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AVR/PSS Structure by Terminal Voltage Phasor

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Abstract

In paper the new structure of the automatic voltage regulator (AVR) and the power system stabilizer (PSS) of the synchronous machines is considered. It is known, that the primary goal, that solved AVR are maintenance of a terminal voltage of the synchronous machine according to the reference. For PSS, the goal is mitigation the electromechanical oscillations of the synchronous machine at various disturbances. For these purposes as inputs of the AVR and PSS the set of state variables of the synchronous machine is used: terminal voltage, armature current, frequency, speed, power, etc. The key feature of offered excitation control system is use only the terminal voltage phasor for the decision of all above-stated problems, that considerably reduces influence of noises and disturbances, simplifies its design and operation.

Keywords: Hilbert transform; terminal voltage phasor; complex argument error function (CAEF); Wirtinger calculus; stability.

1. Introduction

Now, for excitation control of the synchronous machines, the fundamental role played the feedback at magnitude terminal voltage [1]. Excitation control based on the calculation the scalar error between the setpoint (reference) V_{ref} and the measured magnitude terminal voltage V_t . The resulting scalar error $\Delta V = V_{ref} - V_t$ uses as the input of the automatic voltage regulator (AVR), that is PID controller or its truncated variants (PD, PI) [2], for field current control. The purpose of this regulation is the exact

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maintenance V_t in accordance with V_{ref} in all possible operating modes. That determined the large values of the proportional gain of the AVR ($K_P \geq 25$). However, as has been determined theoretically and observed in practice [1], in some operation modes of the synchronous machines, this leads decreasing in damping component T_D of the electric moment T_E , that proportional to the deviation of the speed $\Delta\omega$. This is causing the rotor oscillations of the synchronous machines at disturbances in the grid. Therefore, in addition to the AVR, using feedback to the parameters that reflect the rotor motion – speed, frequency, accelerating power, which used in power system stabilizer (PSS). This greatly complicates the development, subsequent coordination of AVR/PSS and commissioning the excitation control of the synchronous machines. So, promising is the development of the excitation control, which realizes a new type of the feedback, which reflects the states of the terminal voltage and the rotor motion.

Paper includes sections with the following contents. Section II defines the two-dimensional complex argument error function (CAEF) of the terminal voltage phasor and a method of it measuring. Consider the definition of the normal CAEF (NCAEF) for steady state of the plant. Presented the calculation of the differential CAEF at terminal voltage phasor with use the Wirtinger calculus. In section III showed the excitation control of the synchronous machine that used CAEF at terminal voltage phasor. The example for study the small-signal stability with proposed excitation control is given in the section IV. The conclusions are summarized this paper.

2. Complex Argument Error Function (CAEF).

The properties of inertial elements within plant and the limited signal propagation speed are the cause of retardation (lagging) observed between narrow-band output and input signals and state variables. We shall make the following formulations for the error considering the plant output retardation data and for the narrow-band nature of the input and output signals:

Definition 1: The complex argument error function (CAEF) $\bar{e}$ shall be the difference between the input (set point) $\bar{r}$ and output $\bar{y}$ of a plant to be calculated at the complex plane *C*, whose inphase axis *S* has been determined by the direction $\bar{r}$ and whose quadrature axis *Q* has been displaced at the angle *π/2* within the Cartesian coordinate system, and this fact makes it possible to heed the phase displacement $\bar{y}$ against $\bar{r}$.

CAEF $\bar{e}$ [3] can be visualized both in a vector form or in a complex form as follows: $\bar{e} = \bar{r} - \bar{y} = e_s + je_q$, where $j = \sqrt{-1}$ is an imaginary value, e_s and e_q are the CAEF components within the Cartesian coordinate system inphase and quadrature to $\bar{r}$, respectively, and φ is a phase lag proportionate to the quadrature component of the complex output $\bar{y}$:

$$\bar{e} = \bar{r} - \bar{y} = r - \left(y\cos(\varphi) + jy\sin(\varphi)\right) = e_s + je_q, e_s = r - \left(y\cos(\varphi)\right), e_q = -y \cdot \sin(\varphi) \tag{1}$$

Accordingly, the steady-state conditions of a plant can be described by the normal complex argument error function (NCAEF) $\bar{e}_{N0}$:

Definition 2: The normal CAEF (alias NCAEF) $\bar{e}_{N0}$ under the steady-state conditions (equilibrium point) for a plant is characterized by the equality of the magnitudes $\left|\bar{y}_0\right| = \left|\bar{r}_0\right|$ and by the normal phase lag φ_{N0} , which is determined by the steady state of the inertial elements comprised by the plant structure.

In the event of breach of the steady-state conditions, the occurring deviation of the phase lag $\Delta\varphi$ can be calculated thru Hilbert transform (***HT***) [4] by determining the input $\bar{r}$ and output $\bar{y}$ in the form of analytical signals. The imaginary part of the analytical signal $\tilde{s}(t)$ or the ***HT*** of the actual signal $s(t)$ are determined by its convolution with the function $1/\pi t$. So, the difference between instantaneous phases of two arbitrary signals $r(t), y(t)$ [5] shall be:

$$\Delta\varphi_{yr} = \varphi_y(t) - \varphi_r(t) = arctg\frac{\tilde{y}(t)\cdot r(t) - y(t)\cdot\tilde{r}(t)}{y(t)\cdot r(t) + \tilde{y}(t)\cdot\tilde{r}(t)} \tag{2}$$

Next, we consider the application of CAEF and NCAEF for excitation control, Fig. 1:

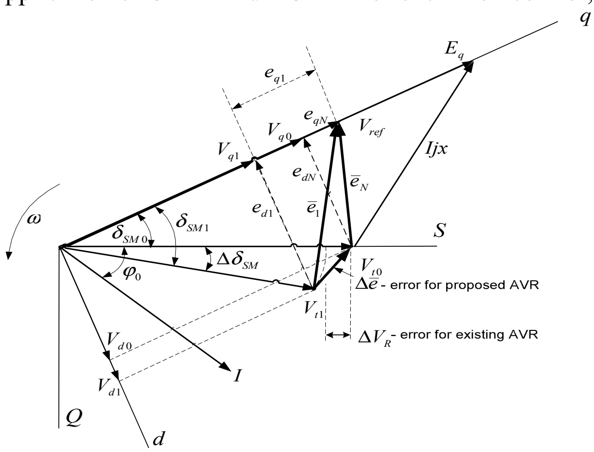


Fig. 1. Vector diagram of the synchronous machine with use of CAEF.

With fig. 1, deviation of CAEF reflects the terminal voltage ΔV_t and rotor angle $\Delta\delta_{SM}$ deviations, and differs from the traditional definition of the error for the AVR:

$$\begin{aligned} \Delta e &= \left|\bar{V}_{t0} - \bar{V}_{t1}\right| = \sqrt{V_{ref}^2 + V_{t1}^2 - 2V_{ref}V_{t1}\cos(\Delta\delta_{SM})} = \sqrt{(V_{q1} - V_{q0})^2 + (V_{d1} - V_{d0})^2}, \\ \Delta V_t &= V_{ref} - V_{t1} = V_{t0} - V_{t1} = \sqrt{V_{q0}^2 + V_{d0}^2} - \sqrt{V_{q1}^2 + V_{d1}^2} \end{aligned} \tag{3}$$

We consider the excitation control at CAEF of terminal voltage phasor and its impact on small-signal stability for model "synchronous machine - infinite bus" (SMIB).

3. CAEF Excitation Control.

If we use the terminal voltage phasor as the input for excitation control, we can react to changes in both the electromagnetic and electromechanical states of a synchronous machine, as take into account the increments of the magnitudes terminal voltage and the rotor angle in case of violation the steady state. Control of the various plants based on the real signals. Therefore, CAEF should be considered as a real function of the complex arguments - the output of the plant. It is known [6], that the nonconstant real-valued function of a complex variable is nonanalytic and therefore does not differentiate in the accepted sense for the complex variables (Cauchy-Riemann conditions). To calculate the stationary points and differential CAEF (3) in the whole domain of the terminal voltage phasor, we used the definition of a real differentiable [6, 7] for CAEF:

Theorem: Let CAEF is determined by real variables: $V_{ts} = \left(\overline{V}_t + \widetilde{V}_t\right)/2$ and $V_{tq} = \left(\overline{V}_t - \widetilde{V}_t\right)/2j$ so that it deviation is $\Delta e(\overline{V}_t) = f(V_{ts}, V_{tq}) = f(\overline{V}_t, \widetilde{V}_t) = \Delta e_s\left(\left(\overline{V}_t + \widetilde{V}_t\right)/2, \left(\overline{V}_t - \widetilde{V}_t\right)/2j\right) + j\Delta e_q\left(\left(\overline{V}_t + \widetilde{V}_t\right)/2, \left(\overline{V}_t - \widetilde{V}_t\right)/2j\right)$, where $\overline{V}_t = V_{ts} + jV_{tq} = V_t\cos(\Delta\delta_{SM}) + jV_t\sin(\Delta\delta_{SM})$ and $\widetilde{V}_t = V_{ts} - jV_{tq} = V_t\cos(\Delta\delta_{SM}) - jV_t\sin(\Delta\delta_{SM})$ complex and complex-conjugate, independent of each other terminal voltage phasor. Then:

1) can be defined Wirtinger derivative [6, 7] of CAEF:

$$\frac{d\left(\Delta e(\overline{V}_t)\right)}{d\overline{V}_t} = \frac{1}{2}\left(\frac{\partial\left(\Delta e(\overline{V}_t)\right)}{\partial V_{ts}} - j\frac{\partial\left(\Delta e(\overline{V}_t)\right)}{\partial V_{tq}}\right); \frac{d\left(\Delta e(\overline{V}_t)\right)}{d\widetilde{V}_t} = \frac{1}{2}\left(\frac{\partial\left(\Delta e(\overline{V}_t)\right)}{\partial V_{ts}} + j\frac{\partial\left(\Delta e(\overline{V}_t)\right)}{\partial V_{tq}}\right) \tag{4}$$

2) necessary and sufficient conditions for a stationary point (equilibrium point) $(\overline{V}_{ref}, \overline{V}_{t0}, \overline{e}_{N0})$ CAEF is:

$$d\left(\Delta e\left(\overline{V}_{ref}, \overline{V}_{t0}, \widetilde{V}_{t0}\right)\right)/d\overline{V}_t = 0 \text{ or } d\left(\Delta e\left(\overline{V}_{ref}, \overline{V}_{t0}, \widetilde{V}_{t0}\right)\right)/d\widetilde{V}_t = 0 \tag{5}$$

Then for differential of the CAEF we obtain [8]:

$$\begin{aligned} d(\Delta\overline{e}) &= 2\,\mathrm{Re}\left\{\frac{\partial(\Delta e(\overline{V}_t))}{\partial(\widetilde{V}_t)}\Delta\overline{V}_t\right\} = 2\,\mathrm{Re}\left\{\frac{1}{2}\left(\frac{\partial(\Delta e(\overline{V}_t))}{\partial(V_{ts})} + j\frac{\partial(\Delta e(\overline{V}_t))}{\partial(V_{tq})}\right)\Delta\overline{V}_t\right\} = \\ &= \mathrm{Re}\left\{j(ctg(\Delta\delta_{SM}) + tg(\Delta\delta_{SM}))\cdot((V_t\cos(\Delta\delta_{SM}) - V_{ref}) + j(V_t\sin(\Delta\delta_{SM})))\right\} = -\frac{2\cos(\Delta\delta_{SM})}{1+\cos(2\Delta\delta_{SM})}V_t \end{aligned} \tag{6}$$

So, the excitation control at CAEF of terminal voltage phasor we define:

$$u = K\left(V_{ref} - \frac{2\cos(N\Delta\delta_{SM})}{1+\cos(2N\Delta\delta_{SM})}V_t\right) = K\left(V_{ref} - V_t\sec\left(N\Delta\delta_{SM}\right)\right) \tag{7}$$

where K - gain at deviation of the magnitude terminal voltage phasor, and N - gain at deviation of the rotor angle. Block diagram for model Heffron - Phillips [1] with static excitation system [2] shown in Fig. 2:

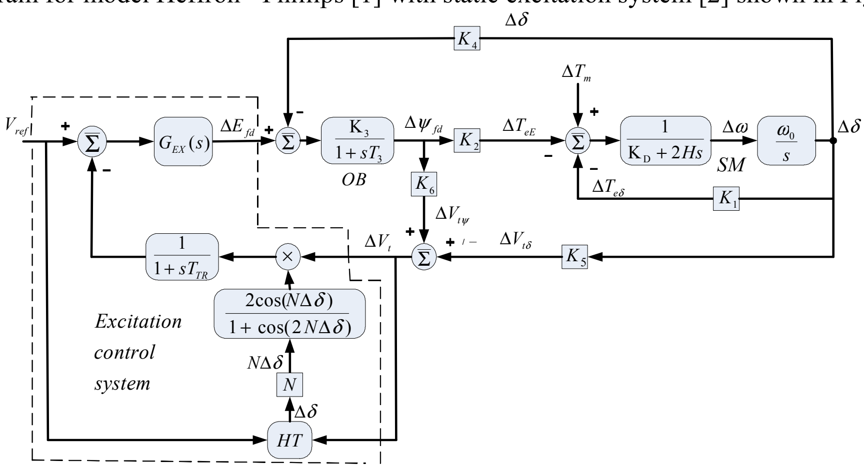


Fig. 2. Block diagram of the SMIB-model with CAEF.

In this diagram, the notation of the state variables, coefficients and time constants in accordance with [1] and in addition the dotted line marked the excitation control system of synchronous machine which are designated: T_{TR} - summary time constant of the excitation control system, HT - block, that performs a Hilbert transform for the signals setpoint and the terminal voltage and then calculate the deviation of the rotor angle $\Delta\delta$, N - stabilizing coefficient, the purpose of which will be discussed below, $G_{EX}(s) = K_A$ - coefficient of the static excitation system. With state-space model [1], and control law (7) the deviation of the field flux linkage $\Delta\psi_{fd}$:

$$\begin{aligned}\Delta\psi_{fd} &= \frac{K_3}{1+sT_3}\cdot\left(-K_4\Delta\delta - \frac{K_A}{1+sT_{TR}}(K_5\Delta\delta + K_6\Delta\psi_{fd})\frac{\cos(N\Delta\delta)}{1+\cos(2N\Delta\delta)}\right) = \\ &= \frac{-K_3\left[K_4(1+sT_{TR})(1+\cos(2N\Delta\delta)) + K_5K_A\cos(N\Delta\delta)\right]}{(1+sT_3)(1+sT_{TR})(1+\cos(2N\Delta\delta)) + K_3K_6K_A\cos(N\Delta\delta)}\Delta\delta\end{aligned} \tag{8}$$

where gain 2 with (7) included in K_A. Then the electrical moment ΔT_{eE} is:

$$\begin{aligned}\Delta T_{eE} &= K_2\Delta\psi_{fd} = \Delta T_{eES} + \Delta T_{eED} == \frac{-K_2K_3\left[K_4(1+j\omega T_{TR})(1+\cos(2N\Delta\delta)) + K_5K_A\cos(N\Delta\delta)\right]}{(1+j\omega T_3)(1+j\omega T_{TR})(1+\cos(2N\Delta\delta)) + K_3K_6K_A\cos(N\Delta\delta)}\Delta\delta = \\ &= \left[\begin{array}{l}\dfrac{-K_2K_3\left[K_4(1+j\omega T_{TR})(1+\cos(2N\Delta\delta) + K_5K_A\cos(N\Delta\delta)\right]}{z}\cdot \\ \cdot[(1+\cos(2N\Delta\delta))(1-\omega^2T_3T_{TR}) + K_3K_6K_A\cos(N\Delta\delta)]\end{array}\right]\cdot(\Delta\delta) + \\ &+ \left[\begin{array}{l}\dfrac{-K_2K_3\left[K_4(1+j\omega T_{TR})(1+\cos(2N\Delta\delta) + K_5K_A\cos(N\Delta\delta)\right]}{z}\cdot \\ \cdot(T_3+T_{TR})(1+\cos(2N\Delta\delta))(-j\omega\Delta\delta)\end{array}\right]\cdot(-j\omega\Delta\delta)\end{aligned} \tag{9}$$

where $z = [(1+\cos(2N\Delta\delta))(1-\omega^2T_3T_{TR}) + K_3K_6K_A\cos(N\Delta\delta)]^2 + [\omega(T_3+T_{TR})(1+\cos(2N\Delta\delta))]^2$.

In the literature [1] noted, that for modern power systems $(K_2, K_3, K_4, K_6) > 0$. Appearance, the negative damping of the synchronous machines is determined by the coefficient K_5 , which can be negative, especially for high-speed excitation control. Derivation of the analytical expressions for determining the values K_A and N with equation (9) is rather cumbersome. Therefore we considered them to calculate a specific example, given in [1].

4. Example: Excitation control with CAEF.

Consider SMIB-model, given in [1], with parameters:

$$K_1 = 1.591, K_2 = 1.5, K_3 = 0.333, K_4 = 1.8, K_5 = -0.12, K_6 = 0.3, T_{TR} = 0.02, T_3 = 1.91, H = 3.0, K_D = 0,$$

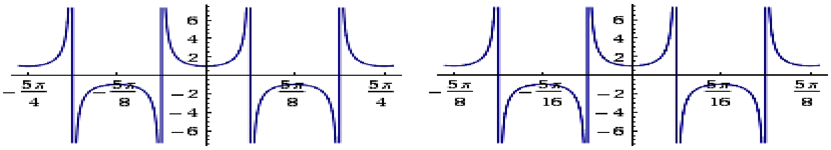
$$G_{ex}(s) = K_A\left(V_{ref} - \frac{2\cos(N\Delta\delta)}{1+\cos(2N\Delta\delta)}V_t\right) = 200\left(V_{ref} - \frac{2\cos(N\Delta\delta)}{1+\cos(2N\Delta\delta)}V_t\right)$$

Using these values, and taking into account (9), we calculate the positive synchronization and damper moments, when the rotor angle deviation is $\Delta\delta = 1$ rad. and $T_{TR} = 0$:

$$\begin{aligned}&\Delta T_{eES} > 0 \rightarrow \; -K_2K_3\left[K_4(1+\cos(2N\Delta\delta) + K_5K_A\cos(N\Delta\delta)\right]\cdot\left[1+\cos(2N\Delta\delta) + K_3K_6K_A\cos(N\Delta\delta)\right] > 0 \\ &\Delta T_{eED} > 0 \rightarrow \; -K_2K_3T_3\left[K_4(1+\cos(2N\Delta\delta) + K_5K_A\cos(N\Delta\delta)\right]\cdot\left[1+\cos(2N\Delta\delta)\right] < 0\end{aligned} \tag{10}$$

That the domain of admissible values N : $0.5(12.56n+3.14) < N < 2(3.14n+0.81), n \in Z$

We define $N = 1.6$. The influence of the gain N on the AVR sensitivity at the rotor angle deviation shown on Fig. 3:



$N = 1.6(\Delta\delta_{\max} = 56^{\circ})$ $N = 3.2(\Delta\delta_{\max} = 28^{\circ})$

Fig. 3. Function $\left(2\cos(N\Delta\delta)/\left(1+\cos(2N\Delta\delta)\right)\right) = \sec\left(N\Delta\delta\right)$ for different N .

Analysis of the above calculation shows, that the excitation control system at CAEF of the terminal voltage phasor has a variable gain of the feedback, that defined the initial value for its steady state (at small rotor angle deviation) $K_A = 200$ and changes as $\dfrac{2\cos(N\Delta\delta)}{1+\cos(2N\Delta\delta)} = \sec\left(N\Delta\delta\right)$ in transients (for large rotor angle deviation). Thus, the natural coordination of tasks by AVR (maintenance of the terminal voltage in accordance with a prescribed setpoint) and PSS (damping of the electromechanical oscillations) is achieved.

5. Conclusion.

In paper presented the new type of the feedback control system, that realized by deviations of magnitude and phase delay of the plant output. In fact, the proposed controller (10) is proportional (P-controller), gain of it is depended by deviation the phase delay (deviation of rotor angle $\Delta\delta_{SM}$) in transients. That provides it high adaptive and robust properties. Excitation control system by terminal voltage phasor of the synchronous machine provides control of it electromagnetic and electromechanical states, and allows us to natural way coordinate the AVR/PSS tasks. The next step should be to determine the method of calculating the required values of the gains *K* and *N*.

References

[1] Kundur P., *Power System Stability and Control*, McGraw-Hill, 1994, pp. 1176.
[2] IEEE Std3.421.5-2005, IEEE *Recommended Practice for Excitation System Models for Power System Stability Studies*, 2005.
[3] Agamalov O. N., *About Structure Complex Error of a Control System with Feedback*, Lecture Notes in Electrical Engineering, Vol. 121: “Advanced in Computer Communication, Control and Automation”, Springer 2011, ISBN 13:9783642255403.
[4] Poularikas A. D., *The Transforms and Applications Handbook: Second Edition*, CRC Press, 2000, pp. 1335.
[5] Agamalov O. N., *Geometrical Model of Control System Presented on Complex Error Surface,* Journal of Automation and Information Sciences, Vol. 43, 2011/Issue 5, pp. 23-39, Begell Digital Library.
[6] Remmert R., *Theory of Complex Functions*, 1991, Springer-Verlag.
[7] Kreutz-Delgado K., *The complex gradient operator and the CR-calculus*, in: Lecture Supplement ECE275A, 2006, pp. 1–74.
[8] Brandwood D. H., *A complex gradient operator and its application in adaptive array theory*, IEE Proceedings, F: Communications, Radar and Signal Processing, vol. 130, no. 1, pp. 11–16, 1983.