator with a single three-phase winding is well developed [2-3], six-phase winding turbogenerators theory still have issues to be researched.

This paper focuses on a development of analytical model for six-phase turbogenerator to investigate two specific processes: sudden six-phase and sudden three-phase short circuiting from rated operational regime.

2. Modelling approach
The modelling approach for the six-phase synchronous generator is to some extent similar to three-phase machines [4-5]. The difference appears due to the mutual inductance of two windings.

2.1. Equivalent circuit
Equivalent circuits, shown in Figure 2, are used to obtain a system of linear differential equations. Here must be done an important assumption that the circuits are valid only for the main harmonic of regime parameters.

To cancel the dependency of machine inductances from rotor position the generator is transformed into an equivalent machine, which two three-phase windings (with 30° phase shift) are represented as two pairs of orthogonal stator windings: two on direct axis and two on quadrature axis. Voltages, applied to these windings are \( U_{d1} (U_{d2}) \) and \( U_{q1} (U_{q2}) \) correspondingly. Direct axis also has rotor excitation winding \( U_{f_d} \) and equivalent damping winding \( U_{k_d} \). Quadrature axis has an equivalent damping winding \( U_{k_q} \). Turbogenerators have their damping windings (or their equivalent) short circuited, thus \( U_{k_d} = U_{k_q} = 0 \).

2.2. Modelling equations
Generator is modeled in the terms of flux linkages in rotating coordinate system fixed with rotor, as was shown in figure 1. To transform the parameters from static coordinate systems \( ABC \) and \( XYZ \) into rotating coordinates \( dq0 \) the following dependences are used.

\[
\begin{bmatrix}
q \\
d \\
0
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\cos(\theta + \alpha) & \cos\left(\theta + \alpha - \frac{2\cdot\pi}{3}\right) & \cos\left(\theta + \alpha + \frac{2\cdot\pi}{3}\right) \\
\sin(\theta + \alpha) & \sin\left(\theta + \alpha - \frac{2\cdot\pi}{3}\right) & \sin\left(\theta + \alpha + \frac{2\cdot\pi}{3}\right) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
A \\
B \\
C
\end{bmatrix}
\]

where \( \alpha \) – initial angle between rotor \( q \)-axis and stator \( A \)-axis. It equals 0 for \( ABC \) winding and 30° for \( XYZ \) winding.

Then the reverse transformation is conducted as:
\[
\begin{pmatrix}
A \\
B \\
C
\end{pmatrix} = \begin{pmatrix}
\cos(\theta + \alpha) & \sin(\theta + \alpha) & 1 \\
\cos(\theta + \alpha - \frac{2\pi}{3}) & \sin(\theta + \alpha - \frac{2\pi}{3}) & 1 \\
\cos(\theta + \alpha + \frac{2\pi}{3}) & \sin(\theta + \alpha + \frac{2\pi}{3}) & 1
\end{pmatrix} \begin{pmatrix}
q \\
d \\
0
\end{pmatrix}
\]

For modeling of transient processes and for the ease of different machines comparison it is convenient to implement per unit values [6]. In this case all simulated parameters are the ratio of its value to a base parameter value.

Rotor angular speed is calculated as:

\[
\omega_r = \frac{1}{2 \cdot H \cdot p} (m_c - m_u)
\]

\[
H = \frac{1}{2} \cdot J \cdot \left( \frac{\Omega_b}{P} \right)^2 \cdot \frac{1}{S_b}
\]

Figure 2. General equivalent circuits for modeling of the processes in six-phase synchronous machine. Here and below subscription "d" stands for direct axis, "q" - for quadrature axis, "0" - zero component.
"1" - ABC winding, "2" - XYZ winding, "k" - damping winding, "f" - excitation winding, "σ" - winding leakage, "a" - magnetizing inductance.

where $m_e$ - generator electromagnetic torque, $m_t$ - applied turbine torque, $J$ - the shaft inertia.

$\Omega_b$ - base angular speed, $S_b$ - base power and $p$ is a number of pole pairs, equals 1 for turbogenerators.

Generator electromagnetic torque is calculated with an equation:

$$m_e = \left( \psi_{d1} \cdot i_{q1} + \psi_{d2} \cdot i_{q2} - \psi_{q1} \cdot i_{d1} - \psi_{q2} \cdot i_{d2} \right),$$

where $\psi$ - flux linkage with a winding and $i$ - current of the winding. To find the torque the following system of equations has to be solved [7-10]:

$$\begin{align*}
\psi_{q1} &= \Omega_b \cdot \left( u_{q1} - \omega_r \cdot v_{d1} - r \cdot i_{d1} \right), \\
\psi_{d1} &= \Omega_b \cdot \left( u_{d1} + \omega_r \cdot v_{q1} - r \cdot i_{q1} \right), \\
\psi_{q1} &= \Omega_b \cdot \left( u_{q1} - r \cdot i_{d1} \right), \\
\psi_{q2} &= \Omega_b \cdot \left( u_{q2} - \omega_r \cdot v_{d2} - r \cdot i_{d2} \right), \\
\psi_{d2} &= \Omega_b \cdot \left( u_{d2} + \omega_r \cdot v_{q2} - r \cdot i_{q2} \right), \\
\psi_{q2} &= \Omega_b \cdot \left( u_{q2} - r \cdot i_{d2} \right), \\
\psi_{q1} &= \Omega_b \cdot \left( u_{q1} - r \cdot i_{d1} \right). \\
\end{align*}$$

(4)

It implements the following relations between parameters:

$$\begin{align*}
\psi_{q1} &= x_{\sigma11} \cdot i_{q1} + x_{\sigma12} \cdot \left( i_{q1} + i_{q2} \right) + x_{aq} \cdot \left( i_{q1} + i_{q2} + i_{q4} \right), \\
\psi_{d1} &= x_{\sigma11} \cdot i_{d1} + x_{\sigma12} \cdot \left( i_{d1} + i_{d2} \right) + x_{ad} \cdot \left( i_{d1} + i_{d2} + i_{d3} + i_{d4} \right), \\
\psi_{d1} &= x_{\sigma11} \cdot i_{d1} + x_{\sigma12} \cdot \left( i_{d1} + i_{d2} \right) + x_{ad} \cdot \left( i_{d1} + i_{d2} + i_{d3} + i_{d4} \right), \\
\psi_{q2} &= x_{\sigma22} \cdot i_{q2} + x_{\sigma12} \cdot \left( i_{q1} + i_{q2} \right) + x_{aq} \cdot \left( i_{q1} + i_{q2} + i_{q4} \right), \\
\psi_{d2} &= x_{\sigma22} \cdot i_{d2} + x_{\sigma12} \cdot \left( i_{d1} + i_{d2} \right) + x_{ad} \cdot \left( i_{d1} + i_{d2} + i_{d3} + i_{d4} \right), \\
\psi_{d2} &= x_{\sigma22} \cdot i_{d2} + x_{\sigma12} \cdot \left( i_{d1} + i_{d2} \right) + x_{ad} \cdot \left( i_{d1} + i_{d2} + i_{d3} + i_{d4} \right), \\
\psi_{q2} &= x_{\sigma22} \cdot i_{q2} + x_{\sigma12} \cdot \left( i_{q1} + i_{q2} \right) + x_{aq} \cdot \left( i_{q1} + i_{q2} + i_{q4} \right). \\
\end{align*}$$

(5)

Obtaining the values of resistances and inductive reactances is a challenging part by itself. It could be done analytically or with numerical finite-element simulations and it is out of the scope of this paper. However it must be noticed that $x_{\sigma12}$ - is a mutual reactance between two three-phase windings and it is a core for understanding the results presented in this paper. An extensive description for determination of this parameter is provided in [11,12].
3. Results
The obtained system of equation is modelled in MatLab/Simulink software and solved for a real turbogenerator. Two transient processes are modelled, sudden six-phase short circuit and sudden three-phase short circuit of XYZ winding.

In both cases, after generator reaches a steady state regime and works in the grid of unlimited power, a sudden simultaneous short circuit at 0.5 seconds happens.

3.1. Six-phase sudden short circuiting
The peak current of six-phase short circuit is $i_{6\text{peak}}=4.8$ p.u. Excitation current $i_{f6\text{peak}}$ increased in 3.2 times. The peak value of electromagnetic torque is $m_{6\text{peak}}=2.8$ p.u. The traces of phase currents are shown in Figure 3.

3.2. Three-phase sudden short circuiting
The peak current of three-phase short circuit in braked XYZ winding is $i_{3\text{peak}}=14.6$ p.u. Although winding ABC continue to work in the grid it also experience transient process due to the presence of mutual reactance $x_{\sigma 12}$. The peak current in healthy winding is $i_{\text{peak}}=9.2$ p.u. Excitation current $i_{f3\text{peak}}$ increased in 2.5 times. The peak value of electromagnetic torque is $m_{3\text{peak}}=1.8$ p.u. The traces of phase currents are demonstrated in Figure 4.

![Figure 3. Transient process after sudden six-phase short circuit in a turbogenerator working with nominal power in a grid of unlimited power.](image-url)
4. Discussion

Six-phase winding turbogenerator models are still rarely discussed in publications. The model used in this paper allowed simulating of no-load, steady-state, and sudden six-phase / three-phase short circuit processes. It could be improved further to model even more specific regimes, as two-phase short circuiting with one phase from $ABC$ winding and second from $XYZ$ winding.

Although the modeling results had acceptable correlations with the experiment, it is clear that simulation results are directly dependent on the accuracy of parameters used. Therefore, the accurate calculation of all reactances and time constants, preferably with finite element modeling, is of a crucial importance.

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