Application of Posicast Controller on Power System Stabilizer and Its Effect on Oscillatory Stability

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Abstract. This paper presents the effect of posicast controller on mitigation of small signal oscillatory stability. Posicast is adopted as a rule of action which could be taken on any dynamic system. Tuning parameters is calculated by inherent characteristic of the system which also indicates the place that the posicast is needed. Each posicast adheres to its defined mode and shows its effect whenever they start to oscillate and does not have any side effect on normal operation of the system. The New England 39-Bus system has been chosen to evaluate the performance of the controller. Improvement in rotor angle, generators active power, lines active power, buses frequency and stability margin have been observed.

Keywords: Posicast controller, Power system stabilizer, small signal oscillatory stability, damping.
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INTRODUCTION

Since 1920s as the generators of power systems start to operate in parallel, the stability of the power system became an important factor for a secure system operation [1]. Demand for energy is growing fast each day which leads to construction of more interconnected power networks that should operate in synchronism together and as there is a possibility for higher loading the operators may push the power network to its stability limit. In a big interconnected power system this sometimes may lead to poorly damped oscillations which results to limitation of power transmission and instability that is called small signal oscillatory stability (SSS).

Controlling the oscillatory stability is relatively a simple task that could be solved by applying power system stabilizer (PSS)[2]. Also different methods for assessment and control of SSS have been proposed by researchers. Improvement in technology also helps us to find out better methods such as: use of wide area measurements [3], [4], [5]and artificial intelligence [6], [7], [8]. Different methods of SSS control may show their ability to mitigate the oscillations most of the time but what they are missing is the way that how they should act and present their output to the system. Any dynamic system has many state variables with different sensitivity.

In case of any disturbance the most sensitive variable, will start its oscillation faster than the other variable which if it could not be damped and handled perfectly it will lead to system instability. This paper presents a control strategy that the PSS controller should follow and presents its output in case of any disturbance to the system which improves damping of the system and its stability margin. The strategy is presenting the output signal with considering its effects to the sensitive state variable of the system at the first place. This could be done by means of posicast controller.

The paper structure is as follows. In next section , a brief definition of power system dynamic and stability is presented. Then, The background of posicast and the controller structure is discussed. Methodology is presented next and the last section is conclusion.

Power System Dynamic

Generally stability of power system is defined as “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” [9]. Stability in power system is divided into three categories:

1. Rotor (or power) angle stability.
2. Frequency stability.
3. Voltage stability.

Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain at the steady state operating conditions after being subjected to a disturbance. Commonly rotor angle stability is characterized in terms of two subcategories: Small-Disturbance Rotor Angle Stability (Small-Signal Stability) and Large-Disturbance Rotor Angle Stability (Transient Stability).

Small signal stability is defined as the ability of power system to maintain synchronous operation under small disturbances which itself divided into two categories: “oscillatory instability and Non-oscillatory instability”. Insufficient damping torque and synchronizing torque are the main reasons of them respectively [10].

Modal analysis is being used to investigate the small signal stability of the power system. Dynamic behavior of power system could be described by a set of nonlinear ordinary differential equations. By using vector-matrix notation it could be shown as:

$$\dot{x} = f(x, u, t) \tag{1}$$

Where:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \quad u = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_r \end{bmatrix} \quad f = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix}$$

The column vector x is referred to as a state vector and its entries x_n are state variables. Column u is the vector of inputs. If the derivatives of the state variables are not explicit function of time (2), is simplifies to:

$$\begin{aligned} \dot{x} &= f(x, u) \\ y &= g(x, u) \end{aligned} \tag{2}$$

y refers to system output variables, f describes the dynamics of the system and g includes equality conditions such as power flow equations of the system [10].

Rotor angle stability is satisfied if each synchronous machine in the power system maintains the balance between mechanical torque and electromagnetic torque which are generator input and output respectively. Damping and synchronizing torque are components of electromagnetic torque which could be shown as:

$$\Delta T_e = K_s \,.\, \Delta\delta + K_D \,.\, \Delta\omega \tag{3}$$

As it could be seen, the synchronizing torque K_s is in phase with rotor angle perturbation $\Delta\delta$ and damping torque is in phase with the speed deviation $\Delta\omega$. These two components are the causes of oscillatory and non-oscillatory instability in the power system as mentioned before [10], [11].the performance of small signal oscillatory stability (SSS) could be investigated by linearizing the (2), around equilibrium point which gives us:

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u \end{aligned} \tag{4}$$

Where:

A is the state or plant matrix of size n×n.
B is the control or input matrix of size n×r.
C is the output matrix of size m×n.
D is the matrix which defines the proportion of input which appears directly in the output, size m×r.

By taking Laplace transform from (4), we could find the state equation of the system in frequency domain. A formal solution is as:

$$\Delta y(s) = C \frac{\mathrm{adj}\,(sI - A)}{\det(sI - A)} [\Delta x(0) + B\Delta u(s)] + D\Delta u(s) \tag{5}$$

The poles of the system then could be calculated by equation (6).

$$\det(sI - A) = 0 \tag{6}$$

The values of s which satisfy the (6), are called eigenvalues of matrix A. Analyzing the stability in the small of nonlinear system is given by the roots of the characteristic equation which is known as “lyapunov’s first method”:

When the eigenvalues have negative real parts, the original system is asymptotically stable.

When at least one of the eigenvalues has positive real part, the original system is unstable.

When the eigenvalues have real parts equal to zero, it is not possible on the basis of the first approximation to say anything in the general.

Real parts of eigenvalues present damping and imaginary parts present frequency of oscillation. A negative real part shows a damped oscillation whereas a positive shows oscillation of increasing amplitude. For a complex pair of eigenvalues:

$$\lambda = \sigma \pm j\omega \tag{7}$$

The damping ratio is given by:

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{8}$$

Damping ratio ζ determines the rate of decay of the amplitude of the oscillation. Based on eigenvalue analysis, there have been lots of different presented methods for assessment and analysis of SSS in the power systems. The power system consists of many machines and elements which increase the order of differential equation that leads to more time for calculating and analyzing [10] .

Controlling the SSS could be done by applying power system stabilizer (PSS). PSS was developed to aid in damping oscillations of small magnitude. Its basic function is to extend stability limits by producing an electrical torque in phase with speed deviation. However, sometimes the PSS could not perform its task and itself will be the cause of instability by producing negative damping. The reason is that they are tuned to perform around operating point and they will not be effective for large changes [2], [12]. Designing and tuning the PSS challenges a hard work. Further information about the PSS could be found in [12] , [13] and [14].

Posicast Controller

O. J. M. Smith in 1957 presented the posicast controller for mitigating the oscillation of lightly damped system [15].The term posicast stems from positive cast. Posicast reshapes the step input command into two parts. 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 scaled and time-delayed to precisely cancel the remaining oscillatory response, thus causing the system output to stay at the desired value. The concept in a simple language and the transfer function form are shown in Fig. 1 and Fig. 2 respectively. In Fig. 1 frame A, the gantry and the load are both at position 1. The motion starts in the frame B, with the gantry moving to midway between positions 1 and 2 which results in the load to swing toward position 2. In the frame C, the load has swung past the gantry to position 2, and is about to swing back. The gantry immediately moves to position 2, so that the load stays at position 2 without overshoot or oscillation [17], [16].

If we define the P(s) as:

$$P(s) = \frac{\delta}{1+\delta}\left[-1 + e^{-s(\frac{T_d}{2})}\right] \qquad (9)$$

The posicast will define as $1 + P(s)$ where δ is overshoot and T_d is damped step response period of a system under the control [17]. The result of using the posicast is shown in Fig. 3.

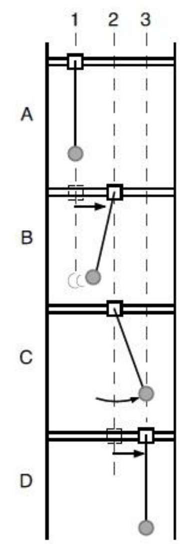

FIGURE 1, Posicast controller example using gantry problem [16].

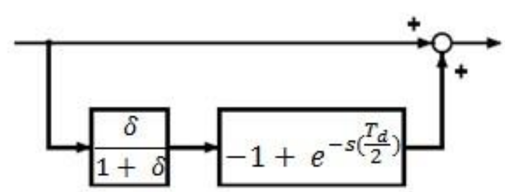

FIGURE 2, Posicast controller transfer function [16].

It could be seen that the posicast has significant effect on damping the oscillation of the system. A comparison study of posicast and PID controller could be found in [17]. In [18] the implementation of posicast within the exciter system has been investigated and the results of 3-phase faults have been reported. The result shows improvement in stability margins based on their contingency. However, they used posicast in a way that the exciter system itself should be changed and the system under study is a single machine infinite bus which is not a good system for study of SSS. Also same study has been proposed in [19]. Their focus is on changes of exciter reference value. They calculated the parameters of posicast with referring to the step response of their case of study which is a single machine infinite bus and in case of bigger system this method could not be an accurate way and further investigation should be done to demonstrate the effect of posicast in the power system.

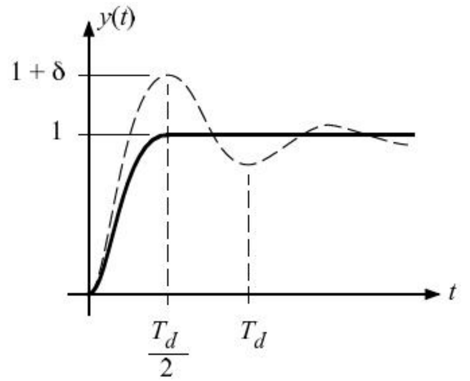

FIGURE 3, System output (dashed without posicast) [17].

Methodology

In this study we look at the posicast as a rule that should be considered in taking actions. The actions could be anything that we need to take for different mode of control to maintain the desire output which in this case is a way that the PSS output signal should act to prevent and mitigate the oscillations of an interconnected network. The New England 39-Bus test system, consist of 10 machines was chosen to investigate the performance of posicast on mitigating the oscillations. The machines have exciter IEEE DC1A type and the models of PSSs are IEEE PSS1A.

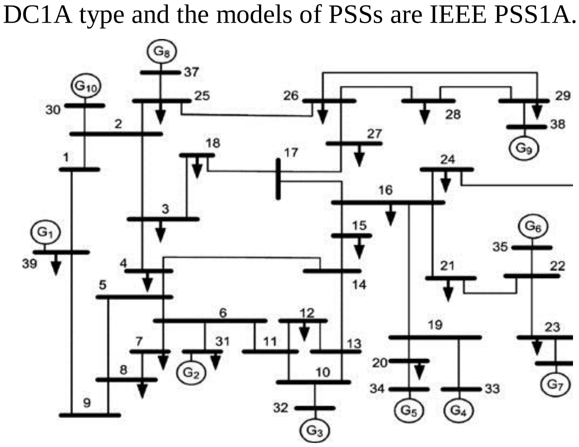

FIGURE 4, New England 39 Bus test system

As it mentioned in section II the stability analysis of a dynamic system is based on system eigenvalues. A power system has many eigenvalues with different rate of damping. According to [20], a damping with ratio of 5% is considered as an adequate system damping and the one with less than 3% is acceptable with caution. Based on this, two sets of eigenvalues are defined as: I) sufficiently damped and II) insufficiently damped. For set I the damping ratio with more than 4.5% and for set II with ratio of between 0% and 4.5% is assigned to distinguish eigenvalues and determines the place that the posicast should be placed.

The dominant state of insufficient damped eigenvalues indicates the place of the posicast. Complete eigenvalues of the system is calculated and filtered between 0% and 4.5% damping rate. According to calculations five machines should be considered to place the posicast which are shown in Table 1.

It could be seen that the system itself is on the edge of oscillatory instability. The control system without posicast could not mitigate the oscillations and it will show its negative effect after few minutes from beginning of the simulation.

TABLE 1. Selected Eigenvalues

Dominant state	Eigenvalue	Frequency (Hz)	Damping %
GEN 1	-0.1677+3.9478i	0.6283	4.24
GEN 2	-0.1909+6.3940i	1.0176	2.98
GEN 3	-0.2866+7.7742i	1.2373	3.68
GEN 9	-0.2333+6.2042i	0.9874	3.76
GEN 10	-0.3019+7.9763i	1.2695	3.78

The values for tuning the posicast are then calculated based on this eigenvalues which are tabled in Table 2.

TABLE 2. Calculated posicast

Gen No	Bus	Posicast (1+P(s))
1	39	$0.6891 + 0.3109e^{-0.7958\,S}$
2	31	$0.6204 + 0.3796e^{-0.4913\,S}$
3	32	$0.5997 + 0.4003e^{-0.4041\,S}$
9	38	$0.6240 + 0.3760e^{-0.5064\,S}$
10	30	$0.5972 + 0.4028e^{-0.3939\,S}$

Variation of loads is one of the reasons that will results in system instability if the system could not adapt itself to it. The Contingency of the simulation in this study is load shedding as:

1. Load shedding at bus 15 by 10 percent.
2. After 20 seconds restoration of the load at bus 15
3. Then after 10 seconds, shedding load at bus 20 by 10 percent

Total period of simulation is 20 minutes and the maximum generator speed deviation is set at 0.1 pu which in case of happening will results in termination of simulation. Generators angle are presented in Fig.5. At time 325sec the generator speed deviation of system without posicast crossed the 0.1pu which results in termination of simulation (red line). However, the system with posicast continues its operation without any violation. A close look effect of posicast on rotor angle of generator number 9 is shown on Fig. 6.

Considering the fact that the posicast is just tuned and placed for 5 generators in the system, the result is satisfying which lead to stabilizing the system operation. Posicast also shows its significant effect on frequency of the system. Fig. 7 shows the results for system without posicast and Fig. 8 shows same system with posicast. The posicast stabilized the frequency of the system on around 60.08 Hz while increase its frequency and reaches to 66 Hz at time 325sec where the simulation is terminated.

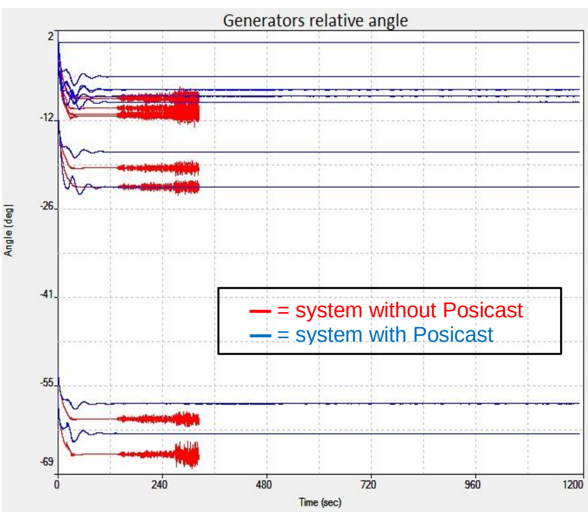

FIGURE 5, Generators angle (degree)

For further investigations a power angle-based stability margin or index has been created for different period of simulation which is gathered in table 3. The index is defined as:

$$\eta = \frac{360 - \delta_{max}}{360 + \delta_{max}} \quad , \quad -100 < \eta < 100 \qquad (10)$$

δ_{max} is the maximum angle separation of any two generators in the system. $\eta > 0$ And $\eta \leq 0$ correspond to stable and unstable conditions respectively [21].

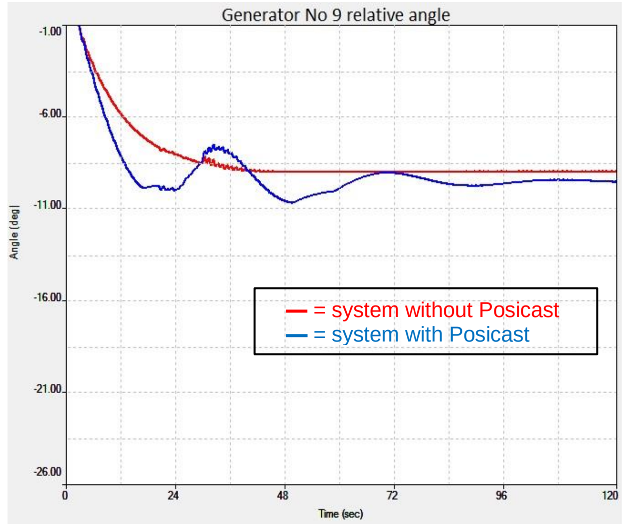

FIGURE 6, Generator No 9 relative angle

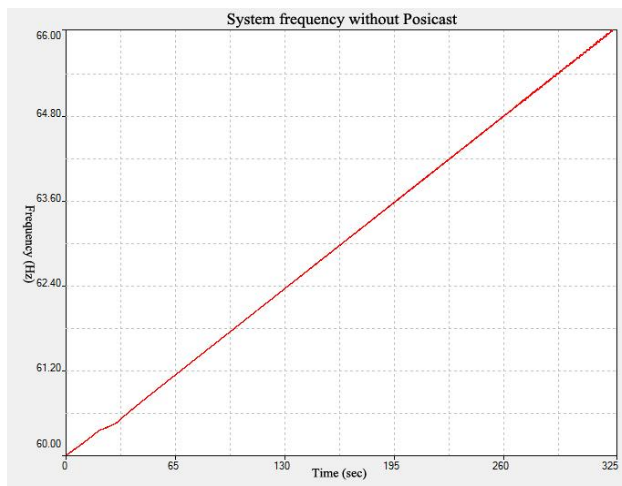

FIGURE 7, System frequency (Hz) without posicast

Results show that posicast helps the system stability margin and tries to keeps it on the initial state of the system where system stability without it is decreasing as the time goes by. At the time 325sec where the system itself crosses the line of limitation of simulation, it reaches to 17.66% from 68.94% while posicast keeps its stability margin by 69.83% for the whole period of simulation. Also at the same time posicast help the stability of the system by 52.17% which is significant.

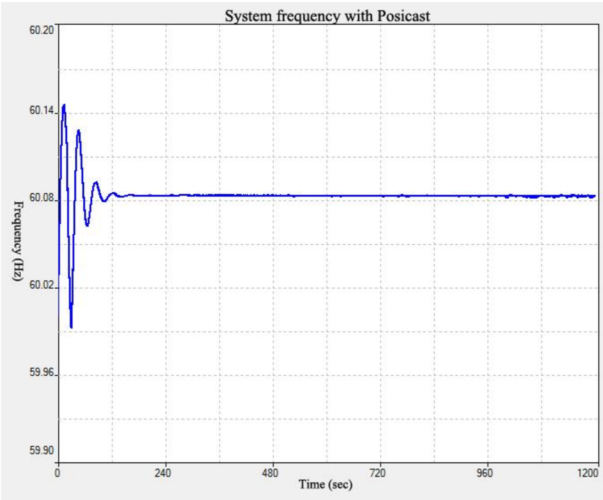

FIGURE 8, System frequency (Hz) with posicast

TABLE 3. Stability index for a system with and without Posicast

Time(sec)	Without posicast	With posicast	Improvement
60	68.94 %	69.83 %	0.89 %
120	68.94 %	69.83 %	0.89 %
180	68.94 %	69.83 %	0.89 %
240	68.81 %	69.83 %	1.02 %
325	17.66 %	69.83 %	52.17 %
1200	---	69.83 %	---

Conclusion

In this paper, the effect of posicast controller on mitigating the oscillation of power system due to small signal oscillatory stability on New England 39-Bus system has been demonstrated. Posicast is considered as a rule of an action that could be taken on any part of a dynamic system. The posicast controller and its parameters are placed and calculated based on inherent characteristics of the system. So the controller does not affect the normal operation of the system and just follow and act on the parameters that have been designed for. Results could be summarized as:

- ✓ Mitigating the rotor angle oscillations of generators.
- ✓ Preventing the oscillatory instability.
- ✓ Stabilization of frequency around operating point with shifting as small as 0.08.
- ✓ Enhancing the stability margin of the system with significant improvement.

The posicast doesn’t get too much attention in power system and its being used on smaller application such as dc-dc convertor [22]. However, the results in this paper show that the posicast has the capability to be used in power system too.

Posicast strategy is simple and rather than other methods its parameter is easy to be tuned while its effects on the system are significant.

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