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Enhancing Transient Stability in Power Systems Using a New Excitation Controller

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Abstract: In this paper a POSICAST controller is designed to improve the power system stability containing the transient and the small signal stability. Unlike most of the recently published excitation control schemes, POSICAST control is an unsophisticated and easy to implement control method that can effectively improve the stability of the system without increasing the complexity of the control system. The proposed controller is simulated under several large and small sudden 3-phase faults occurred in the different parts of the lines. It is also shown that the proposed controller increases the capability of the system in damping the oscillations caused by changing the exciter reference signal. In other words only one controller is used to improve the transient and small signal stability as well as the voltage stability. The results from extensive time domain simulations using MATLAB/Simulink demonstrate that the offered control strategy is superior to the conventional excitation control methods and can improve performance of the system in the all testing conditions. A performance index is also used to validate the effectiveness of the proposed controller in improving the system stability.

Key words: Transient Stability, Automatic Var Regulator (AVR), POSICAST Controller, Excitation System.

INTRODUCTION

Power system stability denotes the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that system integrity is reserved (Kundur, 1994). The high complexity and nonlinearity of power systems together with their almost continuously varying operating conditions intensify the difficulty of stabilizing controller design process.

Using the generator excitation controls is a basic stability control scheme. The principal conventional excitation controller is the automatic voltage regulator (AVR). Together with the AVR, Power System Stabilizer (PSS) is used as a supplementary control loop in order to improve the damping of power swings (Grigsby, 2006). Numerous papers have been published about the excitation control. Using the linear control theory methods such as: root locus, eigenvalue analysis, pole placement and adaptive control and etc have been investigated; however these controllers are designed based on the linearized model of the plant around a working point and their performance diminishes when large variation of operating point occurs due to the sudden faults. On the other hand they are very sensitive to the accuracy of the plant model used in the design process (Zhao and Jiang, 1995). Hence, attention has been focused on the application of nonlinear controllers, which are independent of the equilibrium point and take into account the important non-linearities of the power system model (Wang *et al.,* 1997; Xi *et al.,* 2003; Lin and Shen, 1999). But designing a nonlinear controller that can consider the all nonlinearities of the system increases the complexity of the control system and makes it very expensive to implement. In order to solve this problem feedback linearization scheme is applied that uses a nonlinear feedback in order to linearize the system in the all working points (Akhrif *et al.,* 1999; Chapman *et al.,* 1993). After linearization the system can be controlled even with a linear controller. This method can solve the complexity problem but the performance of the linearization is dependant of the accuracy of the plant nonlinear model. On the other hand we are frequently faced with uncertainty in practical power systems. In this case, it is difficult to exactly linearize the system with nominal parameters. Adaptive versions of the feedback linearizing controls are then developed (Tan and Wang, 1998; Wang *et al.,* 1994). Most of the aforementioned methods use much more complicated control schemes than needed. Indeed there must be a reasonable trade off between the cost of implementation and performance of the offered controller.

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Recently, POSICAST control as an effective and unsophisticated control scheme has been applied successfully in power system applications, such as terminal voltage control of the generator (Ghorbani *et al.,*), digital control of the boost converters (Feng *et al.,* 2003), Dynamic Voltage Restorer (DVR) (Loh *et al.,* 2004), resonant damping of z-source current-type inverter (Loh *et al.,* 2006) and so on. It is used to decrease the overshoot of the step response in linear or nonlinear systems and when properly tuned, the controlled system yields a transient response that has deadbeat nature.

In this paper a POSICAST controller is designed to improve the power system stability containing the transient and the small signal stability. Using a POSICAST controller to improve the voltage stability of the generator has been investigated in the previous work and is also contained in this paper.

Extensive time domain simulations using MATLAB/Simulink is carried out and the results demonstrate that the offered control strategy is superior to the conventional excitation control methods and can improve performance of the system in the all testing conditions. A performance index is also used to validate the effectiveness of the proposed controller in improving the system stability. The outline of this paper is as follows: In section II a brief review of POSICAST controllers is presented. The structure of the system described in section III. The simulation results are presented in section IV. The conclusion is drawn in section V.

Review of Posicast Controllers:

POSICAST is a feed-forward control method that dampens oscillations in systems whose other transient specifications are otherwise acceptable. When properly tuned, the controlled system yields a transient response that has deadbeat. The invention of POSICAST control is due to Prof. Otto J. M. Smith, who described the basic principles in the Sept. Smith, (1957). Whereas the classical applications placed POSICAST before the lightly damped system, recent work suggests that POSICAST be used within a feedback system. The proposed control method is a significant departure from classical POSICAST (Hung, 2007). For historical and detailed description of the POSICAST control refer to (Hung, 2007).

Consider a system having a lightly damped step response as shown in Fig. 1. The overshoot in the response can be described by two parameters. First, the time to the first peak is one half the underdamped response period T_d. Second, the peak value is described by $1+\delta$, where δ is the normalized overshoot, which ranges from zero to one. POSICAST splits the original step input command into two parts, as illustrated in Fig. 1. The first part is a scaled step that causes the first peak of the oscillatory response to precisely meet the desired final value. The second part of the reshaped input is full scale and time-delayed to precisely cancel the remaining oscillatory response, thus causing the system output to stay at the desired value. The resulting system output is sketched in Fig. 1 (solid line); the uncompensated output is also shown for comparison (dashed line) (Hung, 2007).

One block diagram interpretation of the half cycle POSICAST controller is shown in Fig. 2. The model has two forward paths. The upper path is that of the original, uncompensated command input. In the lower path, a portion of the original command is initially subtracted, so that the peak of the response will not overshoot the desired final value (Hung, 2007; Cook, 1966). The transfer function is given by the function 1+P(s), where P(s) is given by:

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

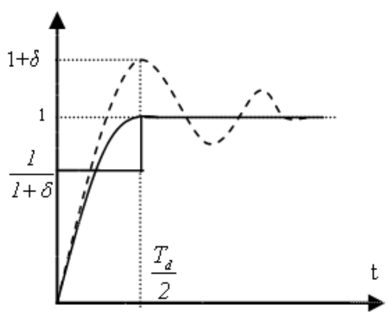

Fig. 1: Step Response of the system with (solid line) and without (dashed line) POSICAST and the control signal generated by POSICAST

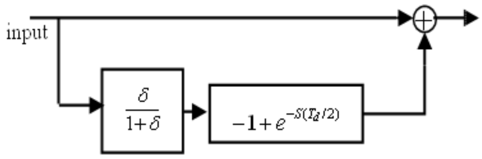

Fig. 2: Open-loop half cycle POSICAST.

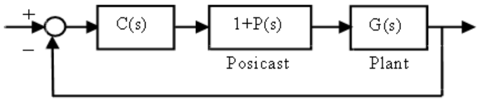

Fig. 3: POSICAST within a feedback system.

The described method is open-loop compensation so it is sensitive to the parameter variations and plant model-mismatch. The sensitivity problem can be reduced if POSICAST compensation is applied within a feedback system rather than in the classical feed-forward configuration (Hung, 2002; 2003). A block diagram explaining the control method is shown in Fig. 3. In this paper the POSICAST is considered after a PI controller in feedback configuration with the nonlinear model of the generator. The controller design procedure is described in the next section.

Structure of the System:

The network to be controlled and the configuration of the simulated power system, studied in this work, are described in this section. The parameters of the POSICAST controller are also designed.

A. Model System:

The configuration studied in this work is shown in Fig. 4. It consists of a synchronous generator connected through two parallel transmission lines to a very large network approximated by an infinite bus. Parameters of the generator is borrowed from the Prof. Kundur's book (Kundur, 1994) and the model used for the excitation system is the standard IEEE model for studing the power system stability (ST1A) (Recommended, 1992). The parameters of the excitation system is listed in table 1.

B. Obtaining Parameters of the Controller:

The structure of the excitation system after adding the POSICAST controller is shown in Fig. 5. It is clear from the figure that the POSICAST is used in a feedback loop. As mentioned earlier using POSICAST in feedback increases the robustness of the system.

In the previous work a POSICAST controller is used to mitigate the oscillations caused by changing the excitation reference signal (Ghorbani). The structure of the excitation system used in that work was the same with the one shown in Fig. 5 but there wasn't any feedback from P_m-P_e. Most of the PSS designs use this signal as an input signal because almost all faults occurred in the network effect this signal (Kundur, 1994). We have used this signal to improve the stability of the system, too. This signal is added to the POSICAST input signal. In other words both changing the excitation reference signal and both the faults occurred in the network can be handled with a POSICAST controller. This is the most important advantage of the offered controller over the designs that use two different controllers for damping the oscillations caused by changing the excitation reference signal and the ones caused by the sudden line faults. Two parameters are required to design the POSICAST controller. First, the time to the first peak and second, the peak value. We can obtain the parameters by applying a step change in the POSICAST input. excitation reference or in the P_m-P_e signal. Here we have used a step change in the exciter reference signal to have a reasonable physical justification. Table 1 shows the obtained parameters.

While comparing figures 3 and 5 it is concluded that the C(s) in the figure 3 is substituted with an integrator and a constant gain. Using the integrator increases the robustness of the controller and causes a zero steady-state error.

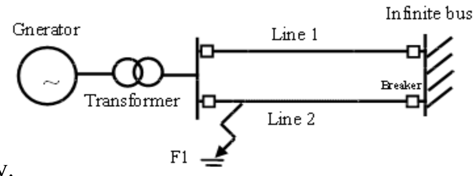

Fig. 4: The network under study.

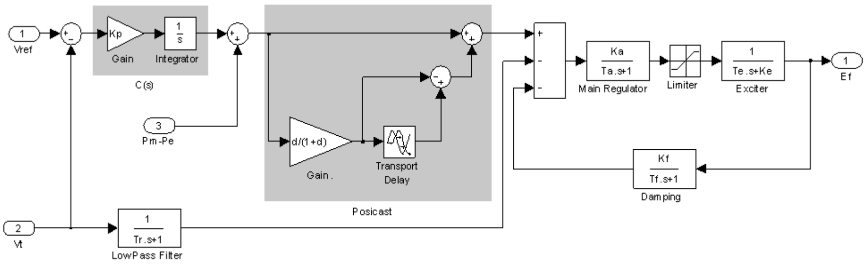

Fig. 5: The AVR and the excitation system after adding POSICAST.

Simulation Results:

In this section the simulation results is presented. The results are classified in 3 different sections: The first section contains the generator terminal voltage control. Small signal and transient stability are investigated in the second and third section, respectively. All the results are obtained using the Power System Blockset (PSB) in MATLAB/Simulink environment.

Table 1: Parameters of the POSICAST, Excitation system and AVR

δ	0.0088	Ke	1
Td /2	0.8057	Te	0.001
Tr	0.015	Kf	0.001
Ka	50	Tf	0.1
Ta	0.2	|Efmax,min|	7

A.Generator Terminal Voltage Control:

In this section it is shown that how POSICAST controller mitigates the terminal voltage oscillations caused by changing the exciter reference signal. The detailed study of this section containing impact of changing the operating point of the generator and mismatching in the obtained parameters, on performance of the designed controller were also studied in the previous work (Ghorbani). Here there is only a brief review to show that the revised version of the POSICAST controller can be used to handle the terminal voltage control as well as the transient and small signal stability.

In order to evaluate the performance of the designed POSICAST controller two step changes in the reference signal of the exciter are considered. The first step is a 1 to 1.05 increase applied at t=1 sec and the second one is a 1.05 to 0.93 change applied at t=5 sec. The terminal voltage and the exciter output signal are shown in Fig. 6. As shown in the figure considerable improvements are obtained both in settling time and both overshoot of the signals. Two different POSICAST controllers are considered here. In the first controller the Pm-Pe signal is used but it is not used in the second one. Since there isn't any fault in the network the P_m-P_e signal hasn't any significant effect on the controller performance.

B. Small Signal Stability:

Small signal stability is defined as the ability of the power system in sustaining the synchronism when it is posed to small disturbances. In order to see how effective the POSICAST controller is in improving the small signal stability, five three-phase to ground faults are considered in different parts of the line. The faults are occurred in t=1 sec and they are cleared after 0.1 sec. Table 2 shows the location of faults. Figu.7 and Fig. 8 show the terminal voltage and the rotor angle diviation after occurring the faults. As shown in the figures the oscillations caused by the fault are rapidly damped by using a POSICAST controller and the system regains the prefault condition of operation. A performance index is used in this section. In this work, the integral of the absolute value of the time derivative of the total kinetic energy divided by the system base power is selected as the objective function. Therefore, the objective function is expressed simply as (Ali *et al.,* 2004):

$$W,(see) = \frac{\int_0^T \left| \frac{d}{dt} W \right| dt}{system\ \ base\ \ power} \tag{2}$$

Where the simulation time is considered 15 sec with a 0.0001 sampling period and W is the total kinetic energy (in joule) which can be calculated easily by knowing the rotor speed of the generator (Ali *et al.,* 2004):

$$W = \frac{1}{2} J \omega_m^2 (J) \tag{3}$$

Again in (3) J denotes the moment of inertia in Kg.m2 and ω_m rotor angular velocity in mechanical radians per second. The smaller the value of W_c, the better the system's performance. Table 2 shows the values of W_c for the system when the faults occur.

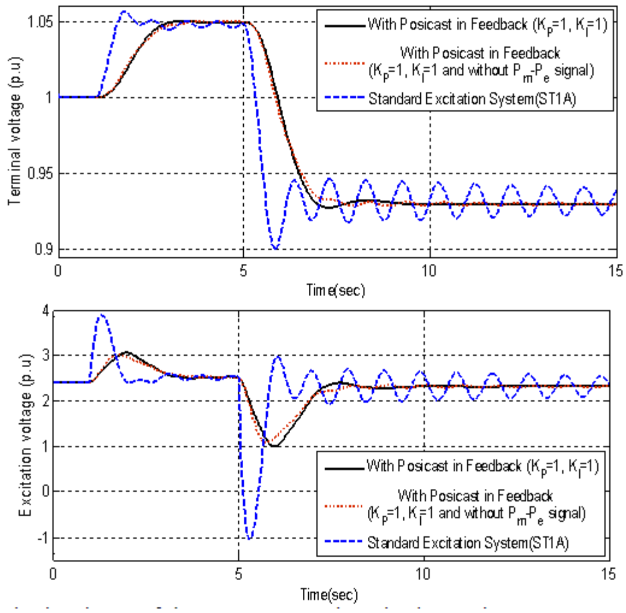

Fig. 6: Terminal voltage of the generator and excitation voltage.

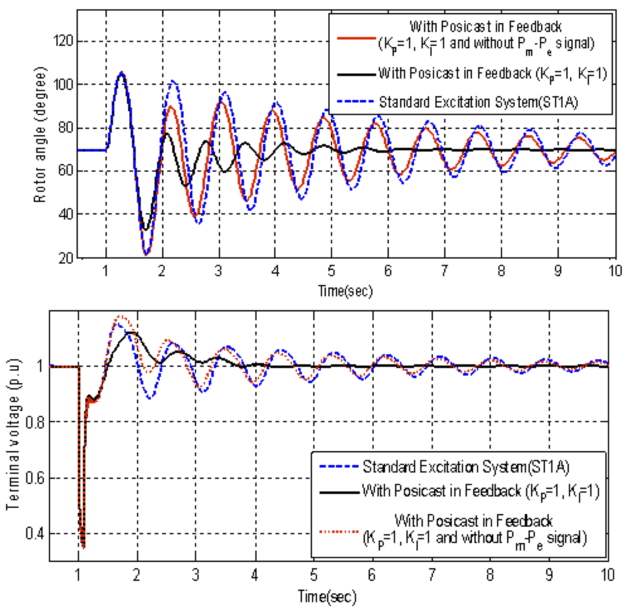

Fig. 7: Rotor angle and terminal voltage of the generator for F1 fault.

C. Transient Stability:

In order to investigate the transient stability of the system it is assumed that three faults are occurred in the beginning, middle and the end of the transmission line. The faults are considered 3-phase short circuit and occur at t=1 sec. After 0.1 sec the line breaker detaches the faulty line from the network. Rotor angle and terminal voltage after fault occurance are shown in figures 9 and 10, respectively. As shown in the figures all the oscillations are damped by using the POSICAST controller feeding back from the P_m-P_e signal and the system reaches to a new postfault operating condition in a few seconds after the fault occurance are shown in figures 9 and 10, respectively. As shown in the figures all the oscillations are damped by using the POSICAST controller feeding back from the P_m-P_e signal and the system reaches to a new postfault operating condition in a few seconds after the fault is cleared.

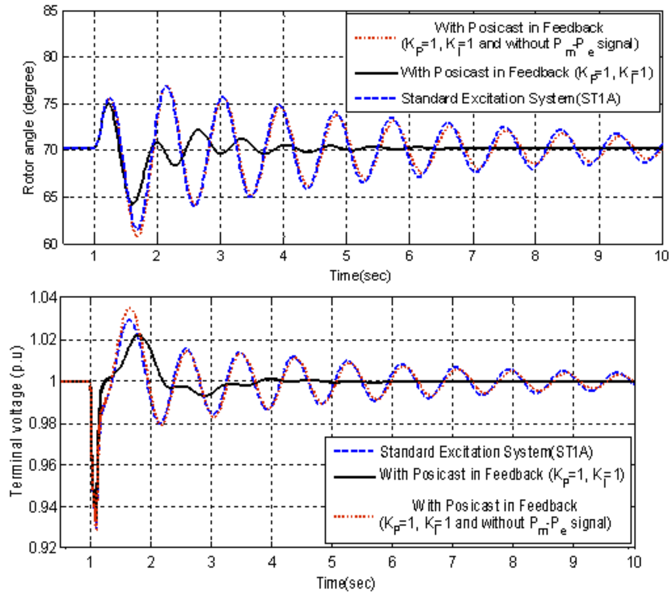

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Fig. 8: Rotor angle and terminal voltage of the generator for F3 fault.

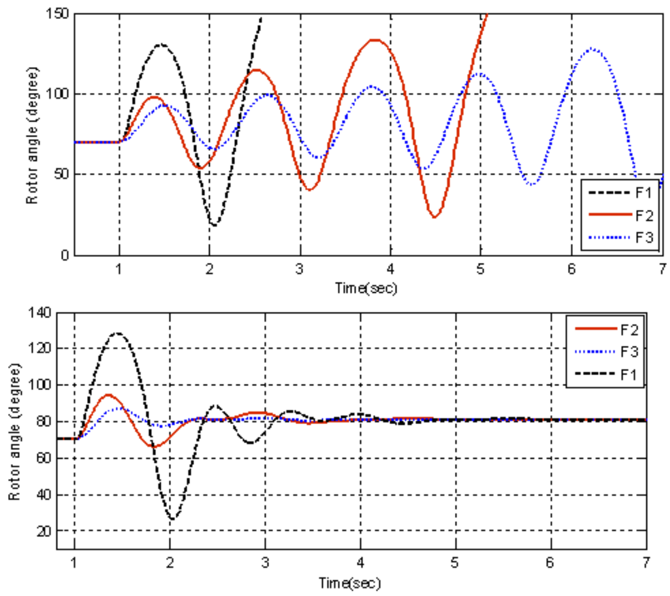

Fig. 9: Rotor angle with standard excitation system (upper) and with using the POSICAST in feedback (lower) (K_P=1,K_I=1 and with P_m-P_e signal).

Table 2: Values of the performance index

Fault point	W_C	
	Standard Excitation System	With POSICAST in Feedback(K_p=K_I=1)
F1(beginning of the Line 1)	0.6171	0.2359
F2(middle of the Line 1)	0.3222	0.0978
F3(end of the Line 1)	0.1198	0.0351
F4(beginning of the Line 2)	0.6378	0.2459
F5(middle of the Line 2)	0.5168	0.1678

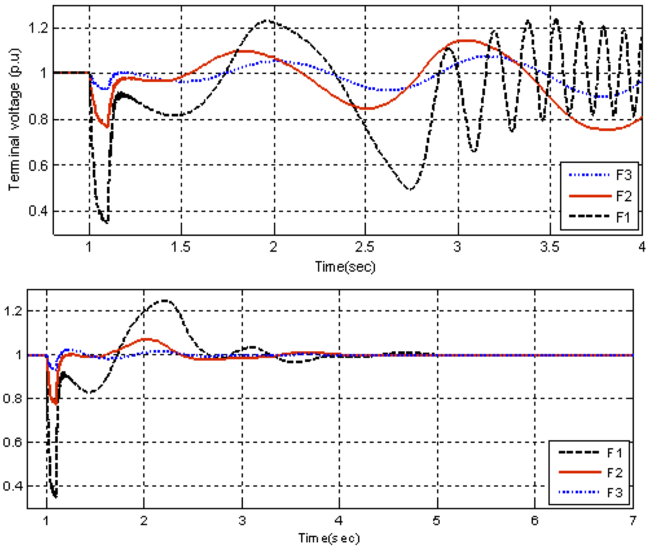

Fig. 10: Terminal voltage of the generator with standard excitation system (upper) and with using the POSICAST in feedback (lower) (K_P=1,K_I=1 and with P_m-P_e signal).

Conclusion:

The In this paper small signal and transient stability of the system has been improved using a POSICAST excitation controller. In addition it has been shown that the voltage stability of the generator can be improved using the offered controller. In other words the generator terminal voltage stability can be improved as well as the transient and small signal stability by using just one POSICAST controller. Several considerable remarks obtained from the simulation results:

1. The overshoot of the responses are considerably improved and it is completely removed from the terminal voltage in the case of changing the exciter reference signal.
2. There are considerable improvements both in overshoot and both settling time of the signal applied to the generator field windings. The smaller the voltage variations applied to the field windings the longer the life of the generator (Kundur, 1994), therefore we can conclude that using POSICAST controller can also extend the life of field windings.
3. The POSICAST controller uses an unsophisticated and easy to implement idea to decrease the peak value, POSICAST infuses the step changes in the input to the system gradually. In other words the POSICAST smoothes the step input in order to eliminate the overshoot in the output signal.
4. Only one POSICAST controller has been used to handle the oscillations caused by two different reasons: the first, changing the exciter reference signal and the second large or small faults occurred in the transmission lines. Therefore the proposed controller is a significant departure from the classical designs that consider two different controllers for the excitation system in order to damp the aforementioned phenomena.

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