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IMPLEMENTATION OF THE COMPENSATED OPERATION MODE OF A SYNCHRONOUS GENERATOR WITH DIRECT AND TRANSVERSE AXIS EXCITATION

РЕАЛІЗАЦІЯ СКОМПЕНСОВАНОГО РЕЖИМУ РОБОТИ СИНХРОННОГО ГЕНЕРАТОРА ПОДОВЖНЬО-ПОПЕРЕЧНОГО ЗБУДЖЕННЯ

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Abstract. The article considers the possibility of putting a synchronous generator into a compensated mode by controlling excitation in the transverse axis. In this mode, the transverse armature reaction is completely compensated by the magnetizing force of the transverse excitation winding, the rotor torque angle is maintained at zero level, and the transverse component of the load current vector is its active component. It is shown that introduction of a positive feedback in the transverse excitation axis on the active component of the load current is sufficient in order to provide for this mode. At the same time, only proportional control of the generator's armature voltage needs to be implemented for the direct excitation axis. Abandoning feedback on the reactive component of the armature current enables a more efficient damping of electromechanical oscillations in the system. As revealed by the study of the equation of dynamic equilibrium of the generator, oscillations of the rotor torque angle are damped at the use of the specified control method and at a loading angle below the critical value. The ratio of the magnetizing excitation forces and the transverse axis armature reaction has been analyzed, which allowed obtaining an analytical dependence of the feedback coefficient for the active component of the load current on the inductive resistance of the armature phase and geometric data of the generator.

Keywords: synchronous generator; direct and transverse axis excitation; transverse armature reaction; active load current.

Анотація. Проведено аналіз можливості забезпечення скомпенсованого режиму роботи синхронного генератора подовжньо-поперечного збудження за рахунок регулювання в поперечній осі за активною складовою струму навантаження. Запропоновано формулу для аналітичного визначення коефіцієнту зворотного зв'язку за активною складовою струму навантаження з метою поперечної реакції якоря та підтримки кута вильоту ротора рівним нулеві.

Ключові слова: синхронний генератор; подовжньо-поперечне збудження; поперечна реакція якоря; активний струм навантаження.

Аннотация. Проведен анализ возможности обеспечения скомпенсированного режима работы синхронного генератора продольно-поперечного возбуждения за счет регулирования в поперечной оси по активной составляющей тока нагрузки. Предложена формула для аналитического определения коэффициента обратной связи по активной составляющей тока нагрузки с целью компенсации поперечной реакции якоря и поддержания угла вылета ротора равным нулю.

Ключевые слова: синхронный генератор; продольно-поперечное возбуждение; поперечная реакция якоря; активный ток нагрузки.

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Problem statement. In comparison with single-axis excitation machines, synchronous machines with direct and transverse excitation have higher stability and controllability [1]. Through control in the transverse axis, it is possible to regulate active and reactive power separately, which in turn ensures a more effective oscillation damping in the electric power system [2] and enhances the dynamic characteristics of the machine itself [3, 4]. From this point of view, of particular interest is a compensated synchronous machine (CSM). In the full compensation mode, it has a remarkable feature: the rotor torque angle δ (which is basically the phase shift angle between the resultant vector of the direct axis EMF $\dot{E}_d$ and the voltage resultant vector $\dot{U}$) under any load is equal to zero (δ = 0) [5]. In this case, control in the transverse excitation axis has the largest effect on the magnitude of the generator's electromagnetic moment, which is crucial for effective damping of the rotor's mechanical oscillations.

Latest research and publications analysis. The load angle Θ is the angle between the total EMF vector $\dot{E}_\Sigma$ and the voltage vector $\dot{U}$. In a synchronous machine with single-axis excitation, δ = Θ in the steady-state mode. To the contrary, at direct and transverse excitation, transverse axis control generates an additional displacement of the $\dot{E}_\Sigma$ vector relative to the rotor, thus, generally δ ≠ Θ. An uncontrolled non-salient pole machine has the critical load angle Θ = 90° [6]. Yet, related publications indicate that the transverse axis excitation control makes it possible to ensure static stability of the machine's parallel operation with other generator sets regardless of the Θ value [7]. This phenomenon eliminates the problem of static overload of a synchronous machine. In other words, static overload of a synchronous machine theoretically becomes equal to infinity.

As a result of synthesis of the transfer function of an excitation controller providing invariant load current regulation [8], it has been established that the excitation current has to vary as a function of the direct component of the armature current in the direct axis and that of the transverse component in the transverse axis. At the same time, analysis of the operation of a compensated synchronous generator (CSG) providing for a high-power network [9, 10] has revealed the possibility of a substantial increase in the static stability limit due to the introduction of a positive feedback on the rotor torque angle in the transverse control axis and a derivative signal on the rotational frequency. Analysis of the single CSG operation with a static active-inductive load [11] confirmed the results obtained earlier and substantiated the necessity of introducing a negative proportional feedback on the armature voltage in the direct excitation axis. It has also been rendered that the direct axis excitation control on the direct component of the stator current largely worsens the static stability of the CSG operation [7].

THE ARTICLE AIM is to elaborate on the possibility of putting a synchronous generator with direct and transverse excitation into the compensated operation mode by controlling excitation in the transverse axis on the active component of the load current.

Basic material. The essence of compensation boils down to balancing the transverse armature reaction with excitation along the transverse axis of the inductor. This corresponds to the following condition:

$$\dot{F}_{aq} + \dot{F}_{fq} = 0 \text{ or } \dot{F}_{aq} = -\dot{F}_{fq}. \quad (1)$$

Here, $\dot{F}_{aq} = \vec{F}_{aq}$ is the temporal complex or the spatial vector of the magnetizing force (MF) of the CSM armature reaction; $\dot{F}_{fq} = \vec{F}_{fq}$ is the same vector (complex) of the MF of the CSM inductor's transverse winding.

Hence, there is no resulting magnetic flux along the transverse axis of the inductor and, consequently, no EMF of the armature reaction along the transverse axis.

The paper considers the problem of putting a CSM in the full compensation mode under varying loading. Thereat, it is necessary to answer the following questions:

1. What is the key parameter for achieving this goal?
2. How to compensate for the MF of the armature winding generated by alternating 3-phase current with the use of direct current of the inductor winding?
3. How does the electromechanical process of the generator entering the full compensation mode occur?
4. Which equipment is necessary for achieving this goal? In other words, what is the structure or functional diagram of the controller providing a solution to the problem?

Let us proceed with these questions in the above order. Thus, which parameter is decisive for achieving full compensation?

For this purpose, let us present the vector diagrams of a synchronous machine for stresses, EMFs, currents and magnetizing forces drawn up in the inductor axes for two cases: a) the machine is not compensated; b) the MF of the armature reaction along the transverse axis of the inductor is compensated. The diagrams are shown in Fig. 1.

It is known that the generator current and its phase with respect to voltage depend exclusively on the magnitude and nature of the load. The load itself is constantly changing in the course of operation. Consequently, the process of compensation is to be continuously adjusted. The question remains: what is the easiest way to achieve the full compensation mode?

Let us turn to the vector diagrams in Fig. 1. They clearly indicate that the active and reactive currents do not depend on the degree of compensation at a constant load (triangles of currents are highlighted in the diagrams). At the same time, the components of the load current along the inductor axes and, consequently, the MF and the EMF of the armature reaction are all functions of the δ angle.

In the case of full compensation, the active component of the load current is the current that generates the transverse armature reaction. If it is compensated by the current of the inductor's transverse winding, the transverse flux of the armature reaction and the transverse EMF of this reaction disappear. As a result, the voltage vector $\dot{U}$ will coincide in phase and space with the main EMF vector $\dot{E}_d$. The rotor torque angle δ will become zero regardless of the magnitude of the load. It follows from the above that the active component of the load

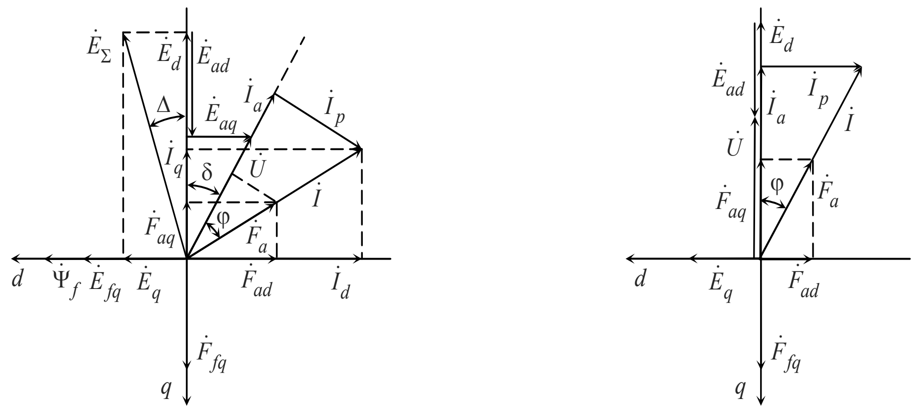

Fig. 1. Vector diagrams of a synchronous generator with direct and transverse excitation

current is the key parameter ensuring that the generator starts operating in the full compensation mode.

The next question is: what is the way of compensating the MF of the armature winding generated by the alternating 3-phase current using the direct current of the inductor winding? The apparent theoretical answer is formula (1). In practice, it is achieved with the fundamental spatial harmonics of these magnetizing forces $\vec{F}_{fq}$ and $\vec{F}_{aq}$ being equal in magnitude and opposite in phase. Our next step is to show how this happens.

In Fig. 2, (γπ) is the zone of so-called small teeth on the pole pitch of the inductor. This is where the main excitation winding is located. It is assumed that the compensating winding will be located in the large tooth zone (1 – γ)π.

The university course on electrical machines touches upon the question of equivalence of the excitation winding MF and the armature winding MF. Particularly, it draws a comparison between the fundamental spatial harmonics of the magnetizing forces of these windings.

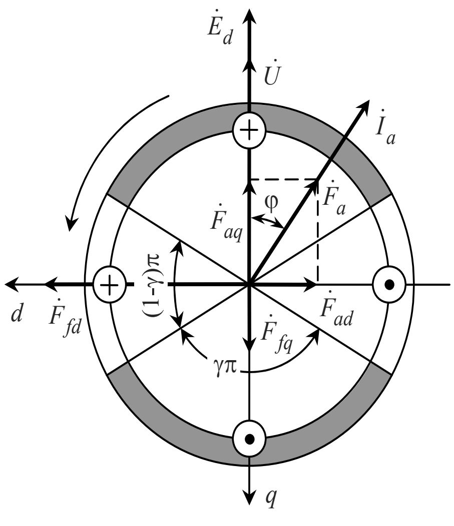

Fig. 2. Inductor with the zones of main and compensating windings

Generally speaking, if the wound part of the inductor's pole pitch occupies the angle (γπ), the amplitude of the fundamental harmonic of the MF will be expressed as follows [12]:

$$F_{\text{в}1} = \frac{8 \cdot \sin(\gamma\pi/2)}{\pi^2 \cdot \gamma} F_{\text{в}} = k_f F_{\text{в}}.$$

Here, k_f is the shape coefficient, $F_{\text{в}} = w_{\text{в}} i_{\text{в}}$ is the excitation winding MF on one pole, wв is the number of winding loops, and iв is the winding current.

Being equivalent to the specified value of the armature reaction MF, the value of the excitation MF F_a is calculated from the equality of amplitudes of their fundamental harmonics:

$$F_a = k_f \cdot F_{\text{вэ}}$$

The latter expression allows calculating the factor of reduction of the armature reaction MF to the excitation winding MF:

$$k_a = \frac{F_{\text{вэ}}}{F_a} = \frac{1}{k_f} = \frac{\pi^2 \cdot \gamma}{8 \cdot \sin(\gamma\pi/2)}.$$

If the compensating winding is to be considered, the area fort its placement on the pole division of the inductor is defined by the angle (1 – γ)π. Therefore, the reduction factor is as follows:

$$k_{aq} = \frac{F_{\text{в}q\text{э}}}{F_{aq}} = \frac{\pi^2 \cdot (1-\gamma)}{8 \cdot \sin[(1-\gamma)\pi/2]}.$$

The magnetizing excitation force equivalent to the transverse armature reaction is calculated with the help of the following expression:

$$F_{\text{в}q\text{э}} = k_{aq} F_{aq} = k_{aq} \frac{m\sqrt{2}}{\pi} \frac{k_{\text{об}} w}{p} I_q. \quad (2)$$

For a compensated machine, $I_q = I_a = I\cos\varphi$.

Having calculated the MF of the compensating winding through the active component of the load current, we can proceed to the question: how will the electromechanical process of the generator entering the full compensation mode occur?

Let us assume that condition (2) is satisfied (at this point not accounting for how it has been achieved). The generator is not yet compensated and is in a state corresponding to the vector diagram shown in Fig. 1, *a*. As the diagram apparently indicates, the inequality δ > 0 inadvertently leads to the dependency $I_q < I_a$; hence, the armature reaction MF Faq will be less than $F_{fq} = F_{вqэ}$. That is, there appears an excess MF $F_{q\Sigma}$ aligned in the positive direction of the transverse axis. The magnetizing force F_{fq} generates a magnetic flux, which in turn creates the EMF $\dot{E}_q$ and together with $\dot{E}_d$ forms the resultant EMF $\dot{E}_\Sigma$. Along with the voltage vector, the latter constitutes the load angle $\Theta_н = (\Delta + \delta + \varphi)$ and forms the electromagnetic power:

$$P_{эм} = \frac{E_\Sigma U}{x_d}\sin(\Theta).$$

In the initial steady-state mode, the mechanical power $P_{мех}$ and the electromagnetic $P_{эм}$ are balanced, which corresponds to the equation of dynamic equilibrium given below:

$$T_j\, p^2\Theta + P_{эм} = P_{мех}.$$

It is evident that at $P_{мех} = P_{эм}$, the rotor acceleration ($p^2\Theta$) is absent and the angle Θ = const.

According to this condition, the value of E_Σ depends only on the active component of the load current, which is defined by the values of the active load and the voltage *U*. However, the angle $\Theta_н$ is greater than the angle $\Theta_к$ which corresponds to the given steady-state mode ($\Theta_н = \delta + \Theta_к$). The positive value of the δ angle leads to an increase in the generator's electromagnetic power and, as a consequence, the braking moment. As a result, the rotor speed will get a negative increment, and the angle $\Theta_н$ will decrease until it reaches the value $\Theta_к$. A negative value of the δ angle will result in a decrease in the braking moment, acceleration of the rotor and an increase in $\Theta_н$ to the value of $\Theta_к$.

Thus, the increment of the braking electromagnetic moment at $F_{aq} \neq F_{fq}$ is such that the angle Θ tends to reach a given value of $\Theta_к$, which corresponds to zero of the rotor torque angle (δ = 0).

Let us now turn to the fourth question: which generator parameters can be measured or established based on the catalog data? First of all, these are current, stator phase reactance, and voltage from the active current sensor that is proportional to the active component of the load current.

Accordingly, using formula (2) we obtain the MF of the transverse excitation winding, which is equivalent to the MF of the transverse armature reaction. In this formula, $I_q = I_a$ and the factor of reduction of the transverse excitation winding MF to the transverse armature reaction MF (taking into account possible placement on the rotor) is calculated as follows:

$$K_{aq} = \frac{F_{вqэ}}{F_{aq}} = \frac{\pi^2\,(1-\gamma)}{8\sin\dfrac{(1-\gamma)\pi}{2}}.$$

In the absence of armature winding data, one can employ the phase reactivity; its value is easily either established experimentally or taken from the catalog [12]:

$$x_a = 2\,m\,f\,\frac{\mu_0\,D\,l_\delta}{k_\delta\,k_\mu\,\delta_{вз}}\left(\frac{k_{об}\,w}{p}\right)^2.$$

The quantities included in this formula are well known, so there is no need for explanation. Let us multiply x_a by $I_a^{\,2}(m/\pi^2)$:

$$\left(\frac{m}{\pi^2}\right)x_a\,I_a^{\,2} = \left(f\,\frac{\mu_0\,D\,l_\delta}{k_\delta\,k_\mu\,\delta_{вз}}\right)\cdot\left(\frac{m\sqrt{2}}{\pi}\,\frac{k_{об}\,w}{p}\right)^2 I_a^{\,2}.$$

This allows calculating the MF of the armature reaction along the transverse axis of the inductor:

$$F_{aq} = I_a\sqrt{\frac{m}{\pi^2}\,x_a\,\frac{k_\delta\,k_\mu\,\delta_{вз}}{f\,\mu_0\,D\,l_\delta}},$$

as well as the sought-for MF of the transverse excitation winding as a function of the active component of the load current I_a:

$$F_{вqэ} = \frac{\pi^2\,(1-\gamma)}{8\sin\dfrac{(1-\gamma)\pi}{2}}\cdot\sqrt{x_a\,\frac{m}{\pi^2}\,\frac{k_\delta\,k_\mu\,\delta_{вз}}{f\,\mu_0\,D\,l_\delta}}\cdot I_a(t),$$

or $F_{вqэ} = k_c I_a(t)$;

$$k_c = \frac{\pi^2\,(1-\gamma)}{8\sin\dfrac{(1-\gamma)\pi}{2}}\cdot\sqrt{x_a\,\frac{m}{\pi^2}\,\frac{k_\delta\,k_\mu\,\delta_{вз}}{f\,\mu_0\,D\,l_\delta}},$$

where k_c is unit conversion factor.

The control action is ultimately the voltage across the transverse excitation winding. Its value is established using the considerations below.

The output voltage of the active current sensor (ДАТ) is calculated as follows:

$$U_{ДАТ}(t) = k_{пр}\,I_a(t),$$

where $k_{пр}$ is the reduction factor depending on the sensor circuit.

The MF of the transverse excitation winding is equal to

$$F_{вqэ} = w_{вq}\,\frac{U_{вq}}{r_{вq}} = k_c\,I_a(t) = \frac{k_c}{k_{пр}}\,U_{ДАТ}(t),$$

whereof the control action is equal to

$$U_{вq}(t) = \frac{k_c}{k_{пр}}\,\frac{r_{вq}}{w_{вq}}\,U_{ДАТ}(t) = k_\Sigma\,U_{ДАТ}(t),$$

where $w_{вq}$ is the number of loops in the transverse excitation winding, and $r_{вq}$ is its active resistance.

CONCLUSIONS. 1. The compensated mode of operation of a synchronous generator with longitudinal-transverse excitation can be achieved when the magnetizing forces of the transverse reaction of the armature and the transverse excitation winding are equal; in this case, the rotor torque angle is zero. 2. To provide full compensation in the entire range of possible operation modes, it is necessary to introduce feedback on the active component of the load current in the transverse excitation axis. In the direct excitation axis, only proportional control of the generator's armature voltage needs to be implemented, which makes one abandon feedback on the reactive load current, thus increasing the level of static stability of the generator operation. 3. Analysis of the equation of dynamic equilibrium showed that oscillations of the rotor torque angle while setting the new operation mode are damped at the control method under consideration and load angles not exceeding 90 electrical degrees. 4. There was obtained an analytical expression for the feedback coefficient in the transverse excitation axis on the active component of the load current. The coefficient depends on the inductive resistance of the armature phase and the geometric data of the generator.

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