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Stabilization of the Electromechanical Oscillations of Synchronous Generator

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Preliminary note

Power system stabilizer (PSS) is used in synchronous generator excitation control system for damping electromechanical oscillations. The objective of the PSS is to generate a stabilizing signal, which produces a torque damping component on the generator rotor. Created torque component must be in phase with speed deviation. Today's power system stabilizers (IEEE types) use speed deviation and/or acceleration of synchronous generator as input signals and are based on a phase compensation method. This paper compares the performance of IEEE type PSS1A and PSS2B stabilizers. The algorithms of stabilizers were implemented into the DSP based digital control system and tested in a laboratory environment on an 83kVA, 50Hz synchronous generator connected by transmission lines to the power system. The stabilizers' performance was compared in cases of voltage and active power change. In case of voltage change, both stabilizers performance is satisfactory, whilst in the case of active power change, only the PSS2B satisfies. The PSS1A stabilizer generates an unwanted stabilizing signal and causes variations in voltage and reactive power.

Keywords
Excitation control
Power system stabilizer
Synchronous generator

Stabilizacija elektromehaničkih njihanja sinkronog generatora

Prethodno priopćenje

Stabilizator elektroenergetskog sustava (PSS) koristi se u sustavima uzbude sinkronog generatora za prigušenje elektromehaničkih njihanja. Zadtak stabilizatora je generirati stabilizirajući signal, koji proizvodi prigušnu komponentu momenta na rotoru generatora. Prigušna komponenta momenta mora biti u fazi sa promjenom brzine rotora. Današnji stabilizatori elektroenergetskog sustava (IEEE tipovi) koriste odstupanje brzine i / ili ubrzanje rotora sinkronog generatora kao ulazne signale i temelje se na metodi fazne kompenzacija. U ovom radu uspoređeno je djelovanje stabilizatora IEEE tipova PSS1A i PSS2B. Algoritmi stabilizatora implementirani su u digitalni sustav temeljen na procesoru za obradu signala i testirani u laboratorijskom okruženju na 83kVA, 50Hz sinkronom generatoru, koji je modelom prijenosnih vodova povezan s elektroenergetskim sustavom. Djelovanja stabilizatora ispitana su za slučajeve promjene napona i djelatne snage. U slučaju promjene napona, djelovanje oba stabilizatora je zadovoljavajuće, dok u slučaju promjene djelatne snage samo stabilizator PSS2B zadovoljava. PSS1A stabilizator generira neželjen stabilizacijski signal i uzrokuje varijacije napona i jalove snage.

Ključne riječi
Sinkroni generator
Stabilizator elektroenergetskog sustava
Upravljanje uzbudom generatora

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1. Introduction

There is a consistent problem of stability in the electrical power system, in fact a problem of electromechanical oscillations of generators, electrical power plants, parts of the whole power system. Electromechanical oscillations are manifested in the fluctuation of state variables of the synchronous generator, e.g. speed, active and reactive power, voltage, load angle, etc. Oscillations can be weakly damped, not damped at all with constant or increasing amplitude, or they can reach a magnitude where the functionality of a power system is at stake.

Symbols/Oznake

δ	- synchronous generator load angle - kut opterećenja generatora
ω	- angular velocity (electrical) - kutna brzina (električna)
ω_{meh}	- angular velocity (mechanical) - kutna brzina (mehanička)
$\Delta\omega$	- generator speed deviation - odstupanje brzine generatora
$\Delta\delta$	- generator angle deviation - odstupanje kuta opterećenja
D	- stabilizer contribution to the damping - doprinos prigušenja stabilizatora
$G_{EP}(s)$	- transfer function of the stabilizer output to the damping component of the electromagnetic torque - prijenosna funkcija od izlaza stabilizatora do prigušne komponente elektromagnetskog momenta
$G_{STAB}(s)$	- transfer function of stabilizer - prijenosna funkcija stabilizatora
K_d	- torque damping component - prigušna komponenta momenta
K_s	- torque synchronization component - sinkronizacijska komponenta momenta
K_{stab}	- stabilizer gain - pojačanje stabilizatora
m_e	- generator electromagnetic torque - elektromagnetski moment generatora
Δm_e	- generator electromagnetic torque deviation - promjena elektromagnetskog momenta generatora
m_m	- mechanical torque - mehanički moment
Δm_m	- mechanical torque deviation - promjena mehaničkog momenta
p_a	- generator rotor accelerating power - snaga ubrzavanja rotora generatora
p_g	- active power - djelatna snaga
T_{d0}'	- excitation winding time constant for no loaded machine - vremenska konstanta uzbudnog namota neopterećenog stroja
T_m	- mechanical time constant - mehanička vremenska konstanta
T_w	- time constant of the real derivative for DC components removal - vremenska konstanta realnog derivacijskog člana za uklanjanje istosmjerne komponente signala
u_g	- generator voltage - napon generatora
u_{ref}	- generator voltage reference value - referentna vrijednost napona generatora
u_{stab}	- stabilizing signal - stabilizacijski signal
v_{smax}	- stabilizer output max. value - maksimalna vrijednost izlaza stabilizatora
v_{smin}	- stabilizer output min. value - minimalna vrijednost izlaza stabilizatora

Electromechanical oscillations occur at frequencies between 0.1 and 0.3 Hz [1].

One way for damping electromechanical oscillations is using a PSS in excitation control system of the synchronous generator. Task of the PSS is to generate a stabilizing signal which creates a damping component of torque at the time of the transient process. PSS output signal is an input signal of summation point before voltage controller in excitation control system. Usual input signals, which are used in classical PSS, are active power, speed or frequency of a generator. The details of stabilizer implementation differ depending on the input signal of the stabilizer. The stabilizer must, however, compensate the amplifications and phase characteristics of the excitation system, generator and power system which determine the transfer function from stabilizer output to torque damping component for any input signal. Figure 1 shows a functional relationship between electromechanical torque m_m, generator rotor speed ω and load angle δ, with a stabilizer employing rotor speed as an input signal [1]. The transfer function $G_{EP}(s)$ depends on voltage regulator gain, generator operating point and power system strength [2].

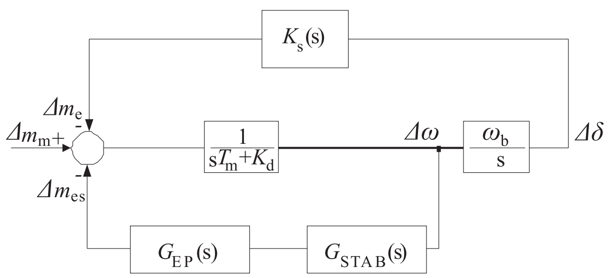

Figure 1. Relationship between electromechanical torque m_m, generator rotor speed ω and load angle δ

Slika 1. Odnosi između elektromagnetskog momenta m_m, brzine rotora generatora ω i kuta opterećenja δ

The electromagnetic torque contains two components, Δm_{es} defined by the stabilizer's contribution in generator excitation system, and Δm_e by contribution via the synchronization component of torque $K_s(s)$.

The contribution of torque due to stabilizer path is defined by expression [3-4]:

$$\frac{\Delta m_{es}}{\Delta\omega} = G_{EP}(s)\cdot G_{STAB}(s) \qquad (1)$$

Transfer function G_{EP}(s) represents the characteristics of the generator, the excitation system and power system strength. This transfer function can be explained by a block scheme (Figure 2), which shows a linear generator model connected to the power system [5]. The model includes a voltage controller and a stabilizer. It is defined by coefficients K_1, K_2, K_3, K_4, K_5 and K_6, which change when the generator operating point does. The coefficients in question are described in [5].

Since K_2 and K_6 are defined by expressions 2 and 3, the dynamic characteristics of $G_{EP}(s)$ are defined by a closed voltage control loop with a constant rotor speed ($\Delta\omega = 0$), i.e. a constant load angle ($\Delta\delta = 0$):

$$G(s) = \left[\frac{1+sT_8}{\left(1+sT_9\right)^M}\right]^N, \qquad (2)$$

$$K_6 = \frac{\Delta u}{\Delta e'_q}\Big|_{\delta=\text{constant}}, \qquad (3)$$

$$G_{EP}(s) = \frac{\Delta m_e}{\Delta u_{ref}} \cong \frac{K_2}{K_6}\cdot\frac{\Delta u}{\Delta u_{ref}}. \qquad (4)$$

Therefore, the phase characteristic of transfer function G_{EP}(s) must be defined by a closed voltage control loop.

The changes of the G_{EP}(s) with the changes in the excitation system, changes in the generator load and the strength of the power system influence on the power system stabilizer and performance. The voltage controller response with a closed loop is determined by the characteristics of the excitation system and the strength of the power system. In case of greater disturbances it is important for the increase of transfer stability that the voltage controller gain is as big as possible, so the disturbance can be regulated quickly. However, a great gain in voltage control significantly decreases natural damping of rotor oscillations and can lead to instability at a greater load, even with strength transfer systems. In situations when the crossover frequency of the voltage control loop is lower than the oscillation frequency of concern, the gain of G_{EP}(s) at the oscillation frequency can be approximated thus [3]:

$$\left|G_{EP}(j\omega_i)\right| \cong K_2\cdot\frac{\left|G_{UZB}(j\omega_i)\right|}{\omega_i\cdot T'_{d0}}. \qquad (5)$$

It is presumed that $1/(K_3T'_{d0})$ is less than the crossover frequency. The hypothesis in expression 5 is usually valid in modern excitation systems. The gain of G_{EP}(s) is then proportional to the excitation system gain and inversely proportional to time constant T'_{d0} and to oscillation frequency. The gain is also proportional to the coefficient K_2, which represents torque change with the excitation flux and increases with generator load with the strength of the power system leading to the conclusion that the gain of G_{EP}(s) is the greatest when the generator is fully loaded and when the power system is most strength [4].

In cases where the crossover frequency is higher than the oscillation frequency, for example in cases of great gains, the G_{EP}(s) gain is inversely proportional to coefficient K_6, as expression 4 shows. K_6 represents the influence of induced voltage behind synchronous reactance E'_q on generator voltage, which decreases as the strength of the power system increases and causes an increase in G_{EP}(s) gain.

Since the voltage control gain with an open control loop is proportional to coefficient K_6, crossover frequency decrease as the power system strength increases. This influences the stabilizer's operation because the more strength power system is, the greater the phase lag will be. This effect is very prominent in the case of great voltage controller gain because the crossover frequency is in the area of inter unit oscillations.

Considering all this, power system stabilizer must operate through the G_{EP}(s) transfer function (Figure 1) which is dependent on the generator, the excitation system

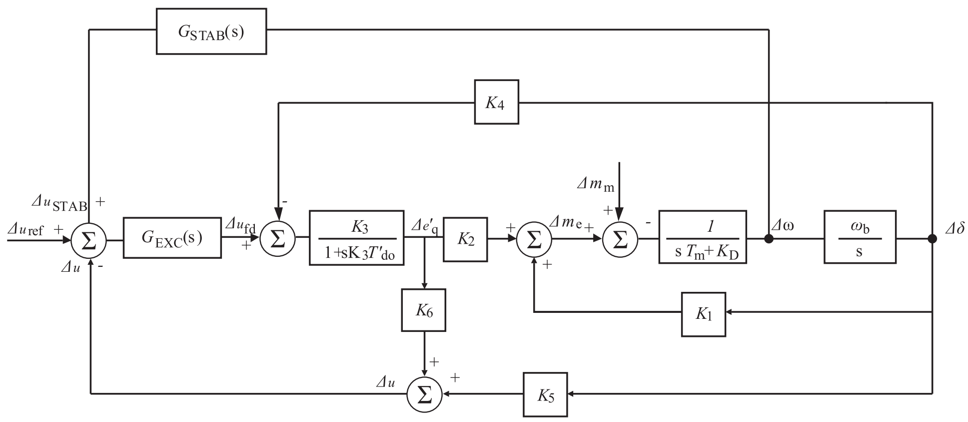

Figure 2. Generator model connected to power system

Slika 2. Model generatora spojenog na elektroenergetski sustav and the power system. The characteristics of the G_{EP}(s) transfer function, important for stabilizer implementation are [4]:

- phase characteristic G_{EP}(s) is determined with a closed voltage control loop
- G_{EP}(s) gain increases with generator load
- G_{EP}(s) gain increases with the strength of the power system, this effect is more prominent in voltage controllers with great gain
- G_{EP}(s) gain is proportional to voltage controller gain, and inversely proportional to time constant T'_{d0} and oscillation frequency
- The phase lag of G_{EP}(s) increases with the increase in strength of the power system, this effect is more prominent with great gain of excitation systems because the voltage control loop crossover frequency approaches oscillation frequency.

The rotor speed, active power and frequency are among the most often used power system stabilizer inputs. Different forms of power system stabilizers have been developed using these signals.

1.1. Speed based stabilizer

Power system stabilizers using rotor speed as input must compensate G_{EP}(s) phase lag to provide a torque damping component in phase with speed changes.

In that case, phase lag between the input signal and torque change should be zero degrees for the oscillatory mode of concern [4] (Figure 3).

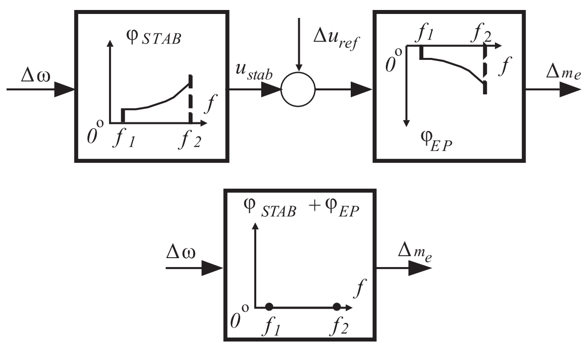

Figure 3. Phase frequency characteristics of φ_{EP} excitation control system and power system stabilizer φ_{STAB} with additional regulation signal $\Delta\omega$

Slika 3. Fazno-frekvencijska karakteristika uzbudnog sustava φ_{EP} i stabilizatora elektroenergetskog sustava φ_{STAB} sa stabilizacijskim signalom $\Delta\omega$

The ideal stabilizer characteristic would be inversely proportional to G_{EP}(s):

$$G_{STAB\omega}(s) = \frac{D}{G_{EP}(s)}, \tag{6}$$

where *D* represents the desired contribution to stabilizer damping. Such a stabilizer characteristic is unpractical, because the gain must be decreased at high frequencies. In practical stabilizer with speed input gain is decreased at high frequencies to restrict the influence of noise and torsion modes, and this is the reason for using low pass and band pass filters.

The stabilizer must operate through G_{EP}(s), the characteristics of which change significantly depending on the operating mode. The gain of the transfer function G_{EP}(s) increases with an increase of generator load, which is desirable, because the load increase brings the generator closer to stability limit. However, G_{EP}(s) gain is very great with a strength power systems and decreases as the power system weakens [4]. This last effect decreases the influence of the speed input stabilizer when the excitation system needs it most. The G_{EP}(s) phase lag increases with the strength power system. These conditions determine the maximum allowed gain of the speed input stabilizer. Without an adjustable gain change, stabilizer gain would be too small in conditions of lesser power system strength when it is most needed.

Stabilizers that use direct rotor speed measuring ($\Delta\omega$ stabilizers) have been in use since the mid 1960s. The important thing, when measuring rotor speed deviation, is to minimize signal noise and filter torsion modes. The noise must be removed without influencing the measured variable. In some designs rotor speed is measured at several points on the rotor which has it's limitations in terms of long-term reliability.

Designing a stabilizer demands a careful consideration of the influences on torsion oscillations as well. The stabilizer might decrease the natural damping of low frequency torsion modes as it dampens rotor oscillations unless adequate filtering is applied.

1.2. Frequency based stabilizer

Frequency is also used as an input signal for the application of the power system stabilizer. Using frequency as stabilizer input results in changes of the stabilizer operating mode and adjustments in comparison to using rotor speed as input signal. The main difference is that the frequency signal's sensitivity to rotor oscillations increases when the strength of the power system decreases which leads to a gain decrease, from stabilizer output to electromechanical torque [4].

Analyses show that stabilizer gain should be adjusted for optimal operation in the case of a less strength of the power system, where an operating stabilizer is necessary, with no fear of too great gain that would influence stabilizer instability when the power system becomes more strength [4].

Furthermore, frequency signal is more sensitive to oscillations between power plants and large areas than to the oscillations in one generator, including the units within a power plant. This conclusion is drawn from the fact that frequency is relatively constant until the generators begin to oscillate coherently. Consequently, it is possible to achieve greater oscillation damping between power plants and large areas with a frequency based stabilizer than with a speed input stabilizer.

The frequency signal has the advantage of being more sensitive to oscillation in larger areas than local ones. It seems possible therefore to retain the bigger contribution to damping oscillations between larger areas, than a speed input stabilizer might have. The frequency measured on turbo generators contains torsion modes of oscillation, which must be filtered.

1.3. Active power based stabilizer

Considering the simplicity of active power measuring, it is often used as a stabilizer input signal. The most common approach to analyzing a stabilizer with an active power input is to treat its input signal as having a phase lag with respect to the rotor speed deviation and the application of analysis for a stabilizer with a speed input signal. This approach leads to the conclusions that power input stabilizer characteristics are the same as those of a rotor speed input stabilizer. This conclusion is valid for different types of power system oscillations where the rotor acts as a strength body (changes in mechanical power were compensated by using a average value rotor acceleration power at stabilizer input). Due to torsion oscillations on the rotor the values of generator rotor acceleration power are different to the average value of the acceleration power of the entire rotor, so using speed derivation as input signal is not entirely correct.

An ideal active power input stabilizer is determined by the expression:

$$G_{\mathrm{STABP}}(\mathrm{s}) = -\frac{D}{\mathrm{s}\cdot G_{\mathrm{EP}}(\mathrm{s})}\,. \tag{7}$$

This result is identical to the result that one might get by using active power as speed deviation, because integrating the negative active power results as speed deviation, which multiplied by the ideal $G_{\mathrm{STAB}\omega}(\mathrm{s})$ from expression 6, gives expression 7.

The equation for rotor motion is defined by the expression:

$$\frac{d}{dt}\Delta\omega = \frac{1}{T_m}\left(\Delta p_m - \Delta p_g\right), \tag{8}$$

where T_{m} is the mechanical time constant, Δp_{m} mechanical power input change, Δp_{g} active power change and $\Delta\omega$ generator rotor speed deviation.

Disregarding the mechanical power change, this equation shows that the signal proportional to rotor acceleration (i.e. that which leads the speed for 90°) is available from the active power change measurements. This principle was used as a basis for stabilizer designs. Combined with high-pass and low-pass filtering, the resulting stabilizing signal in this case can give a pure damping torque at exactly one electromechanical frequency.

The active power change introduced with a negative sign ensures, without additional processing and reduced to rotor speed change, a phase leading 90°. Using the generator active power signal, and not the rotor speed as an additional input signal, also enables the omitting of one derivational block (Figure 4).

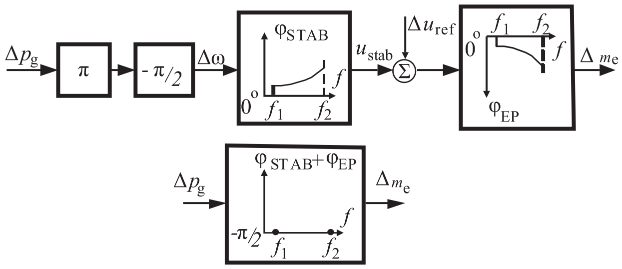

Figure 4. Phase frequency characteristics of excitation control system φ_{EP} and stabilizer φ_{STAB} with the input signal Δp_{g}

Slika 4. Fazno-frekvencijska karakteristika uzbudnog sustava φ_{EP} i stabilizatora elektroenergetskog sustava φ_{STAB} sa stabilizacijskim signalom Δp_{g}

2. Conventional structure of synchronous generator excitation control system

In Figure 5 conventional structure of voltage control for synchronous generator, which consists of inner excitation current loop and of outer terminal voltage loop, is shown. Reactive power controller and PSS are used based on requirements of electrical power system on particular generator. Terminal voltage controller is proportional-integral (PI) type and it is superior to excitation current controller which is proportional (P) type. Output of terminal voltage controller is a reference value of excitation current i_{fref}. Output signal of an excitation current controller is a duty cycle for the PWM input of an IGBT converter. Both outputs from controllers are limited. Based on measured values of terminal voltages and currents, values of active and reactive power of synchronous generator are determined.

PSS has to perform phase compensation between an input of excitation control system and electromagnetic torque in an interesting range of frequency oscillation. PSS must compensate a transfer function $G_{\mathrm{EP}}(\mathrm{s})$ which includes synchronous generator excitation system and connection between synchronous generator and power system.

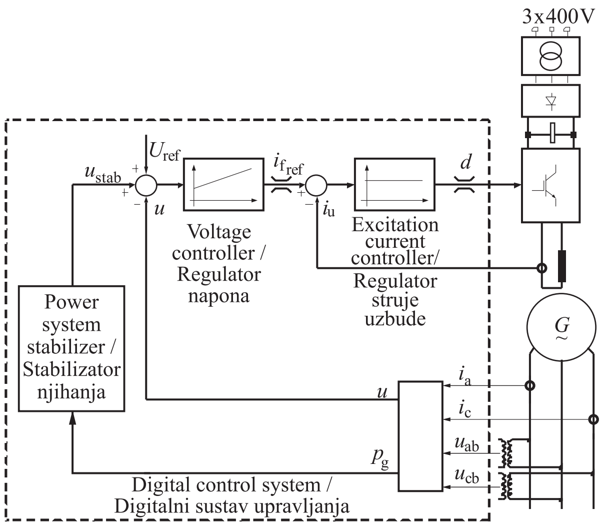

Figure 5. Conventional structure of synchronous generator excitation control system

Slika 5. Klasična struktura upravljanja uzbudom sinkronog generatora

2.1. Structure of the stabilizer PSS1A

In Figure 6 a structure of IEEE PSS1A type is shown [10].

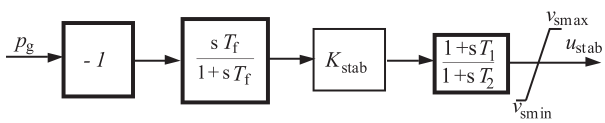

Figure 6. Structure of PSS1A (IEEE type)

Slika 6. Struktura stabilizatora PSS1A (IEEE tip)

Wash out filter, with a time constant T_f, enables passing of active power deviation signal without any changes made to it. Without this block a permanent active power change would cause a generator voltage change. This block enables that a stabilizer operates only in case of transient change of active power deviation signal. Time constant value must be big enough so that active power deviation signal passes through without any changes made to it, in an interesting frequency range.

Gain K_{stab} determents a damping ratio which is introduced with a stabilizer. To some point increasing of gain increase a damping ratio, but further increasing of gain decreases a damping ratio [2]. Phase compensation block compensates a phase lag between excitation control system input and electromagnetic torque. With a use of two or three first order blocks or one second order block with complex solutions, it is possible to achieve desirable phase compensation characteristic. Output signal of a stabilizer has positive v_{smax} and negative v_{smin} limit. Positive limit can be set to a relatively big value (0.2 p.u.) according to IEEE settings [6-7], so that operation of a stabilizer is ensured when big oscillations occur. Negative limit of -0.1 p.u. is considered to be satisfying. With that kind of limitation a stabilizer operation is ensured.

Stabilizer must damp local mode oscillations and inter area mode, in fact system oscillations. Depending on a type of oscillations, stabilizer executes phase compensation in an interesting frequency range. Phase characteristic, which needs to be compensated, varies with a system changes. So, stabilizer settings for one state of a system do not guarantee satisfactory settings for some other state of a system [2].

The power system stabilizer PSS1A parameters are determined based on the phase compensation technique and shown in Table 1.

Table 1. PSS1A parameters

Tablica 1. Parametri PSS1A stabilizatora

T_f	K_{stab}	T_1	T_2	v_{smax}	v_{smin}
1 s	2	0.01 s	0.1 s	0.2 p.u.	-0.2 p.u.

2.2. Structure of the stabilizer PSS2B

Limitations in other oscillation stabilizer designs have lead to the development of a stabilizer based on the integral-of-accelerating power. This type of stabilizer is IEEE standard called stabilizer PSS2A [7].

The concept of stabilizer PSS2A was made by F.P. de Mello in 1978 with the goal of compensating generator active power stationary change to stop an unwanted stabilizing signal from occurring in those conditions. The initial solutions of stabilizer PSS2A combine electrical power measurements with mechanical power measurements, in order to get the integral-of-accelerating power based on those measurements. Due to the need for adaptations on every machine, a new method of indirect derivation of acceleration power was developed, by making rotation speed and electrical active power of a synchronous generator PSS2A stabilizer's input signals, in order to get the integral-of-accelerating power signal based on speed and active power. The IEEE standard PSS2A model used for representing this stabilizer design is shown in Figure 7.

The principle on which the PSS2A stabilizer works starts with the synchronous machine motion equation given in expression 8.

Expression 9 can also be written in the form of electrical and mechanical power deviation differential integral:

$$\Delta\omega = \frac{1}{T_m}\int\left(\Delta p_m - \Delta p_g\right)dt \,. \tag{9}$$

Furthermore, the mechanical power integral can be expressed using speed deviation and electrical active power deviation integral, as follows:

$$\int \Delta p_{\mathrm{m}}\, dt = T_{\mathrm{m}} \Delta\omega(t) + \int \Delta P_{\mathrm{g}}\, dt \,. \tag{10}$$

The PSS2A stabilizer uses expression 10 to get a signal proportional to the mechanical power deviation integral by adding signals proportional to speed deviation and the electrical active power deviation integral. Such a signal may contain torsion modes and it is necessary to use a low-pass filter to remove oscillation torsion modes.

The integral of accelerating power is defined by the following expression:

$$\frac{1}{T_{\mathrm{m}}}\int \Delta p_a\, dt = \frac{1}{T_{\mathrm{m}}}\left[\int \Delta p_{\mathrm{m}}\, dt - \int \Delta p_{\mathrm{g}}\, dt\right]. \tag{11}$$

When expression 10 is added into expression 11, the integral of accelerating power is determined by rotation speed deviation and generator electrical active power deviation:

$$\frac{1}{T_{\mathrm{m}}}\int \Delta p_{\mathrm{a}}\, dt = G(\mathrm{t})\cdot\left[\Delta\omega(\mathrm{t}) + \frac{1}{T_{\mathrm{m}}}\int \Delta p_{\mathrm{g}}\, dt\right] - \\ - \frac{1}{T_{\mathrm{m}}}\int \Delta p_{\mathrm{g}}\, dt\,, \tag{12}$$

where G(t) is the low-pass filter transfer function.

Expression 12 written in the Laplace domain determines the calculation of the integral of accelerating power using rotor speed and electrical active power values:

$$\frac{1}{T_{\mathrm{m}}}\frac{\Delta p_{\mathrm{a}}(\mathrm{s})}{\mathrm{s}} = -\frac{1}{T_{\mathrm{m}}}\frac{\Delta p_{\mathrm{g}}(\mathrm{s})}{\mathrm{s}} + \\ + G(\mathrm{s})\left[\frac{1}{T_{\mathrm{m}}}\frac{\Delta p_{\mathrm{g}}(\mathrm{s})}{\mathrm{s}} + \Delta\omega(\mathrm{s})\right], \tag{13}$$

where G(s) is the low-pass filter transfer function.

Using this method with G(s)=1, stabilizer PSS2A is equivalent to phase minimal stabilizer with a rotor speed input signal. Under the condition of G(s)=0, stabilizer PSS2A becomes an active power input stabilizer.

Papers [8] and [9] describe stabilizer parameter adjustments based on the integral of accelerating power. The method of adjustment comes down to choosing phase compensation, gain and stabilizer output limitations. The goal is to adjust the parameters so as to get the integral of accelerating power for oscillation damping, at the same time taking into consideration stationary changes of mechanical power, so they will not create an unwanted stabilizer output.

Although stabilizer PSS2A has many advantages over a single input stabilizer, it is sensitive to the relations between rotor speed and active power. If the adjustments are to be satisfactory, two signal paths, 1-3 and 2-6 in Figure 7, must be adjusted with respect to gain and time constants of the filter.

Active power signal path 2-6 (Figure 7) contains blocks for the derivation of electrical active power deviation integral:

$$\frac{1}{T_{\mathrm{m}}}\frac{\Delta p_{\mathrm{g}}(\mathrm{s})}{\mathrm{s}} = \left(\frac{\mathrm{s}T_{\mathrm{w}}}{1+\mathrm{s}T_{\mathrm{w}}}\right)\left(\frac{k_{\mathrm{s2}}}{1+\mathrm{s}T_7}\right)p_{\mathrm{g}}\,. \tag{14}$$

According to [8] the following adjustments should be made:

$$T_{\mathrm{w3}} = T_7 = T_{\mathrm{w}} \text{ i } K_{\mathrm{s2}} = T_{\mathrm{w}} / T_{\mathrm{m}},\ T_{\mathrm{w4}} = 0. \tag{15}$$

Because of the need for the speed and power signal paths to be adjusted, there are blocks at speed input whose time constants are adjusted as follows:

$$T_{\mathrm{w1}} = T_{\mathrm{w}},\ T_{\mathrm{w2}} = 0. \tag{16}$$

With this kind of adjustment, the signal at point 4 in fig. 7 will be proportional to the changes in the integral of mechanical power Δp_{m}. When, with additional filtering, the active power deviation integral is deducted from that signal, the result is integral of accelerating power. The integral of accelerating power is equivalent to speed

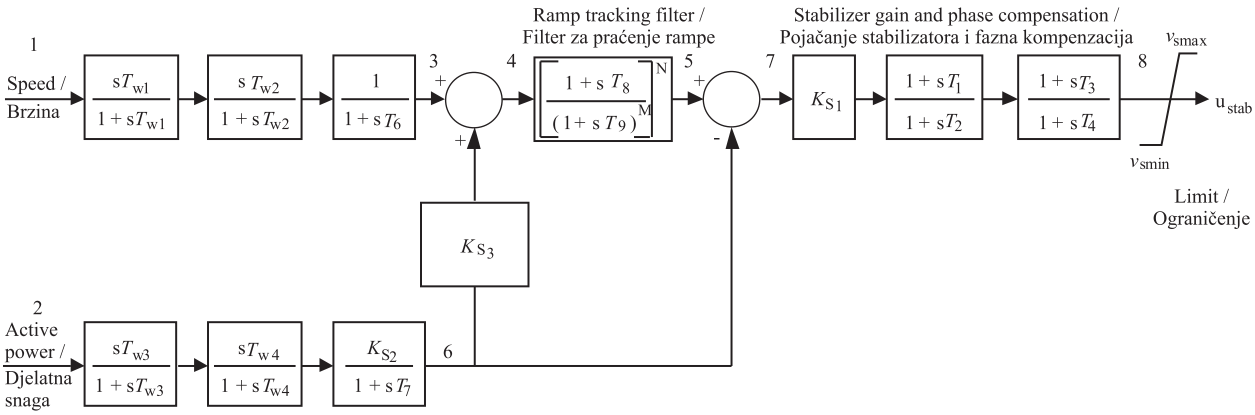

Figure 7. Structure of PSS2A-type stabilizer based on speed and active power

Slika 7. Struktura stabilizatora PSS2A temeljena na signalu brzine i djelatne snage deviation and adding phase compensation blocks will result in a stabilizing signal, which will then produce a torque damping component.

Electromechanical oscillations stabilizers are required to damp the local oscillation mode (oscillation frequency 0,7-3 Hz), and to damp the inter area mode of oscillations (oscillation frequency 0,1-0,7 Hz).

They are also required not to produce an unwanted stabilizing signal in case of mechanical power change, as that would result in voltage and reactive power deviations.

In case of electrical active power change by ramp (Figure 7, point 2), the active power deviation integral (Figure 7, point 6) will change depending on high-pass filter time constant T_{w3} and mechanical time constant of the rotor. From point 6 onward the active power deviation integral passes through two output paths. One of the paths is a direct link to point 7 used to get an equivalent speed deviation signal. The other path is through a ramp tracking filter, situated between points 4 and 5. Ideally, these signals will annul each other, since the stabilizer may not produce a stabilizing signal under those conditions. This will not be the case if the values of the time constant and the ramp slope, which conditions active power changes, are too big. In these conditions, the error signal will be transferred to stabilizer output and change the voltage and generator reactive power. The initial designs of low-pass filter $G(s)$ had the transfer function:

$$G(\mathrm{s}) = \frac{1}{\left(1+\mathrm{s}T_{w_3}\right)^M} \,. \tag{17}$$

Such a transfer function is achieved if $T_8 = 0$ and $N = 1$ are inserted into the proposed model of PSS2A stabilizer. The order of filter M and time constant T_9 are selected to ensure lowest frequency damping of torsion oscillations.

Further research [9] has shown that sensitivity to changes in stationary value of mechanical power could be reduced if the low-pass filter G(s) is designed with a transfer function:

$$G(s) = \left[\frac{1+\mathrm{s}T_8}{\left(1+\mathrm{s}T_9\right)^M}\right]^N \,. \tag{18}$$

The G(s) block is, in this case, called the ramp tracking filter because of its characteristic when parameters T_8, T_9, M and N are selected according to the following criteria:

- High frequency component damping in input signal
- Bypassing low frequency changes in mechanical power
- Minimizing stabilizer output in case of stationary value change of mechanical power.

To understand the advantages of a ramp tracking filter and the selection of its parameters a calculation was made of the integral of accelerating power in cases of various mechanical power changes. The integral of mechanical power deviation is in this case presented by following inputs:

- Step change $A\cdot u(t)$
- ramp $B\cdot t$
- parable $C\cdot t^2$

where t is time in seconds, and A, B and C amplitudes of individual inputs in the p.u. system. The stationary value of output y for each of these inputs can be calculated using the end-value theorem:

$$\lim_{t\to\infty} y(\mathrm{t}) = \lim_{s\to 0}(\mathrm{s}\cdot x\cdot(G(\mathrm{s})-1)) \,, \tag{19}$$

where x is the input. According to the end-value theorem, stationary output values can be calculated for different inputs (Table 2). Stationary output value of a ramp tracking filter is zero, which is in this case its main advantage compared to a low-pass filter.

Table 2. Stationary values of blocks outputs for different inputs

Tablica 2. Stacionarne vrijednosti izlaza blokova za različite ulaze

	Stationary output value / Stacionama izlazna vrijednost	
	Low-pass filter / Niskopropusni filter	Ramp tracking filter / Filter za praćenje rampe
Step change / Skokovita promjena $A\cdot u(t)$	0	0
Ramp / Rampa $B\cdot t$	$-B\cdot M\cdot T_9$	0
Parable / Parabola $C\cdot t^2$	infinite / beskonačno	$-C\cdot f(M,T_9)$

This claim is valid under the condition that $T_8 = M\cdot T_9$. The most often used parameters for a ramp tracking filter are N = 1 and M = 4. To ensure -20 dB damping at a frequency of 10 Hz (torsion oscillations), T_9 is 0.05 s, which means that T_8 = 0.2 s.

With this type of ramp tracking adjustments the integral of mechanical power change can follow fast active power changes and thereby stop unwanted stabilizer output under the conditions of mechanical power stationary value change. The PSS2B stabilizer parameters are defined using a technique of phase compensation and are shown in Table 3.

3. Experimental results

Laboratory model, which structure is shown in Figure 8, enables an experimental verification of excitation control system algorithms for voltage control and electromechanical oscillation stabilization. This model enables testing of excitation control system components and it also enables testing a system in different characteristic working modes (step change of active power reference/voltage reference).

Table 3. Parameters of PSS2B stabilizer

Tablica 3. Parametri PSS2B stabilizatora

T_{W1}	T_{W2}	T_6	T_{W3}	T_{W4}	K_{S2}	T_7	K_{S3}	T_8
1.0 s	0 s	0 s	1.0 s	0 s	0.5	1.0 s	1.0	0.2 s
T_9	K_{s1}	T_1	T_2	T_3	T_4	v_{smax}	v_{smin}	
0.05 s	5.0	0.3 s	0.05 s	0 s	0 s	0.2 p.u.	-0.2 p.u.	

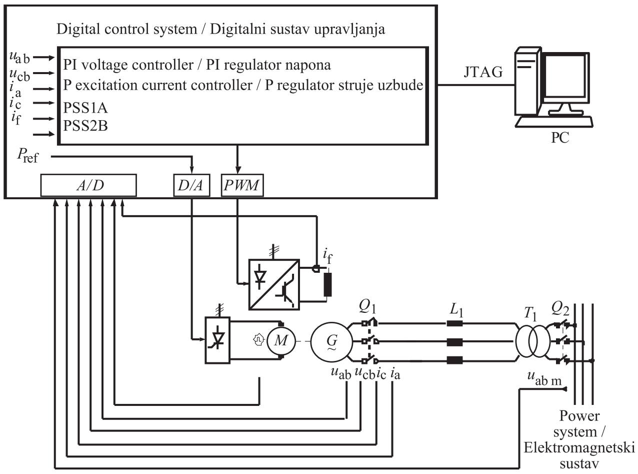

Figure 8. A Laboratory model basic scheme

Slika 8. Struktura laboratorijskog modela

Laboratory model consists of: thyristor converter (100kW) with an output current controller, two DC motors (one on each generator side), salient-pole synchronous machine (83kVA), between a generator and

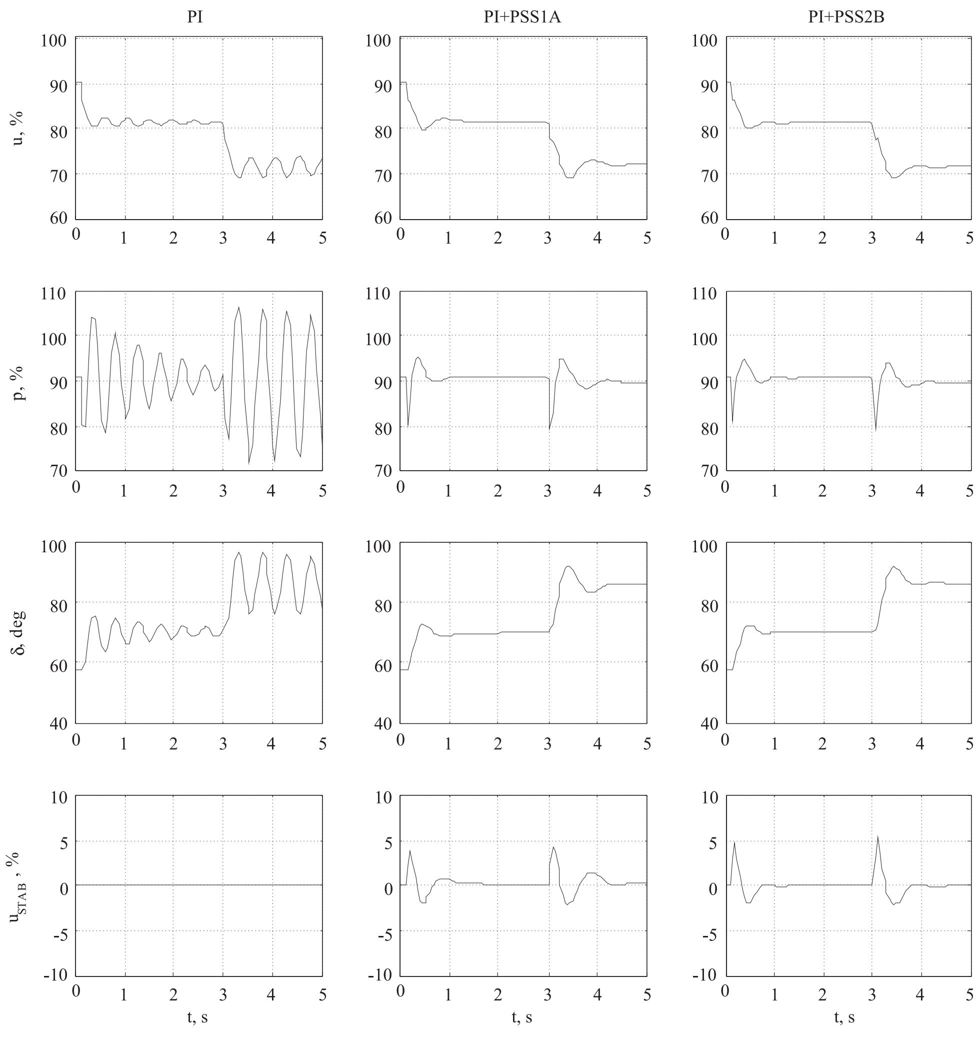

Figure 9. Experimental results for a voltage reference change from 0.9 p.u. to 0.8 p.u. and after that to 0.7 p.u. for a system without PSS, a system with IEEE PSS1A and a system with IEEE PSS2B

Slika 9. Eksperimentalni rezultati za promjenu referentne vrijednosti napona s 0.9 p.u. na 0.8 p.u. i nakon toga na 0.7 p.u. za sustav bez stabilizatora, sa stabilizatorom IEEE PSS1A i sa stabilizatorom IEEE PSS2B a power system is a model which represents two parallel transmission lines and a transformer, two-quadrant IGBT AC/DC converter as an excitation current source. Rotor speed and position are measured with a optical encoder.

Experimental results are shown for a system without PSS, a system with IEEE PSS1A and a system with IEEE PSS2B stabilizer.

Figure 9 shows experimental results for a voltage reference change from 0.9 p.u. to 0.8 p.u. and after that to 0.7 p.u. Experimental results show that both stabilizers work satisfactory for this kind of disturbance. Generators trajectory is considerably lesser when using a stabilizer apposed to a generator trajectory when no stabilizer is used.

Figure 10 shows experimental results for an active power reference change from 0.5 p.u. to 0.8 p.u. and after that to 0.5 p.u. Experimental results show that IEEE PSS1A does not function satisfactory (this conclusion is based on voltage and load angle response) for this kind of disturbances.

The stabilizer PSS2B functions satisfactory for this kind of disturbance. Generators trajectory is considerably lesser when using a PSS2B opposed to a generator trajectory when no stabilizer or an IEEE PSS1A.

4. Conclusion

This article presents a comparison of the operation of various IEEE type stabilizers implemented into a synchronous generator excitation system. Operation of IEEE PSS1A stabilizer with generator active power as input signal was compared to IEEE PSS2B stabilizer, whose work is based on the integral of accelerating power. The integral of accelerating power 's signal was got from rotor rotation speed and generator active power input signals.

Both the stabilizers were implemented into the digital excitation control system of the generator. The functionalities of stabilizers IEEE PSS1A and IEEE PSS2B were compared for an 83kVA, 50Hz synchronous

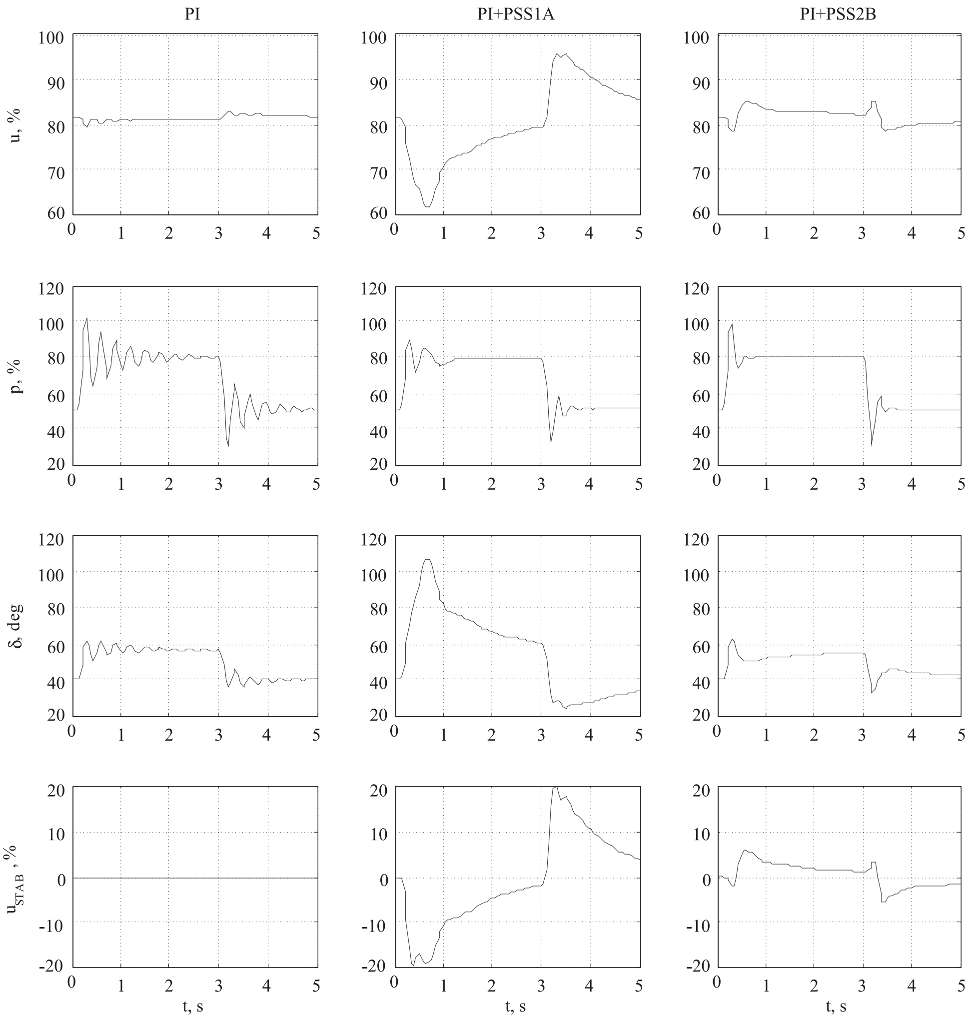

Figure 10. Experimental results for an active power reference change from 0.5 p.u. to 0.8 p.u. and after that to 0,5 p.u. for a system without PSS, a system with IEEE PSS1A and a system with IEEE PSS2B

Slika 10. Experimental results for an active power reference change from 0.5 p.u. to 0.8 p.u. and after that to 0,5 p.u. for a system without PSS, a system with IEEE PSS1A and a system with IEEE PSS2B generator connected over transmission lines to the power system. Experimental results show that PSS2B works better than PSS1A. When changing an active power static value, IEEE PSS1A did not function satisfactory. In that case, its functionality must be blocked. IEEE PSS1A only works if there is no change in an active power stationary value. Stabilizer PSS2B showed satisfactory results for changes in an active power stationary value.

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