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Application of new POSICAST control method to synchronous generator excitation system

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Abstract

In this paper, modeling, analysis, design and simulation of a POSICAST controller are presented for application in a generator's excitation system. Simple structure is the most important characteristic of this controller. The controller is a feedforward compensator; it eliminates intensive over/undershoots in system dynamic response. Since changing the reference signal in the excitation system of the synchronous generator causes oscillations in the terminal voltage, the POSICAST controller (PC) is applied at the outset of the excitation system to mitigate these oscillations. The impact of the proposed controller on the stability of the studied power system is evaluated by both eigenvalues analysis and experimental results. In order to validate the theory, the performance of the designed controller is verified in OPAL-RT by experimental approach.

Keywords: POSICAST controller; generator excitation system; automatic voltage regulator (AVR); real time simulation; eigenvalues analysis

1. Introduction

Changing the reference signal of the synchronous generator's excitation system is one possible method that can be used in large-scale conventional power plants to control voltage and, consequently, the reactive power. However, this method causes undesired oscillations in the overall scale. To guarantee the stable and continuous operation of the power system, the oscillations must be damped very quickly to ensure a satisfactory degree of performance. In addition, the power system oscillations may overheat the field windings; therefore, mitigation of the oscillations can extend the life of the field windings [1]. The use of an automatic voltage regulator (AVR) is a well-known method suggested in [2–6] to control the voltage of the synchronous generators through changing the generator field.

Traditionally, to provide a proper damping coefficient in the generator's design, some controllers based on linearized dynamic equations are offered (see e.g., [1] and [7]). Recently, attention has been focused on the use of modern control techniques, e.g., adaptive linear control [8], intelligent control such as fuzzy logic [9], neural networks [10], adaptive nonlinear control [11] and others. In [12] and [13] they proposed a sliding-mode (SM) controller, which has been studied for a single synchronous machine connected to an infinite bus. However, all the mentioned controllers can be categorized as feedback control methods. These complicated controllers have been designed to guarantee the stability and sound operation of the power systems against the various types of perturbations. Moreover, applying such controllers increases the complexity of the excitation system. On the other hand, knowing the possible sources of disturbances, more simple and effective feed-forward controllers can be designed.

In this paper, the POSICAST control method as a feedforward controller is proposed to be applied into the excitation system of the synchronous generators. It is shown that, despite the simplicity of the method used in the design stage, the performance of the controller in damping the oscillations has been increased drastically.

The PC concept was first presented by Prof. Otto J. M. Smith, who described the basic principles in 1957 [14]. Since then it has become a solution for damping oscillations in mechanical and electrical systems [15–19]. The first research results were for mechanical applications, but, recently, POSICAST-based feedback control has been used in the field of power engineering. Reference [20] has proposed a digital POSICAST-based controller for a buck type

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DC-DC converter in order to obtain the advantage of POSICAST's superior damping qualities while reducing the sensitivity of classical feed-forward POSICAST. In addition, rather than a conventional two-step PC, a three-step compensator based on the PC concept has been presented in [21]. As a combination approach for damping of PWM current-source rectifiers, this approach was also carried out in [22] for shaping the modulation signals for high switching frequency DC-DC converters, inverters and PWM rectifiers. For compensating for voltage sags and damping of high-frequency oscillations at medium voltage of distribution system, an investigation of Dynamic Voltage Restorer (DVR) transient response was carried out in [23], where, by employing a closed-loop control and a PC, it presented an efficient resonance damping method.

Recently, this controller has been introduced as a simple and effective solution for oscillation damping and improving dynamic behavior in electrical power systems [24–27]. However, all reports in this field have been limited to a simulation environment.

This work is an extension of [28] by the same authors. Comparing to [28], the following contributions are made in this paper: 1) the eigenvalue analysis of the study system in classic and various modified conditions of the exciter which is equipped by the PC and the sensitivity of the proposed controller under different KP values; 2) evaluation of its performance in real time testing.

The other sections of this paper are organized as follows: the fundamental concepts of the PC are explained in Section II. The focus of Section III is on modeling the controller. Section IV is allocated to explain the eigenvalues analysis of the power systems and the evaluation of the effectiveness of the controller on the small signal stability. The sensitivity analysis of the controller is also studied in this Section. The structure of the HIL test-bed is described in Section V. In this section, the experimental evaluation based on real time (RT) is also demonstrated. Finally, the conclusions drawn from this study are presented in Section VI.

2. POSICAST Control Method

POSICAST is an effective feed-forward control method that damps created oscillations in a well-tuned condition. This control method has the capability to offer a transient response with deadbeat reflection. Fig. 1 demonstrates in a step-response diagram that it can be an analytical structure of POSICAST.

The overshoot in the response is defined by two parameters: 1) "Td", which denotes the time of the underdamped response period; 2) "1+δ", which is the peak value of the overshoot. It is notable that δ denotes the normalized overshoot factor that ranges from zero to one [29].
PC divides the step-reference signal into two separate parts. In the classical half-cycle POSICAST, which is depicted in Fig. 2, the controller first subtracts a scaled amount from the input signal (in the lower path).

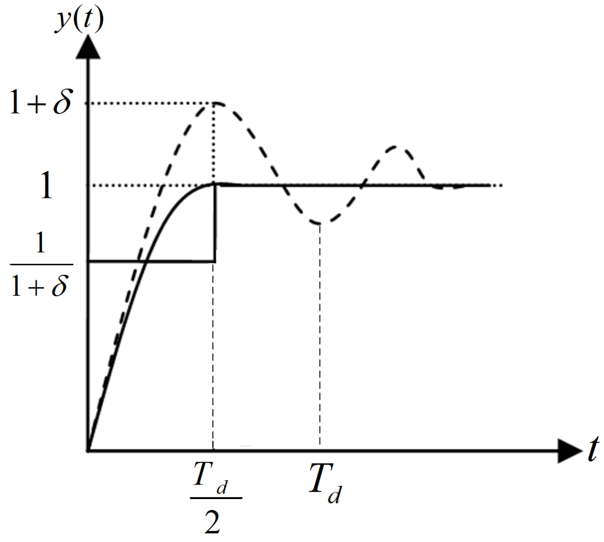


Figure 1: Step-response of a lightly damped system

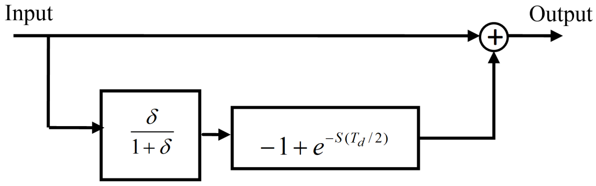


Figure 2: Open-loop half cycle POSICAST

Consequently, the peak of the lightly damped response coincides with the desired final value of the system response. The time of the peak step-response is equal to one-half of the natural damped period (Td/2). This path makes a time delay. Then, the original value of the input step signal is applied to the system (in the upper path). Finally, the output remains at the desired final value. The system output is shown in Fig. 1 (solid line); the uncompensated output is also shown for comparison (dashed line) [29, 30].

The PC is an open-loop compensation; therefore, it has high sensitivity to the parameter variations or any mismatch problem. This weakness could be improved by applying the POSICAST compensation within a feedback system, as is shown in Fig. 3 [30]. The transfer function of the control structure of Fig. 3 is given by the function 1+P(s), where P(s) is:

$$P(s) = \frac{\delta}{1+\delta}\left[-1+e^{-S(T_d/2)}\right] \tag{1}$$

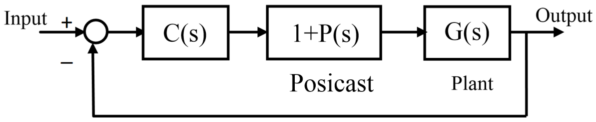


Figure 3: POSICAST within a feedback system

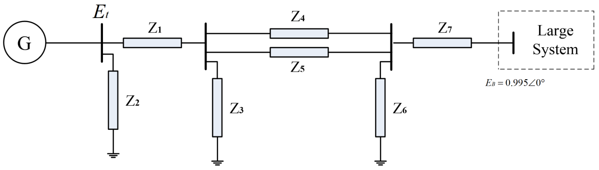


Figure 4: General configuration of the test system

3. Modeling the Test System

Modeling of the test system is described in this section. First, a detailed model of a single-machine system and the specifications of the associated synchronous machine are presented. Then, the modeling of the PC within the excitation system is described.

3.1. Power system benchmark

The configuration of the test system is shown in Fig. 4 in which a thermal power plant is connected to a large power system through a transmission line. Altogether, the power plant generates 2220MVA, 24kV, 60Hz. This standard system is represented in [1]. AVR and power system stabilizer (PSS) are also considered in the modeling of the system.

The Heffron-Phillips model of the test system is simulated in MATLAB environment. Fig. 5 shows that the POSICAST is applied to the outset of the exciter. This feed-forward controller can be considered as an open-loop or it can be within a closed-loop. However, the performance of both states is analyzed in the next section. All the parameters used are listed in Table 1.

The generator is modeled according to the 6th order nonlinear mathematical model. The offered model involves the dynamics of the stator, field, and damper windings. The equivalent circuit of the generator, in p-q frame, is shown in Fig. 6, in which all the rotor parameters and quantities are transmitted to the stator side.

The transmitted values are identified by primed variables. The equations of the simulated synchronous generator are listed here:

$$V_d = R_s i_d + \frac{d}{dt}\phi_d - \omega_R \phi_q \tag{2}$$

$$V_q = R_s i_q + \frac{d}{dt}\phi_q - \omega_R \phi_d \tag{3}$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\phi'_{fd} \tag{4}$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\phi'_{kd} \tag{5}$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\varphi'_{kq1} \tag{6}$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\varphi'_{kq2} \tag{7}$$

$$\varphi_d = L_d i_d + L_{md}(i'_{fd} + i'_{kd}) \tag{8}$$

$$\varphi_q = L_q i_q + L_{mq} i'_{kq} \tag{9}$$

$$\varphi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i_d + i'_{kd}) \tag{10}$$

$$\varphi'_{kd} = L'_{kd} i'_{kd} + L_{md}(i_d + i'_{fd}) \tag{11}$$

$$\varphi'_{kd1} = L'_{kd1} i'_{kd1} + L_{mq} i_q \tag{12}$$

$$\varphi'_{kd2} = L'_{kd2} i'_{kd2} + L_{mq} i_q \tag{13}$$

The parameters and subscripts are defined in Table 1.

3.2. POSICAST Control

The generator excitation system model, modified with the proposed controller, is shown in Fig. 7. The original excitation is a thyristor-based excitation system, which is delineated as IEEE type ST1A [31].

PC is applied as an open-loop controller; however, it can be also considered within a feedback system (as illustrated in Fig. 5). The performance of both the open-loop and closed-loop application of the POSICAST controller is described in the following sections.

As shown in Fig. 7, the terminal voltage (Vt) is fed back into the controller and compared with the set-point. In comparison with the controller of Fig 3, in Fig 7, the C(s) block is replaced with a constant gain and an integrator. By use of the integrator, the robustness of the controller is increased and the steady-state error is eliminated as well.

As mentioned above, the proposed POSICAST controller is designed by setting the time of the peak step-response (Td/2) and the peak value of overshoot (1+δ). These parameters have been obtained from the step-response of the study power system and are listed in Table 2.

4. Eigenvalue Analysis

In this section, to clarify the effectiveness of the proposed controller, the small-signal stability of the test system is analyzed in the presence of PC. It should be noted that the modal analysis is used from the presented Heffron-Phillips block diagram in Fig. 5. The state-space model of the classic system (with ST1A excitation) as a matrix 6×6 has been presented in [1]. In this analysis, the effects of the amortisseurs have been ignored in the offered model. The definitions of the associated parameters are shown in Table 1.

The complete state-space model, including the PC, is given by (with ΔTm=0):

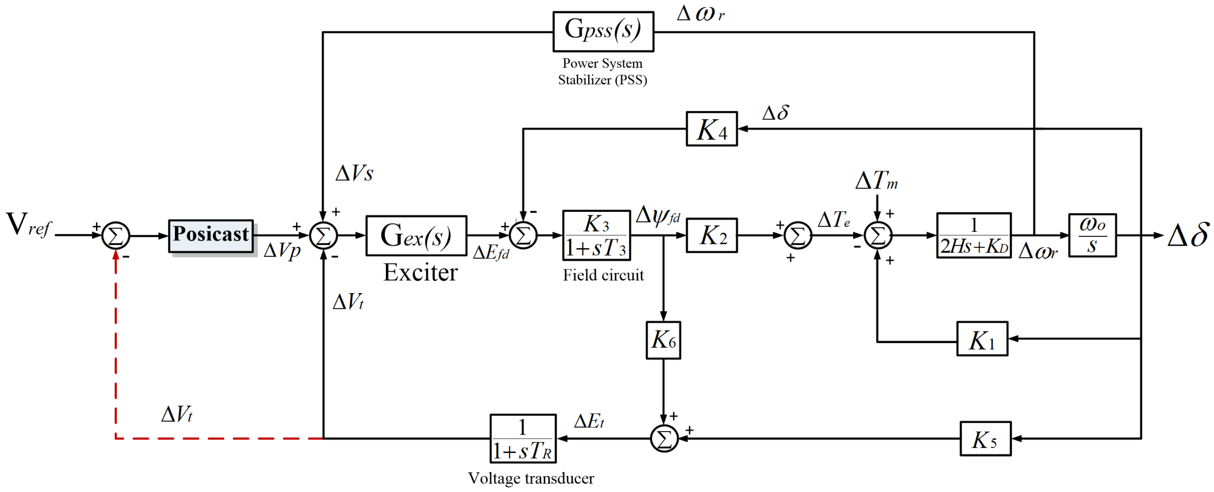


Figure 5: Heffron-Phillips model of single-machine system representation with exciter, AVR, PSS, and POSICAST controller

Table 1: Parameters definition

Symbol	Definition	Values	Units
d, q	d and q axis quantity		
F	Frequency	60 Hz	Hz
fd	Field winding quantity		
$G_{ex(s)}$	Exciter gain	200	
H	Inertia constant	3.5	MW.s/MVA
k	Damper winding quantity		
K_D	Damping coefficient	0	
K_P	Gain quantity of C(s) block	1.5	
L	Leakage inductance		
m	Magnetizing inductance		
P	Generated active power	0.9	p.u
P_e	Electrical power		W
P_m	Mechanical power		W
Q	Generated reactive power	0.3	p.u
s	Stator quantity		
S	Laplace operator	1.0 36	p.u
V_t	Terminal voltage	0.3	p.u
X'_d	Inner reactance of generator		p.u
$\Delta\omega_r$	Speed deviation		elec.rad
$\Delta\delta$	Rotor angle deviation		
$\Delta\Psi_{fd}$	Field circuit dynamic deviation		
Δv_t	Deviation of the generator terminal voltage		
Δv_1	Terminal voltage transducer/ AVR		
Δv_s	Terminal voltage PSS		
Δv_p	Deviation of reference signal at PC output		

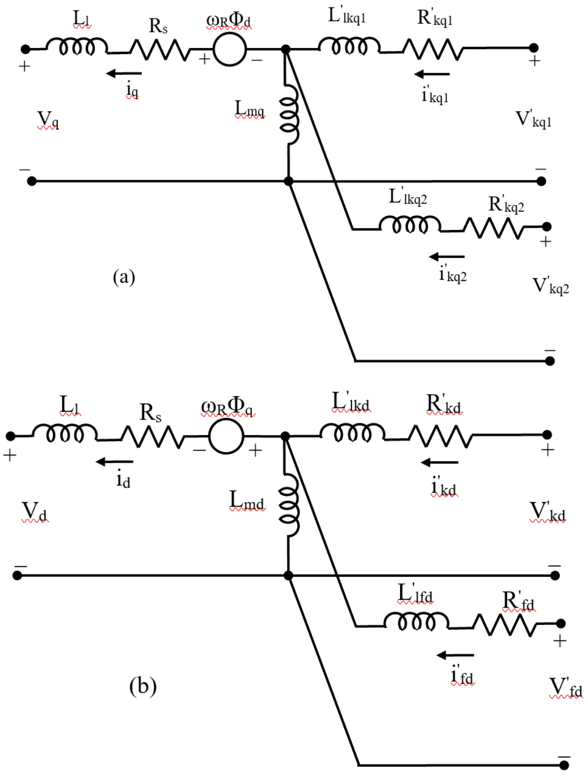


Figure 6: Electrical model of the generator. (a) q axis. (b) d axis

Table 2: Parameters definition

Parameters / symbol	Values	Units
δ	0.3815	Per unit
$\frac{T_d}{2}$	0.2582	sec

$$\begin{bmatrix} \Delta\omega^{\bullet}r \\ \Delta\delta^{\bullet} \\ \Delta\psi^{\bullet}fd \\ \Delta v^{\bullet}t \\ \Delta v^{\bullet}1 \\ \Delta v^{\bullet}s \\ \Delta v^{\bullet}p \end{bmatrix} \begin{bmatrix} a11 & \cdots & a17 \\ \vdots & \ddots & \vdots \\ a71 & \cdots & a77 \end{bmatrix} \begin{bmatrix} \Delta\omega r \\ \Delta\delta \\ \Delta\psi fd \\ \Delta vt \\ \Delta v1 \\ \Delta vs \\ \Delta vp \end{bmatrix} \qquad (14)$$

By adding PC through feedback into the excitation system, the matrix dimensions increased to 7×7. Definitions of the classical model of the matrix elements are described in [1]; however, according to the PC position in the block diagram of Fig. 5, the flux linkage ($\Delta\psi fd$) is modified.

$$KE = \frac{1}{1+sTR}\left[K5\Delta\delta + K6\Delta\psi fd\right] \qquad (15)$$

Hence, $\Delta\psi fd$ due to POSICAST is

$$\begin{aligned} \Delta\psi fd\,|Posicast = \tfrac{K3}{1+sT3}\{-K4\Delta\delta- \\ -Gex(s)\left[KE(1+Kp(1+P(s))) + Gpss(s)\Delta\delta\right]\} \end{aligned} \qquad (16)$$

By use of the equations (1) and (15), the flux linkage and the modified reference signal ( ) are given by:

$$\Delta Vp = KP.(1+P(s)).(Vref - KE) \qquad (17)$$

All of the presented variables are thoroughly explained in [1].

Table 3 shows the impact of the various values for K_P on the eigenvalues of the state matrix. Table 3 also offers a comparison between the classic exciter and the proposed PC when it is used as a closed-loop controller. The table also indicates, for each mode, the state variable with the highest participation.

Moreover, the summarized results in Table 3 determine that, in most cases, a PC with a proportional K_P leads the power system to instability. Their changing rates are ignored, but it improved the mode (λ1) position which was causing oscillations in the power system. The role of this mode associates to the damping coefficient. The controller has a positive effect on that.

According to the presented results in Table 3, as well as the analysis of the K_P impacts on the POSICAST performance, the associated results of which are shown in Fig. 8, the increase of the K_P has a specified limitation. This limitation is due to the fact that, by increasing the KP, modes λ4 and λ5 are moving to an unstable condition. In fact, these modes limit the increase of the KP factor, which should be considered in the design process. Fig 8 (b) is the zoomed illustration of Fig. 8 (a).

On the other hand, the nearest pole to the imaginary axis relates to λ6. The variation of this mode has the most impact on the power system's dynamic behavior. The state variableΔvs has the highest participation in this mode. However, there is the advantage that the stated mode has minimum sensitivity to K_P, and has negligible variation for K_P initialized error.

The other important influence of the PC is in improving power system performance via elimination of steady state error. Fig. 9 shows the impact of the proposed POSICAST controller on mitigation of the power oscillation for various magnitudes of K_P. This figure also shows that the controller has removed steady state error.

5. Experimental Results

The proposed POSICAST controller is evaluated by use of the hardware in the loop (HIL) approach. HIL is used to consider the errors that do not appear in the off-line simulations. In this section, the HIL setup devices are explained. Moreover, the results of various case studies are also presented and explained here.

5.1. Experimental setup

Two applications were developed for this experiment: initially, the standard test grid was designed on a command station using MATLAB and then, using the RT-LAB, the

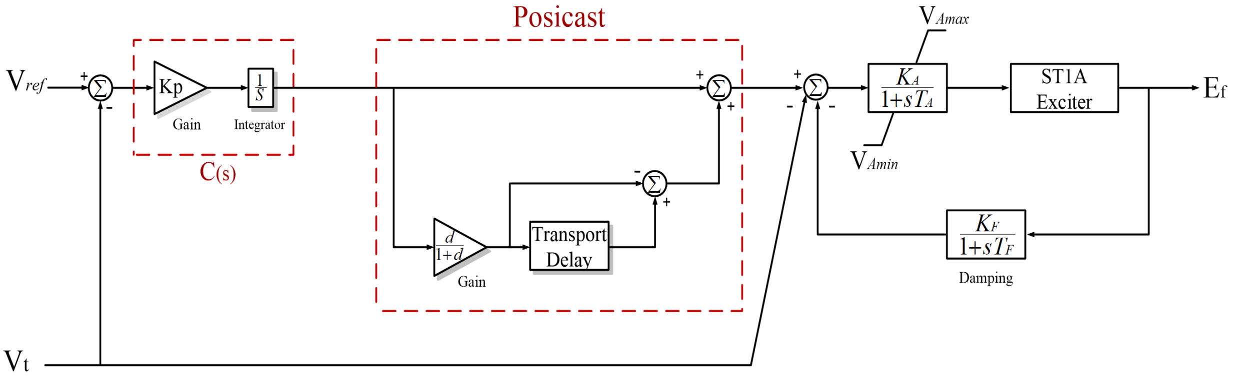


Figure 7: Structure of POSICAST controller integrated into AVR and excitation system

Table 3: Parameters definition

States	Kp	Eigenvalues				
		λ_1	$\lambda_2\lambda_3$	$\lambda_4\lambda_5$	λ_6	λ_7
ST1A Exciter	-	-37.1340	-20.5298±20.5984i	-1.2285±7.2007i	-0.7348	-
POSICAST in the loop	1	-37.3644	-19.9651±20.3264i	-1.1176±7.0060i	-0.6795	-1.1763
POSICAST in the loop	1.5	-37.4822	-19.6687±20.1947i	-1.0346±6.9167i	-0.6988	-1.7979
POSICAST in the loop	3	-37.8456	-18.7169±19.8254i	-0.7043±6.7485i	-0.7086	-3.9890
POSICAST in the loop	4.5	-38.2229	-17.6626±19.5194i	-0.3749±6.7526i	-0.7108	-6.3769
POSICAST in the loop	6	-38.6126	-16.5047±19.3219i	-0.1288±6.8481i	-0.7118	-8.7941
POSICAST in the loop	7.5	-39.0132	-15.2730±19.2890iv	0.0419±6.9703i	-0.7123	-11.1978
Dominant States		Δv_1	$\Delta\Psi_{fd}$,Δv_t	$\Delta\omega_r$,$\Delta\delta$	Δv_s	Δv_p

model was compiled into an application and transferred to the OP5600 HIL box. The second application was developed for the DK60 board in C++ and involved the implementation of the POSICAST's algorithm and the IEC61850 communication configuration. To determine the controller operation as HIL, the setup presented in Fig. 10 was used, which consisted of the following hardware resources:

5.1.1. OP5600 HIL box from OPAL

To simulate the study power system in real-time, the OPAL-RT digital simulator was used. The OP5600 is a real-time digital simulator with a multi-processor configuration and an FPGA for fast computation. The board is equipped with multiple analog and digital inputs/outputs for connecting to different hardware and provides a powerful tool for HIL testing. In this test, the study power system is first simulated by MATLAB/SIMULINK. Then, by use of the RT-LAB software, the simulated power system is transferred to OPAL-RT. In fact, the RT-LAB software works as an interface between the MATLAB software and the OPAL-RT.

5.1.2. Command station

The command part is a stationary computer which is used to design the Matlab/Simulink model that will run on the OPAL-RT target, transfer it to the real-time simulator and monitor/supervise the operation of the hardware in the loop setup.

5.1.3. DK60 development board

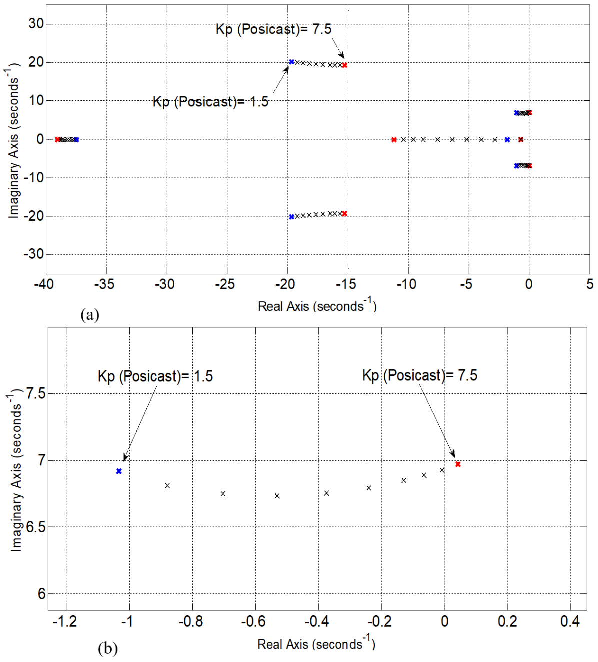
This development board is used to implement the proposed controller. In fact, this board operates as a real controller which is connected to a real power system. For this reason, an application has been developed by C^{++} based on the algorithm of the proposed PC.

5.1.4. Router

This is used for connecting all the devices in the same subnetwork. During the experiment, the output of the OPAL-RT, which is simulating the real-time behavior of the study system, is transmitted to the board through Ethernet ports. This type of data transfer could be a model for the networks used in power plants for automation aims. The board receives the input signals (Pm-Pe) from the OPAL-RT and applies the control signal, according to the POSICAST algorithm, to the simulated power system in OPAL-RT.

5.2. Results and Discussion

When changing the reference signal, the system suffers from oscillations; hence, this phenomenon was used as a disturbance case. Initially, the signal was increased from 1 to 1.03, which was applied at t=10 Sec. Then, as a second evaluation, Vref decreased from 1 to 0.97 and applied at t=10 sec



(a)

(b)

Figure 8: The effect of KP on POSICAST operation

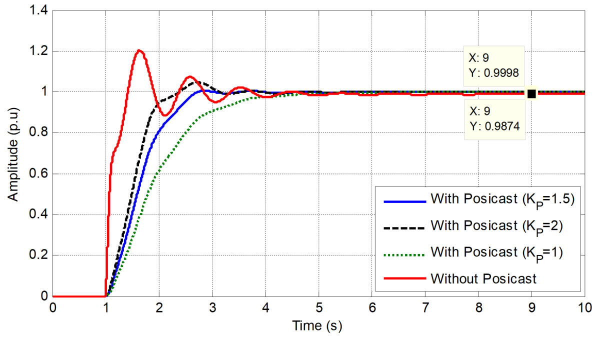


Figure 9: Power system dynamic response in different exciter conditions

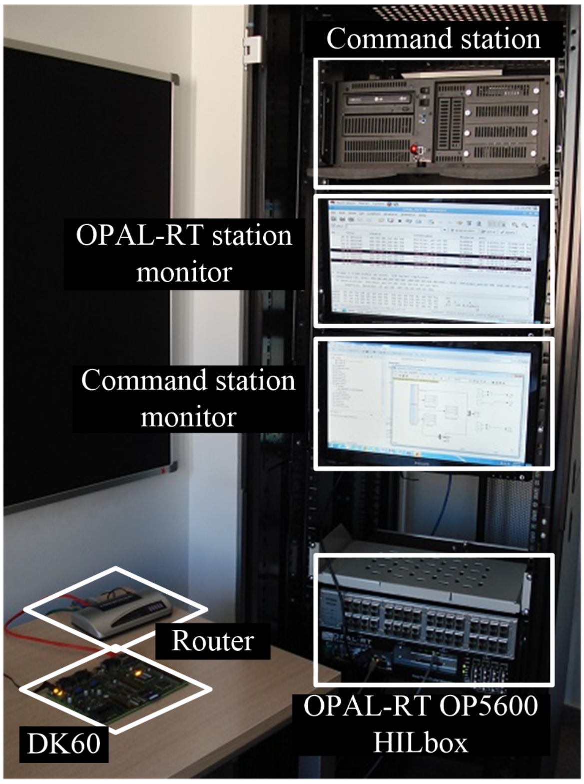


Figure 10: Experimental setup of SEER research group, UPC University

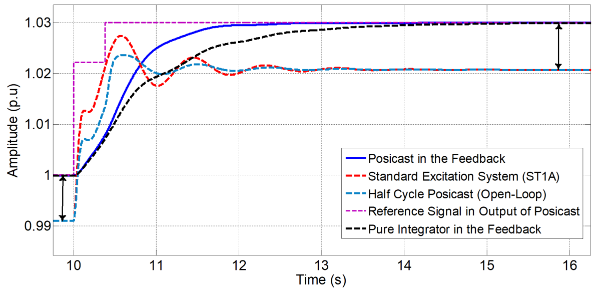


Figure 11: Terminal voltage of the generator after increasing Vref

separately. The terminal voltages of the generator are shown in Fig. 11 and 12. Simulations offer a comparison between the open-loop half cycle POSICAST, Integral controller (C(s)) and the PC used within the feedback system. The best performance is delivered by the operation of PC in the loop.

As shown in the figures above, PC has eliminated the first overshoot or undershoot for step change in the reference signal (V_{ref}). To eliminate the fluctuation, POSICAST smooths the step input and, as a result, improves the damping capability of the system. Damping variation of the applied voltage to field windings extends the life of the excitation system and field windings. Moreover, due to the presence of the integrator in the structure of the controller, terminal voltage meets final values precisely and removes steady state errors.

Dynamic behavior of the nonlinear systems depends on the operating point. The synchronous generator is a perfect example of a nonlinear and complicated system. In the case of a synchronous machine, changing the operating point in a wide range is not recommended as a strategy [28]; however, in order to evaluate the operating range of the designed controller there is a need to change the operating point of the generator in a practical order. Thus, the new operating conditions are considered as follows: the output terminal voltage of the generator in the steady-state condition is 1p.u and the output active power is considered 0.9p.u.

In this case, the first step was a 1 to 1.04 increase applied at t=10 sec and the second was a 1.04 to 0.98 change applied at t=25 sec. The POSICAST controller used in this case is the same as the designed controller before changing the operating conditions, i.e., we assumed that the operating conditions were changed after designing the controller. The terminal voltage of the generator is shown in Fig. 13. As shown in the figures above, PC improves the transient dynamics of the system, even in the new operating conditions. As shown in Fig. 14, in order to evaluate PC operation from

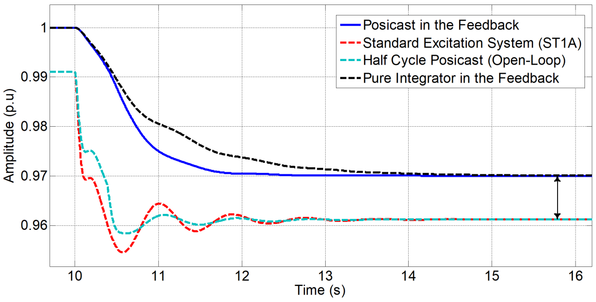


Figure 12: Terminal voltage of the generator after decreasing Vref

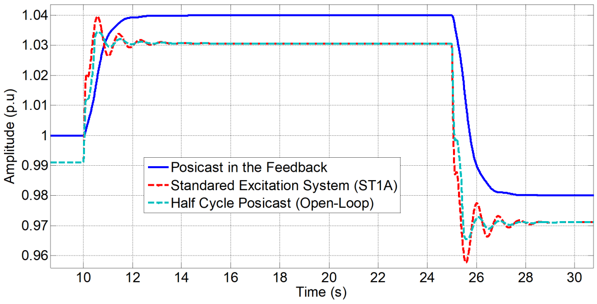


Figure 13: Output active power in the new operating point

other stability aspects, a disturbance was created at t=10 on the synchronous machine's turbine. According to the result achieved in the previous section, PC does not negatively impact the other modes. As a result, the applied PC on the excitation system is only effective on the voltage control issue.

6. Conclusion

This paper proposed a POSICAST controller for the excitation systems of synchronous generators. It has been shown that the PC is able to improve the performance of the power systems in damping oscillations without harming power system stability. The following main results were obtained from the simulations:

1) The dynamic of the system response was considerably improved and over/undershoots completely removed from the voltage profile in the case of changing the excitation reference signal.

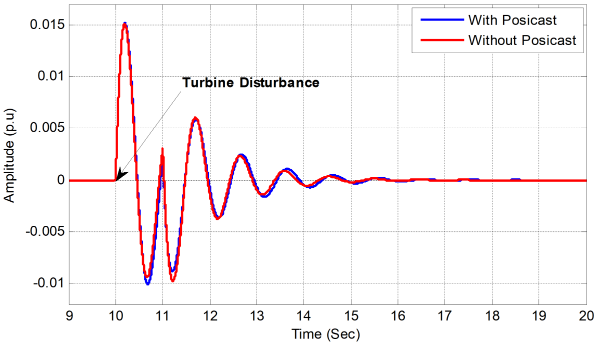


Figure 14: Rotor speed deviation of the generator

2) The controlling signals of generator field windings have no overshoot and reduced settling time. The smaller variation of the signals which are applied to the field windings results in longer life time of these windings in the generator. As a result, it is possible to conclude that implementation of proposed PC will extend the field winding life time.

3) The PC removed the steady state error and improved system performance to precisely meet desired values under normal conditions.

4) In order to study the PC's effect on power system stability, the state space of the test system was obtained. The advantage of this approach is that the output of the PC block is a state variable and, hence, can be monitored directly by computing the state variable.

The performance of the proposed controller was evaluated by using the HIL approach. The HIL approach confirms that the proposed method works properly and improves system stability with a very simple control method.

Acknowledgments

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