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POWER SYSTEM STABILITY AND ROBUSTNESS OF SYNCHRONOUS MACHINE’S EXCITATION CONTROL WITH MAGNITUDE-PHASE VOLTAGE REGULATOR*

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The conditions necessary to provide the robust stability and robust control of synchronous machine’s excitation control with magnitude-phase automatic voltage regulator are determined. References 4, figures 1.

***Key words**:* power system stability, synchronous machine, voltage phasor, magnitude-phase automatic voltage regulator, robustness.

Power System stability depends on different factors, but considerably depends on excitation control of synchronous machines (SM) with used types and settings of automatic voltage regulators [1, 2]. Therefore the improvement of SM’s excitation control effectiveness is an important power system problem. Conventional excitation control systems are designed based on linearized models of SM and power system. These models are designed for a given operation mode, and therefore the conventional excitation controllers sometimes work improperly if power system operation conditions are changed considerably. Nonlinear excitation controllers usually have a more complicated structure and more parameters, and therefore are harder to implement in practice.

Excitation control is based on the evaluation of the scalar mismatch error between a reference voltage V_{ref} and a measured terminal voltage V_t. The obtained scalar error $\Delta V = V_{ref} - V_t$ is used as the input of a PID controller or its simplified variants (PD, PI) to control the excitation current I_f of SM. The purpose of this control is the precise maintenance of the SM terminal voltage V_t according to the reference voltage V_{ref} in all possible operation conditions. In order to achieve this, it is necessary to set the greatest possible value of the automatic voltage regulator’s (AVR) proportional gain. However, in some operation conditions of SM this leads to a decrease of damping component of the electric moment that is proportional to the rotor speed deviation $\Delta\omega$ and to electromechanical oscillations. Therefore, additionally in SM excitation control the feedbacks on the parameters which characterize the rotor motion (a frequency deviation Δf, a rotor speed deviation $\Delta\omega$, a field current deviation ΔI_f or an accelerating power P_a) are used. These additional feedbacks are implemented as stabilizing channels in automatic excitation regulators of a strong action in Russia [4] or as separate devices - power system stabilizers (PSS) [2]. This greatly complicates the design, subsequent coordination of regulation and stabilization channels, holding of the commissioning works and operation of excitation control systems. Therefore the development of an excitation control system which implements a new feedback type is the urgent problem. The structure of such a feedback reflects both the electromagnetic state, determined by terminal voltage magnitude, and electro-mechanical state, defined by the SM rotor movement. In order to achieve this, it is necessary to increase the dimension of the mismatch error in such a way that this error is able to reflect both the deviations of the terminal voltage and the deviations of rotor angle of the SM. According to this requirement the terminal voltage phasor of the SM is used as input of the magnitude-phase automatic voltage regulator (MP-AVR**)**.

Parameters and sometimes even structure of power system elements under the different operation conditions are subjected to significant nonlinear changes. Therefore the MP-AVR should have the property of robustness to these changes, providing the required robust stability and robust performance of control under a given structured and unstructured uncertainty of synchronous machine and power system models.

We define a setpoint of the SM excitation controller as some phasor $\overline{V}_{ref}$ (p. u.), which coincides in the steady-state with the field current I_f (p. u.) or synchronous EMF phasor $\overline{E}_q$ (p. u.). The magnitudes of the setpoint and terminal voltage phasors are equal $\left|\overline{V}_{ref}\right| = \left|\overline{V}_{t0}\right|$, (p. u.), but these phasors are shifted by the steady-state rotor angle δ_{SM0}, in accordance with the diagram presented in Figure, where $\Delta\overline{e}$ is an error for MP-AVR, and ΔV is an error for existent AVR. In transient, as a result of disturbance in the power system, the increment ($\Delta\overline{e}$) of an error function of a complex argument (CAEF) is defined as

$$\Delta\overline{e} = f(\Delta V_t, \Delta\delta_{SM}) = \overline{e}_{N0} - \overline{e}_1 = (V_{t1}\cos\delta_{SM1} - V_{t0}\cos\delta_{SM0}) + j(V_{t1}\sin\delta_{SM1} - V_{t0}\sin\delta_{SM0}) = (V_{q1} - V_{q0}) + j(V_{d1} - V_{d0}) \quad (1)$$

Taking into account $\left|V_{t0}\right| = \left|V_{ref}\right|$ the CAEF increment $\Delta\overline{e}$ reflects the increments of the terminal voltage magnitude ΔV_t and rotor’s angles ($\Delta\delta_{SM}$), and generalizes the traditional definition of the error by magnitude terminal voltage:

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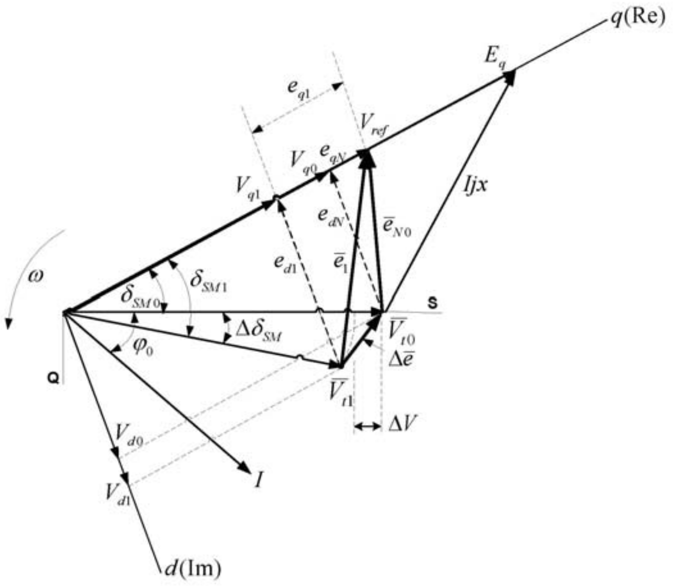
$$\Delta\bar{e}=\left|\bar{V}_{t0}-\bar{V}_{t1}\right|=\sqrt{V_{ref}^2+V_{t1}^2-2V_{ref}V_{t1}\cos(\Delta\delta_{SM})}=\sqrt{(V_{q1}-V_{q0})^2+(V_{d1}-V_{d0})^2},\ \Delta V_t=V_{ref}-V_{t1}=V_{t0}-V_{t1}=\sqrt{V_{q0}^2+V_{d0}^2}-\sqrt{V_{q1}^2+V_{d1}^2}. \tag{2}$$



The calculation of the CAEF increment based on the Wirtinger partial derivatives. Taking into account that output of the excitation control is oriented in the direction of the antigradient (1) we obtain the following control law with MP-AVR

$$\Delta V_f=K\left(\Delta V_{ref}-\frac{2\cos\left(N\Delta\delta_{SM}\right)}{1+\cos\left(2N\Delta\delta_{SM}\right)}\Delta V_t\right)=$$
$$=K\left(\Delta V_{ref}-\sec\left(N\Delta\delta_{SM}\right)\Delta V_t\right), \tag{3}$$

where K – a gain of the proportional channel by the magnitude deviation of the terminal voltage phasor $\left|\Delta V_t\right|$, and N – a gain by rotor angle deviation $\Delta\delta_{SM}$. When $\Delta V_{ref}=0$ the equation (3) in increments is

$$\Delta V_f=K_F\,\Delta V_t,$$

where $K_F=-K\sec\left(N\Delta\delta_{SM}\right)$ – an adaptive feedback gain of the excitation control by terminal voltage phasor.

Using the expression for the rotor angle deviation by means of the rotor speed deviation we obtain

$$\Delta\delta=\Delta\omega\cdot\Delta t\ \rightarrow\ \Delta V_f=-K\sec\left(N\Delta\omega\,\Delta t\right)\Delta V_t,$$

$$-K\sec\left(N\Delta\omega\Delta t\right)=\frac{\Delta V_f}{\Delta V_t}=C_{MP-AVR}\left(t\right). \tag{4}$$

Let us define a transfer function of MP-AVR (C_{MP-AVR}). Taking into account that for the trigonometric function *secant* the direct Laplace transform does not exist we present this function in the expression (4) by the series expansion

$$\sec\left(N\Delta\omega\Delta t\right)=\sum_{n=0}^{\infty}\frac{|E_n|\left(N\Delta\omega\Delta t\right)^{2n}}{\left(2n\right)!}=1+\frac{1}{2}\left(N\Delta\omega\Delta t\right)^2+\frac{5}{24}\left(N\Delta\omega\Delta t\right)^4+\frac{61}{720}\left(N\Delta\omega\Delta t\right)^6+\ldots, \tag{5}$$

where E_n – the Euler number.

Using first three terms of the series (5), we obtain the "restricted" direct Laplace transform, and then the transfer function C_{MP-AVR} will be presented at $\Delta\omega\equiv s$ in the form:

$$C_{MP-AVR}=-K\,s^{-1}\,(1+N^2+5N^4).$$

To ensure the robust stability and robust performance of SM excitation control it is necessary to find a stabilizing controller such as [3]

$$\sup_{\omega\in R}\mu\left[F_l\left(SM,C\right)\left(j\omega\right)\right]<1,\quad \inf_{C(s)}\sup_{\omega\in R}\mu\left[F_l\left(SM,C\right)\left(j\omega\right)\right], \tag{6}$$

where μ – structural singular values of the matrix $F_l\left(SM,C\right)\left(j\omega\right)$, ω – frequencies of the electromechanical transient, *SM* – transfer function (matrix) of the SM model, *C* – transfer function (matrix) of the excitation controller model. The maximum μ of the many input-many output (MIMO) system is considered the worst gain in the worst direction. The requirement of the robustness of excitation control system is achieved with a large feedback gain in low frequency range and with small values of the feedback gain in the high frequency band. If the conventional notations for sensitivity function $S\left(j\omega\right)$ and complementary sensitivity function $T\left(j\omega\right)$ are used [3]

$$S\left(j\omega\right)=\frac{1}{1+SM\left(j\omega\right)C\left(j\omega\right)},\quad T\left(j\omega\right)=\frac{SM\left(j\omega\right)C\left(j\omega\right)}{1+SM\left(j\omega\right)C\left(j\omega\right)},$$

then the next trade-off must be executed

$$S\left(j\omega\right)+T\left(j\omega\right)=1.$$

Therefore it is necessary to maintain these functions' values low enough at the appropriate points in time which correspond to the stages of the operation modes. Also, in accordance with Bode's stability criterion [3], the feedback gain should be less than 1 at the critical frequency wherein the closed loop's phase delay is 180º. In order to achieve this aim, the gain N is introduced in the MP-AVR, thus in the feedback the polarity change at rotor angle deviation $\Delta\delta > \pi / 2N$ is achieved. After some substitution in the first of the expressions (6) we can obtain the inequality that allows to determine the vector of parameters (K, N) for MP-AVR, depending on the transfer function of the nominal model *SM*.

Conclusions. The non-complicated structure of the nonlinear MP-AVR with complex input signal is proposed. The parameters of such signal are used to regulate the terminal voltage magnitude and to damp the SM's electromechanical oscillations. The control law and transfer function of MP-AVR are presented. The conditions of the robustness of excitation control system are determined. Experimental studies have confirmed the effectiveness and robustness of the proposed MP-AVR.

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СТІЙКІСТЬ ЕНЕРГОСИСТЕМИ ТА РОБАСТНІСТЬ КЕРУВАНИЯ ЗБУДЖЕННЯМ СИНХРОННОЇ МАШИНИ З АМПЛІТУДНО-ФАЗОВИМ РЕГУЛЯТОРОМ НАПРУГИ

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Визначено умови, необхідні для забезпечення робастної стійкості та робастного керування збудженням синхронної машини з амплітудно-фазовим автоматичним регулятором напруги. Бібл. 4, рис. 1.

Ключові слова: стійкість енергосистеми, синхронна машина, вектор напруги, амплітудно-фазовий регулятор напруги, робастність.

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УСТОЙЧИВОСТЬ ЭНЕРГОСИСТЕМЫ И РОБАСТНОСТЬ УПРАВЛЕНИЯ ВОЗБУЖДЕНИЕМ СИНХРОННОЙ МАШИНЫ С АМПЛИТУДНО-ФАЗОВЫМ РЕГУЛЯТОРОМ НАПРЯЖЕНИЯ

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Определены условия, необходимые для обеспечения робастной устойчивости и робастного управления возбуждением синхронной машины с амплитудно-фазовым автоматическим регулятором напряжения.
Библ. 4, рис. 1.

Ключевые слова: устойчивость энергосистемы, синхронная машина, вектор напряжения, амплитудно-фазовый регулятор напряжения, робастность.

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