Journal of Engineering Science and Technology
Special Issue on Applied Engineering and Sciences, October (2014) 39 - 50

MITIGATION OF POWER SYSTEM SMALL SIGNAL OSCILLATION USING POSICAST CONTROLLER AND EVOLUTIONARY PROGRAMMING

S. MIRFENDERESKI*, N. I. A. WAHAB, J. J. M.LUFTI OTHMAN

Department of Electrical & Electronic, Faculty of Engineering,
Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
*Corresponding Author: s.mirfendereski@yahoo.com

Abstract

This research work explores the effect of posicast controller on mitigation of small signal oscillatory stability. Power system stabilisers (PSS) are a prevalent means to enhance the damping of oscillation in power system. However, sometimes the PSS could not perform its task and itself will be the cause of instability by producing negative damping. In this study, 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. Also, evolutionary programming is used to optimise the performance of posicast for each dominant state. The New England 39-Bus Test System is chosen to evaluate the performance of the controller. Improvements in rotor angle, generators active power, generators terminal voltages and system frequency have been observed.

Keywords: Evolutionary programming, Posicast controller, Power system stabiliser, Small signal oscillatory stability, Stability margin.

1. Introduction

In recent years, as interconnected power systems are becoming more and more complex, the subsistence of poorly damped low-frequency inter-area oscillations have strained its stability constraints, and thereby, limited its power transfer capacity. Therefore, adequate damping of inter-area modes is paramount in order to secure system operation, ensure system reliability and increase power transfers.

Nomenclatures

A	Plant matrix
B	Control or input matrix
C	Output matrix
$C(s)$	Compensation to reduce mismatch
D	matrix which defines the proportion of input which appears directly in the output
g	Nonlinear matrix
K	Gain
$p(s)$	Transfer function
T_d	Period of damped step response, s
u	Input vector
x	State vector
$\dot{x}$	State vector differential

Greek Symbols

Δ	Small deviation
λ	Eigenvalue
δ	Overshoot
σ	Damping ratio
ω	Angular frequency
η	Power angle-based stability margin or index

Abbreviations

EP	Evolutionary programming
IEEE	Institute of electrical and electronics engineers
PSS	Power system stabilizer
SSS	Small signal stability

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". Oscillatory stability is a subcategory of Small Signal Stability (SSS) which is defined as the ability of power system to maintain synchronous operation under small disturbances.

The oscillations usually are concerned with frequencies between 0.2 to 3 hertz with insufficient damping. There are three types of oscillations that have been observed in the power system which are inter-unit oscillations, involves typically two or more synchronous machines at a power plant or nearby power plants swing against each other, with the frequency ranging between 1.5 Hz to 3 Hz, local mode oscillations generally involve one or more synchronous machines at a power station swinging together against a comparatively large power system or load centre and the frequency of oscillation is in the range of 0.7 Hz to 2 Hz, finally, inter-area oscillations which involve combinations of many machines on one part of the power system swinging against machines on another part of the power system and the frequency range is normally less than 0.5 Hz [1].

Controlling these kinds of oscillations is relatively a simple task that could be solved by applying Power System Stabilizer (PSS) [2]. Different methods for analysing the problem have been proposed by researchers in this area which could be found in [3-7]. 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 [8].

Designing and tuning the PSS challenges a hard work. Further information about the PSS could be found in [8-10]. What is not considered in different methods of control is the way in which the controller should act and presents its output by considering sensitive modes in the first place. In this paper, posicast controllers are designed to act in such a way. Furthermore, evolutionary programming (EP) technique is used to optimise the gain of the posicast controller.

2. Methodology

2.1. Power system analysis

To investigate the power system we need to represent it by set of nonlinear differential equations. Generally a nonlinear system like a power system could be described as in Eq. (1).

$$\dot{x}_i = f_i(x_1, x_2, ..., x_n; u_1, u_2, ..., u_r; t) \tag{1}$$

i=1,2,…,n t=time

In Eq. (1), x_i represents the ith state element of the system and "n" is the order of the system. The inputs of the system are represented by "u" and the numbers of inputs are equal to "r".

By using vector-matrix notation we could represent the Eq. (1) with the output of the system as in Eq. (2).

$$\dot{x} = f(x, u) \tag{2}$$

$$y = g(x, u)$$

where x and u are state vector and vector of input respectively and "g" is a vector of nonlinear functions that relates the state and input vector to the output. The performance of SSS could be investigated by linearizing Eq. (2) around an equilibrium point as:

$$\Delta\dot{x} = A\Delta x + B\Delta u \tag{3}$$

$$\Delta y = C\Delta x + D\Delta u$$

In Eq. (3) "A" is the state or plant matrix, "B" is the control or input matrix, "C" is the output matrix and "D" is the matrix which defines the proportion of input which appears directly in the output. The prefix Δ presents small deviation. The matrix "A" is shown in Eq. (4) and the eigenvalues of matrix "A" could be determined by Eq. (5).

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \tag{4}$$

$$det\ (sI\text{-}A) = 0 \tag{5}$$

The values of *s* which satisfy Eq. (5) are called eigenvalues. The small signal stability analysis of the power system depends on the eigenvalues of matrix "A". Based on Lyapunov's first method, if all eigenvalues have negative real parts the system is asymptotically stable and if at least one eigenvalue has positive real part the original system is not stable. If it has zero real parts, it is not possible to say anything about the system [1].

For each eigenvalue as it is shown in Eq. (6), there are two important properties which are frequency and damping ratio.

$$\lambda = \sigma \pm j\omega \tag{6}$$

The power system has many eigenvalues and for SSS analysis we also need to classify them based on their properties which in this case are damping and the frequency of their oscillations. To maintain the sufficient damping for the system, all modes should have at least 5% damping and for each mode the damping with less than 3% should be accepted with caution [11] . Based on this observation, we would have two categories of eigenvalues in the system known as: sufficiently damped and insufficiently damped. The interests here are to locate the insufficient damped ones where the posicast should be tuned for each of them. In this study the eigenvalues with damping ratio between 0 to 5% are considered as insufficiently damped and the posicast controllers are tuned for them.

2.2. Designing the posicast controller

It was presented by O. J. M. Smith in 1957 for mitigating the oscillation of lightly damped system [12]. 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 [13, 14].

Referring to Fig. 1, if we define the *P(s)* as:

$$P(s)=\frac{\delta}{1+\delta}\left[-1+e^{-s(\frac{T_d}{2})}\right] \tag{7}$$

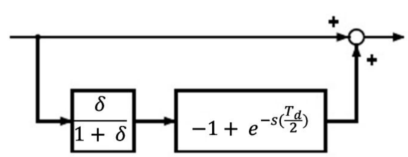

Fig. 1. Posicast Controller Block Diagram [14].

The posicast will be defined as *1+P(s)* where δ is overshoot and T_d is damped step response period of a system under the control [13]. The result of using the posicast is shown in Fig. 2. Posicast used in a feedback loop requires an additional compensation to reduce mismatch which is an integrator with gain, *K*. the integrator in Laplace's form is as following:

$$C = \frac{K}{s} \tag{8}$$

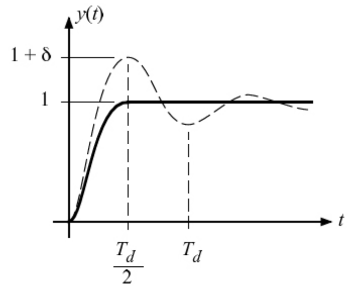

Fig. 2. A System with Posicast Output (Dashed without Posicast).

The posicast has significant effect on damping the oscillation of different systems. A comparison study of posicast and PID controller could be found in [13] which shows that the posicast controller significantly mitigate the oscillations while the PID could not do such a thing. As have been mentioned before three values are needed to tune and design the posicast. The overshoot (δ) and the damped time (T_d) could be easily calculated by Eqs. (9) and (10). The calculation of the value "*K*" depends on our assumption and expectation of what we need to see as the result of each posicast regarding to its specified eigenvalue.

$$\delta = e^{\frac{-\pi}{\omega}} \tag{9}$$

$$T_d = \frac{2\pi}{\omega} \tag{10}$$

We need the posicast to function accurately for a specific eigenvalue, in the other words the aim is that: "the output of the each PSS should be in a way that it does not excite the most sensitive eigenvalues in its area in advance and also in case of it happening, the oscillations should be mitigated as fast as possible with identifying the minimum overshoot occurring in the system". Each posicast is required to be tuned for a specific eigenvalue. In the analysis we could consider these two components (posicast and eigenvalue) as a separate system and calculate the value of "*K*" for each case separately. The complete system is shown in Fig 3.

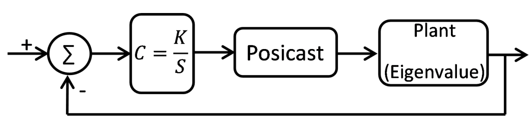

Fig. 3. Posicast and Eigenvalues for Calculating *K*.

The value "*K*" affects the total response of the posicast together with the eigenvalue. Here, the "*K*" plays and important role. By changing its value, we would have different response for the designed posicast and the specific eigenvalue. In order to prevent the oscillations in the power system, the value of "*K*" should be calculated in a way that there would be no overshoot. However, fast response is important for us too, so totally no overshoot and as fast as possible. Also the phase lag characteristic of "*C(s)*" will introduce overshoot if the gain "*K*" chosen is too high [14]. Due to the inherent characteristic of the eigenvalues the value of K for more than 100 will results in huge overshoots. So the value of "*K*" is chosen between 0 and 100 which is not in p.u. There are so many possible values for *K* which will result in no overshoot in this range. Based on the accuracy that we need for calculating the *K*, we are dealing with huge amount of values. The best method would be to use an optimisation method that could search within the dynamic of the system and its functionality to find the maximum values of *K*, rise time while maintaining the zero overshot for the system.

2.3. Optimising the compensator gain of posicast controller based on targeted eigenvalues using evolutionary programming

The EP is one of the evolutionary computing techniques that use the models of biological evolutionary process to solve complex engineering problems. It was first proposed by "L.JFogel" as one of the first steps for developing artificial intelligence technique. The search for an optimal solution is based on the natural process of biological evolution and is accomplished in a parallel method in the parameter search space. It belongs to the generic fields of simulated evolution and artificial life. It is robust, flexible, and adaptable and it can yield global solutions to any problem, regardless of the form of the objective function [15]. The flow chart and steps in EP employed in this work are shown in Fig. 4. Initialisation is an important step as we generate and filter random numbers that satisfies our assumption for the system. The total population of random numbers affects the results of the optimisation. For example for big range of values small population may not reach to the best result.

Choosing the number of population depend on the trade-off between accuracy of *K* and its sensitivity to the total results. In this study we chose 1000 population for *K* which satisfies the requirements of the system. Next step is the first fitness which is the function that we want it to be optimised. The results are mutated by Gaussian mutation technique to generate offspring. Next, the results of parents and offspring are combined in combination step and after that new generation will be generated by selection which is based on elitism. If the new generation is converge the criterion which is the error that we need for our system, then the optimisation is finished and if they do not converge, they will back to first fitness step and another evolution will start and continues until it is converged. In this study the criteria for converge test is chosen as 0.0001.

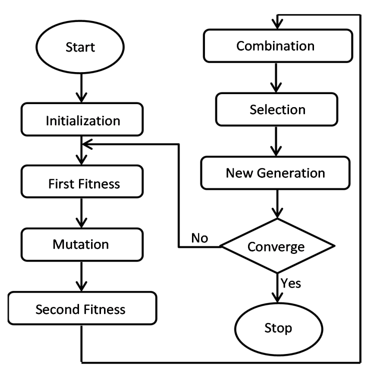

Fig. 4. Algorithm of Evolutionary Programming.

3. Results and Discussions

To analyse the performance of posicast controller and also the proposed method of optimisation the New England 39-bus test system was chosen. The structure of the system is shown on Fig. 5. It consists of 10 machines and all the exciter of them are IEEE DC1A type. Also the models of PSSs are IEEE PSS1A. It should be noted that in this test system the PSSs are not well tuned and the effects of the Posicast is being investigated in an untuned situation. By referring to the section two part A, we could analyse the system and find the desired eigenvalues and their related machines.

Table 1 provides eigenvalues and their dominant state. It could be seen from Table 1 that the system itself is on the edge of instability and we are dealing with a high sensitive system in case of disturbances.

Table 2 presents the designed posicast for each machine. As the small signal oscillatory instability is concerned with variation of load most of the time, load shedding also was chosen as a contingency for the system. Total period of the simulation is 20 minute and the criterion for termination is speed deviation of machines which is set to 0.1p.u. DSA Tools [16] was chosen as the main simulation software and as the total amount of data is too much the MATLAB software also used for plotting some of data obtained. For each posicast a system as shown on Fig. 3, is designed and the transfer function is then calculated and used as the fitness function of EP to optimise the *K*.

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 8	-0.4313+9.4295i	1.5008	4.57
GEN 9	-0.2333+6.2042i	0.9874	3.76
GEN 10	-0.3019+7.9763i	1.2695	3.78

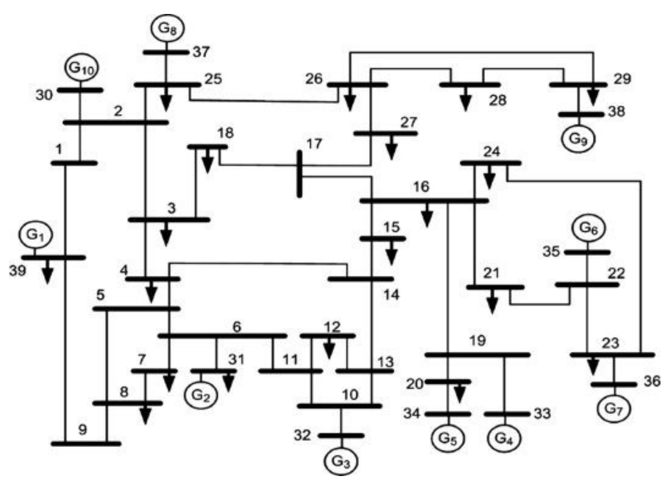

Fig. 5. The New England 39-busTest System.

Table 2. Designed Posicasts.

Gen No	Bus	Posicast (1+P(s))
1	39	$0.6891 + 0.3109e^{-0.7958\,s}$
2	31	$0.6204 + 0.3796e^{-0.4912\,s}$
3	32	$0.5997 + 0.4003e^{-0.4041\,s}$
8	37	$0.5825 + 0.4175e^{-0.2222\,s}$
9	38	$0.6240 + 0.3760e^{-0.5084\,s}$
10	30	$0.5972 + 0.4028e^{-0.2929\,s}$

Optimised values for *K*s are presented in Table 3. The values of *K* before the optimisation were chosen randomly. From the table, the value of *K* for generator number 8 is calculated as 99.9497. It should be noted that this is not a saturation value and it's due to the range of the *K*. If the range changes the *K* value may be changed based on the expectation of the design.

Figure 6 shows calculated values for *K* per each evolution for generator No. 3. It could be seen that after 31 evolutions the EP could reach to the maximum value of *K* which satisfies the assumption too.

Table 3. OptimisedValues of *K*.

Generator No	K before optimisation	Optimised K
1	100	14.3716
2	70	42.4486
3	5	84.1668
8	30	99.9497
9	80	45.7706
10	100	90.7301

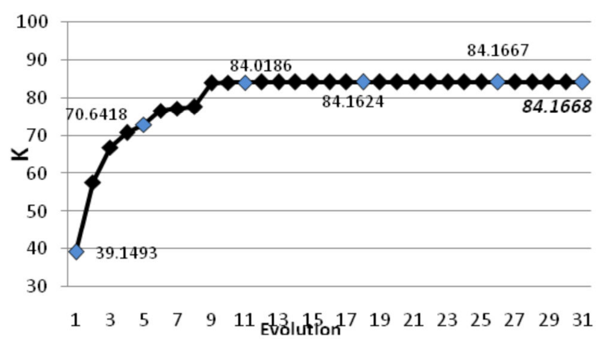

Fig. 6. Value of *K* for Each Evolution for Generator Number 3.

In Fig. 7, generators relative angle of the system with generator number two (G2) chosen as the reference is presented for three cases. What could be understood is that the system oscillations will show themselves from around two minutes after the beginning of simulation.

The test system without posicast controllers are not able to mitigate the oscillations and eventually at 375 seconds will cross the limitation criteria of simulation which will result in termination. On the other hand, the system with posicast and optimised posicast controllers will not face such a problem and will try to mitigate the oscillations and keep the system stable. The generator number 1 active's power is illustrated on Fig. 8.

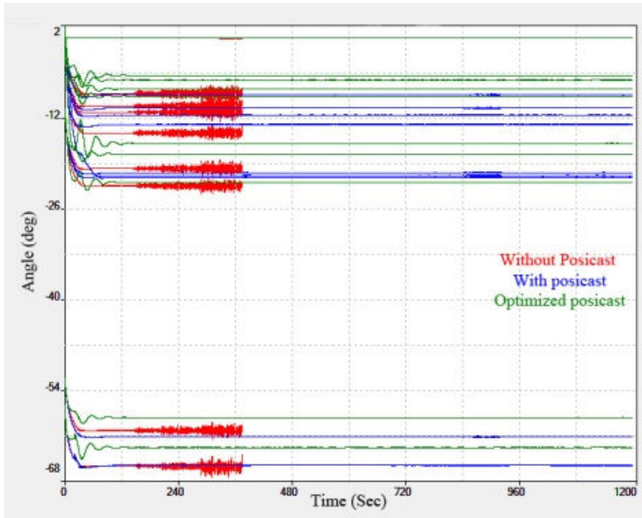

Fig. 7. Generators Angle for Different Cases.

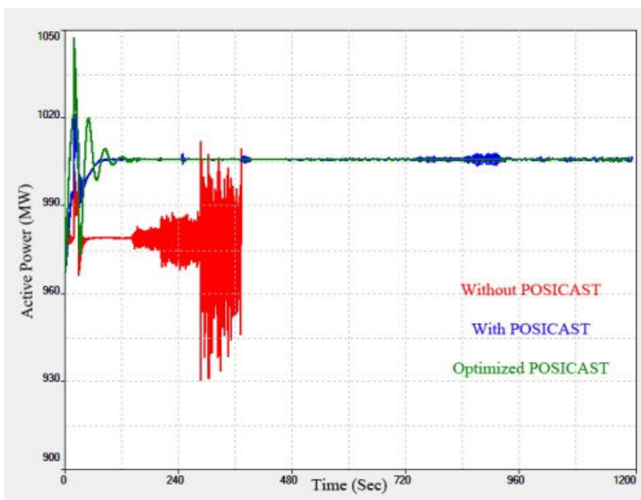

Fig. 8. Generator Number 1 Active Power.

It could be seen that the posicast here also could mitigate the oscillations. However the posicast without optimisation presents some oscillations to the system starting from 890seconds. A closer look is shown on Fig. 9. Optimised posicast shows significant improvement on mitigating the active power oscillations. The system with posicast shows 5 MW oscillations for about 30 seconds while the optimised posicast prevent the oscillations and just shows 0.5MW of active power oscillations for less than 5 seconds.

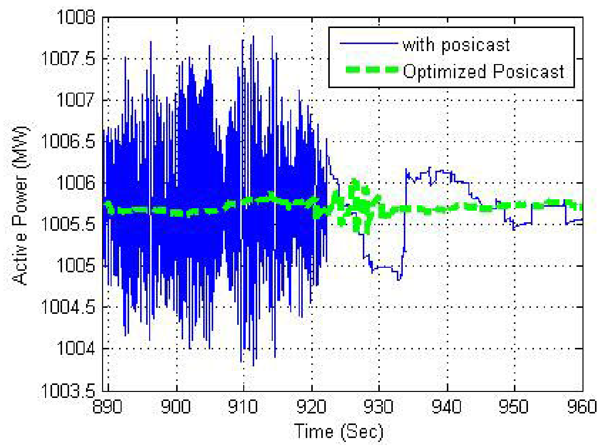

Fig. 9. Generator Number 1 Active Power (Closer Look).

Other improvements in generator terminal voltage and system frequency also were observed which are shown on Figs. 10-12. The optimised posicast prevent too much violation in generator terminal voltage and also keeps the system frequency close to 60 Hz. The frequency of the system without the posicast keeps increasing until 66 Hz where the simulation is then stopped as it cross the limitation criteria.

For further investigations a power angle-based stability margin or index [16] has been used for different cases which is descried in Eq. (11) and provided in Table 4.

$$\eta = \frac{360-\delta_{\max}}{360+\delta_{\max}} \quad -100 < \eta < 100 \tag{11}$$

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

The value of K plays an important role in determining the response of the posicast. Also the range of it is an issue which directly depends on the inherent characteristic of the system physical limitation of producing it and also expectations that operator needs to fulfil for the system. Table 4 shows that optimised posicast helped in improving the system stability by 0.56 percent.

Table 4. Stability Index.

Condition	Stability index (%)	Time (s)
Without posicast	25	375
With posicast	68.98	1200
Optimisedposicast	69.54	1200

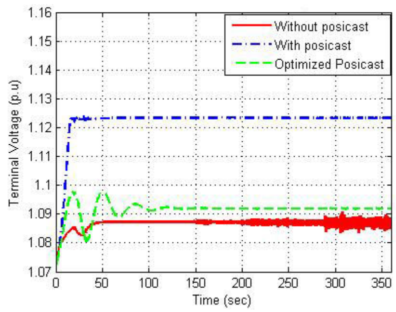

Fig. 10. Generator Number 9 Terminal Voltage.

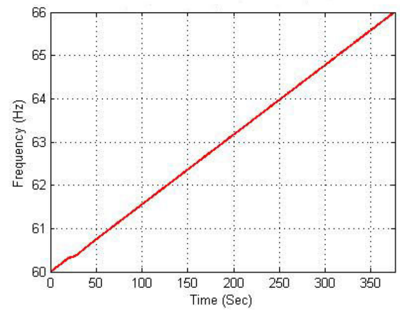

Fig. 11. System Frequency without the Posicast.

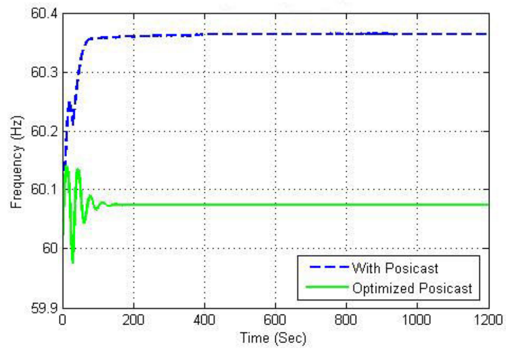

Fig. 12. System Frequency with Posicast and Optimised.

4. Conclusions

In this paper, posicast controller and EP were combined and their effect on preventing the small signal oscillatory instability and mitigating oscillations on New England 39-bus test system is investigated. EP is used as an optimisation method as it searches within the system functionality in all stages. The posicast is considered as a rule of an action that the PSS should follow in presenting its output to the system. Eigenvalues of the system are the keys in designing and determining the posicast and the place that it should be placed. Important results could be summarised as:

- Mitigation of generators angle oscillations.
- Preventing in appearance of oscillations in produced active power by generators.
- Stabilising the frequency of the system around operating point.
- Stabilising the terminal voltage of generators.
- Enhancing the stability margin of the system.

Posicast is relatively simple to design and its parameters are easy to be tuned while its effects on a system are significant as shown in this work. However for best functionality, it should be optimised for any mode that it is designed for.

References

1. Kundur, P. (1994). *Power system stability and control*. McGraw- Hill, New York.
2. Kundur, P.; and Lei, W. (2002). Small signal stability analysis: Experiences, achievements, and challenges. *International Conference on Power System Technology*, 1, 6-12.
3. Xiaoqing, H.; Nannan, T.; Zhijing, Z. (2009). Small signal stability analysis on power system considering load characteristics. *Power and Energy Engineering Conference*,1-4.
4. Karawita, C.; and Annakkage, U. (2010). A hybrid network model for small signal stability analysis of power systems. *IEEE Power and Energy Society General Meeting*, 25(1), 443-451.
5. Singhvi, V.; and Halpin, S.M. (2007). Small signal stability of an unregulated power system. *Thirty-Ninth South Eastern Symposium on System Theory*,32-36.
6. Xiaorong, X.; Shuqing, Z.; Jinyu, X.; Jingtao, W.; and Ying, P. (2005). Small signal stability assessment with online eigenvalue identification based on wide-area measurement system. *Asia Pacific Transmission and Distribution Conference and Exhibition*, 1-5.
7. Teeuwsen, S.P.; Erlich, I.; and El-Sharkawi, M.A. (2003). Neural network based classification method for small-signal stability assessment. *Proceedings of IEEE Power Tech Conference*, 3.
8. Larsen, E.V.; and Swann, D.A. (1981). Applying power system stabilisers Part I: General concepts. *IEEE Transactions on Power Apparatus and Systems,* PAS-100(6), 3017-3024.
9. Larsen, E.V.; and Swann, D.A. (1981). Applying power system stabilisers Part II: Performance objectives and tuning concepts. *IEEE Power Engineering Review*, PER-1(6), 63.
10. Larsen, E.V.; and Swann, D. A. (1981). Applying power system stabilisers Part III: Practical considerations. *IEEE Transactions on Power Apparatus and Systems,* PAS-100(6), 3034-3046.
11. Breulmann, H.; Grebe, E.; Lösing, M; and Energie, R. (2000). Analysis and damping of inter-area oscillations in the UCTE/CENTRAL power system. *CIGRE*, 38-113.
12. Smith, O.J.M. (1957). Posicast control of damped oscillatory systems. *Proceedings of the IRE*, 45(9), 1249-1255.
13. Hung, J.Y. (2003). Feedback control with posicast. *IEEE Transactions on Industrial Electronics*, 50(1), 94-99.
14. Hung, J.Y. (2007). Posicast control past and present. *IEEE Multidisciplinary Engineering Education Magazine*, 2.
15. Kamari, N.A.M.; Musirin, I.; and Othman, M.M. (2010). EP based optimisation for estimating synchronizing and damping torque coefficients. *Australian Journal of Basic and Applied Sciences*, 4(8), 3741-3754.
16. Powertech Labs Inc. (2012). *DSATools User Manual V12*.