# Situational Awareness of Power System Stabilizers' Performance in Energy Control Centers

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***Abstract*—Undamped power system oscillations are detrimental to stable and security of the electric grid. Historically, poorly damped low frequency rotor oscillations have caused system blackouts or brownouts. It is required to monitor the oscillation damping controllers such as power system stabilizers' (PSS) performance at energy control centers as well as at power plant control centers. Phasor measurement units (PMUs) based time response and frequency response information on PSS performance is collected. A fuzzy logic system is developed to combine the time and frequency response information to derive the situational awareness on PSS performance on synchronous generator's oscillation(s). A two-area four-machine benchmark power system is simulated on a real-time digital simulator platform. Fuzzy logic system developed is evaluated for different system disturbances. Situational awareness on PSS performance on synchronous generator's oscillation(s) allows the control center operator to enhance the power system operation more stable and secure.**

***Index Terms*—Fuzzy logic system, phasor measurement unit, power system stabilizer, situational awareness, synchronous generators.**

## I. Introduction

Electric power system operation requires the oscillation damping controllers such as power system stabilizers (PSSs) to provide better performance for changing system operating conditions. PSS provides an auxiliary signal to the synchronous generators' automatic voltage regulators to damp oscillations when a system disturbance is detected [1]. PSSs parameters are tuned using simulations to improve the oscillation damping capabilities of synchronous generators. There is no mechanism to evaluate the performance of these controllers unless the tuned parameters are dispatched to the field. Evaluating power system stabilizer performance routinely is good for the system health check. The smart measurement devices such as phasor measurment units (PMUs) installed in the power system provides remote system measurements received at energy control centers at hundred times faster compared to exisitng supervisory control and data aquisition (SCADA) technology [2].

PMUs are installed in the major transmission corridors and next to generating stations to monitor electric power system operation effectively. PMU provides system wide synchronized measurements for monitoring and control purposes. Typical 2-4 seconds SCADA update rate is not sufficient to get the low frequency oscillation modes identified accurately. It is proven PMU measurements received every 33ms at the energy control center is sufficient enough to capture most of the system disturbance events. PSS performance can be derived by time and frequency response analysis of these system disturbance data. The combination of the time and frequency response performance of PSS provides a situational awareness (SA) for system disturbance.

SA is the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their future status [3]. SA based system performance improvement has been achieved in many different fields including aviation, space, environmental medicine and power systems, etc [4]. Reports on large power system blackouts concluded that the insufficient SA at energy control centers [5] did let the power system to blackout. Future power grid designs are incorporated to include SA [6]. In order to make quick correct decision by an energy control center operator, enhancing SA at energy control centers is inevitable [7]- [8]. Situational awareness computational engine (SACE) is used to combine the time response and frequency response performances of PSSs as shown in Fig 1. In this study SACE is developed using fuzzy logic. Fuzzy logic based decision making is already implemented for power system applications [9] - [11]. Monitoring SA of PSS performance at energy control center alerts the system operator when PSS performance is degrading as the system operating condition changes.

The remaining sections of the paper are organized as follows: Section II presents the situational awareness on PSS performance. In section III, the fuzzy logic system developed to derive the situational awareness on PSS performance is described. The results are summarized in section IV. Section V is conclusion.

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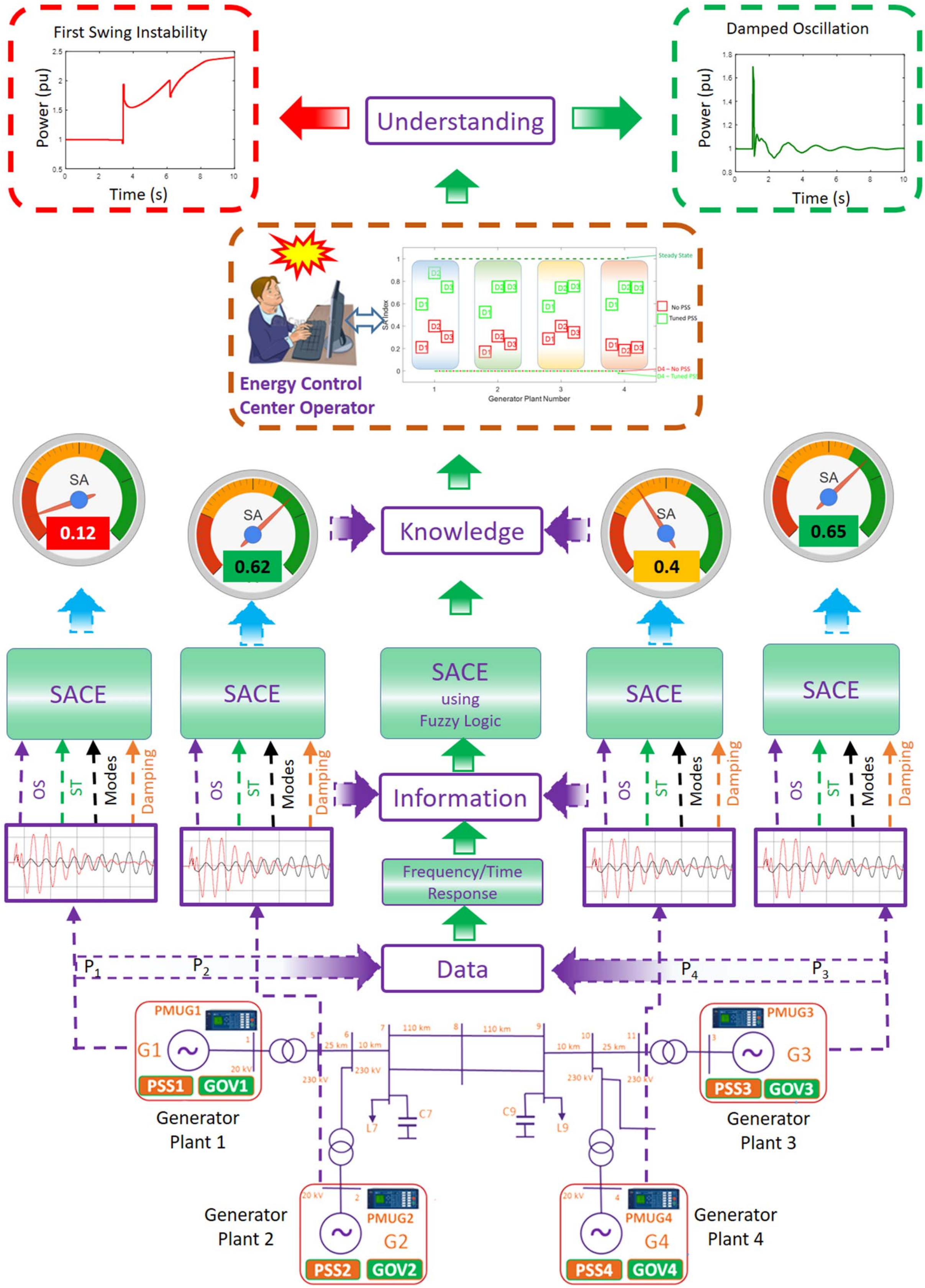


Fig 1. Situational awareness on PSS performance on a generator's oscillation(s) for two-area four-machine power system

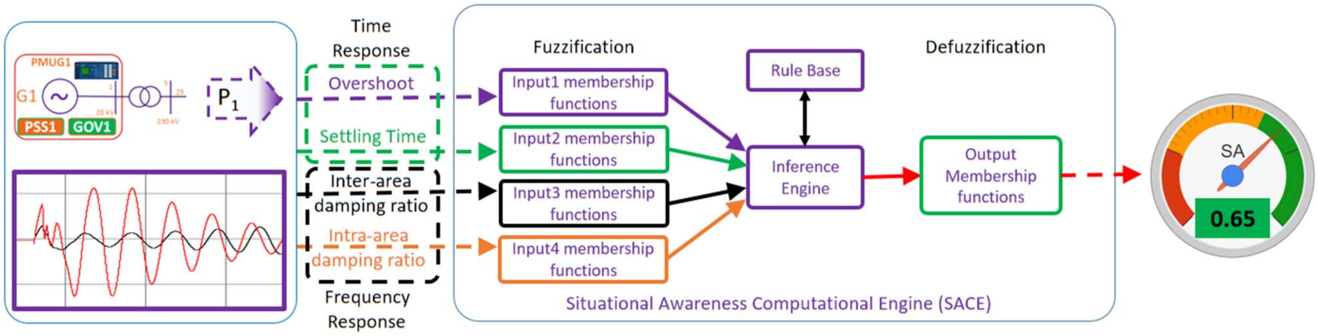


Fig 2. A fuzzy logic system design to calculate the situational awareness on PSS performance on a generator's oscillation(s)

## II. Situational Awareness

It is learned that the inadequate situational awareness at energy control centers did let the electric power grid to either blackout or brownout [12]. Since August 2003 North American blackout, the energy control center modernization projects are initiated utilizing advanced technologies [13]. The smart grid concept became a very common topic and the deployment of smart measurement devices and the use of intelligent algorithms are proposed for electricity generation, transmission and distribution. Massive amount of data flow from the smart measurements devices need to be turned into useful intelligent decision making tools for the control center operators [14]. Typical reaction time of human brain for visual stimulus is 0.25 seconds [15], therefore, multi-color visualizations are developed to display at control center to attract operators for quick responses. The transformation of these measurements to make situational awareness in control centers is happening in the following four stages: data, information, knowledge and understanding. Fig. 1 shows these four stages integrated to PSS performance evaluation using PMU measurements on a test power system.

PMUs installed in the close proximity to the synchronous generators are providing the required system measurements and the PSS performance on time and frequency response are derived to get the situational awareness on PSS performance for system disturbances. In time response, metrics such as overshoot and settling time are observed and in frequency response, oscillation modes and the corresponding damping ratios are obtained using prony analysis [16]. These system measurements and the metrics derived in the time and frequency responses of a generator are the inputs to an information fusion. This information is interpreted by a fuzzy logic system in a way power system control center operator understands the performance of PSS in the system. The fuzzy logic system developed to derive the situational awareness index on PSS performance is described in the next section.

## III. Fuzzy Logic based PSS Performance

Fifty five years ago Lofti Zadeh produced the foundations of infinite-valued logic with his mathematics of fuzzy set theory [17]. Since then much research has been done in the theory of fuzzy systems and applied to various fields including control, information systems, facial pattern recognition, transmission systems and multi objective optimization of power systems, etc. The concept of approximate reasoning is implemented mathematically by defining an element belongs to a set to a degree, indicating the certainty of membership. There are three stages in a fuzzy logic system design, which are fuzzification, rules definition and defuzzification.

In this study a fuzzy logic system is developed to measure the performance of PSS using the power system measurements. Power system oscillation data is collected for system disturbances. Synchronous generators' oscillation data has been analyzed to find out the overshoot, settling time and damping ratio of oscillation modes in the inter-area and intra-area. These are the four inputs to the fuzzy logic system developed as shown in Fig. 2. All four inputs are normailzed and the crisp input values are converted to a fuzzy value using the membership functions and it is called fuzzification. The first fuzzy input variable is the percentage overshoot and the five membership functions defining are 'excellent', good', 'average', 'poor' and 'very poor', as shown in Fig. 3. The five membership functions defined are spanning zero to one representing the percentage overshoot/undershoot in per unit.

Second fuzzy input variable is the settling time. There are five membership functions defined as shown below Fig. 4 to represent the settling time input variable. Settling time of 4s (0.2) and below is defined 'excellent'and 20s (1.0) and above is considered very poor. Other three membership functions 'good', 'average' and 'poor' are defined in between.

Third and fourth fuzzy inputs are respectively the damping ratios of inter-area oscillation modes and intra-area oscillation modes. There are five membership functions defined to represent the damping ratio input variable for the inter-area damping (D-inter) and intra-area damping (D-intra) inputs as shown in Fig. 5. Damping ratio of 20% or above is defined excellent and 0 to 20% is defined by other four membership functions.

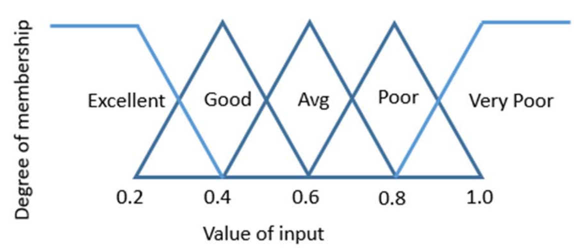


Fig 3. Fuzzy Input I (Overshoot - OS) membership functions

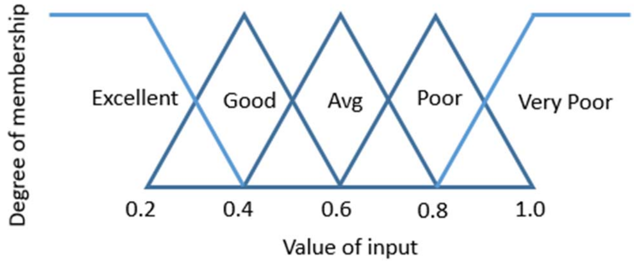


Fig 4. Fuzzy Input II (Settling Time - ST) membership functions

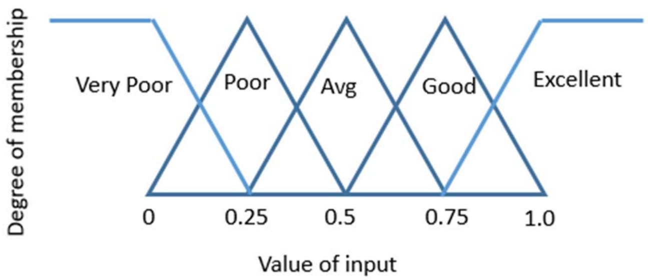


Fig 5. Fuzzy Inputs III and IV (Damping ratio) membership functions

Rules are defined taking the different combinations of the input variable membership functions mapping to an output membership function. Fuzzy inference engine is evaluating the rules defined and then the fuzzy output value is calculated for a particular set of inputs. Fuzzy output value will then be converted to an actual value by defuzzification process. Defuzzification is a reverse operation of the fuzzification. The fuzzy logic system developed in this study provides SA index on PSS performance as the output. SA index is also normalized. For system measurements without an oscillation, there is no overshoot and the settling time is zero therefore SA index is defined one for such scenarios. For worst case scenarios like first swing instability, SA index is defined zero, and for all other disturbances it is between zero and one. Very low SA index means poor PSS performance, the higher SA index means very good PSS performance and in between is the average PSS performance.

## IV. Results and Discussions

Test power system [1] shown in Fig. 1 is simulated on a real-time digital simulator (RTDS) platform and integrated to Matlab based fuzzy logic system. RTDS is capable of simulating each power system component in real-time at a step time of 50 micro seconds [18]. During normal operation there is a 400MW power transfer from area 1 to 2. Area 1 and 2 loads are concentrated on bus 7 and 9 respectively. The following system disturbances are simulated on RTDS to collect the system oscillation data to calculate the situational awareness index using the fuzzy logic system described in the section III.

- Disturbance 1 (D1) – A sudden load increase of L7 from 967MW to 1120MW (L9 remained constant at 1767MW)
- Disturbance 2 (D2) – A sudden load decrease of L9 from 1767MW to 1180MW (L7 remained constant at 1120MW)
- Disturbance 3 (D3) – A 10 cycles duration three phase line to ground short circuit placed at bus 8
- Disturbance 4 (D4) – A permanent line outage connecting bus 6 and bus 7

All four generators' active power output waveform captured for these above disturbances D1 and D2 for without PSSs (NPSS) and with tuned PSSs (TPSS) are shown in Figs. 6 and 7, respectively. Time response and frequency response metrics for D1 and D2 are summarized in Table I.

### A. *Disturbance 1 – D1*

G1 without PSSs has poor oscillation damping capabilities with 0.66Hz inter-area mode damping 0.2%, 1.34Hz intra-area mode damping 4.9%, settling time of 17.97 seconds and an overshoot 76%, which defines the fuzzy input membership functions respectively, 'very poor', 'very poor', very poor' and 'average/poor'. Therefore the fuzzy output membership function is very poor and it results a very low SA index of 0.2107. Tuned PSSs configuration decreased the settling time to 10.40 seconds, overshoot to 51% and increased the damping ratios to 12.7% of 0.63Hz mode and 7% and 10.6% of 1.04Hz and 1.75Hz modes, which defines the fuzzy input membership functions respectively, 'good/excellent', 'average', 'good/excellent' and 'good/excellent'. Therefore an improved SA index of 0.5960 is derived .

Similar changes in fuzzy input membership functions are observed for other three generators in the system with tuned PSSs configuration. SA index of G2 is improved from 0.1714 to 0.5255. SA index of G3 is improved from 0.2886 to 0.5775. SA index of G4 is improved from 0.2350 to 0.5938.

### B. *Disturbance 2 – D2*

G1 without PSSs has poor oscillation damping capabilities with 0.67Hz inter-area mode damping 3.7%, 1.33Hz intra-area mode damping 3.7%, settling time of 17.30 seconds and an undershoot 59.9%, which defines the fuzzy input membership functions respectively, 'very poor', 'very poor', very poor' and 'average'. Therefore the fuzzy output membership function is very poor and it results a very low SA index of 0.4010. Tuned PSSs configuration significantly decreased the settling time to 3.45 seconds, increased the undershoot to 67.6% and the damping ratios to 23% of 0.67Hz mode and 17.4% of 1.31Hz mode, which defines the fuzzy input membership functions respectively, 'excellent', 'average', 'excellent' and 'good/excellent'. Therefore an improved SA index of 0.8750 is observed.

Similar changes in fuzzy input membership functions are observed for other three generators in the system with tuned PSSs configuration. SA index of G2 is improved from 0.3113 to 0.7500. SA index of G3 is improved from 0.4000 to 0.7499. SA index of G4 is improved from 0.1849 to 0.7500.

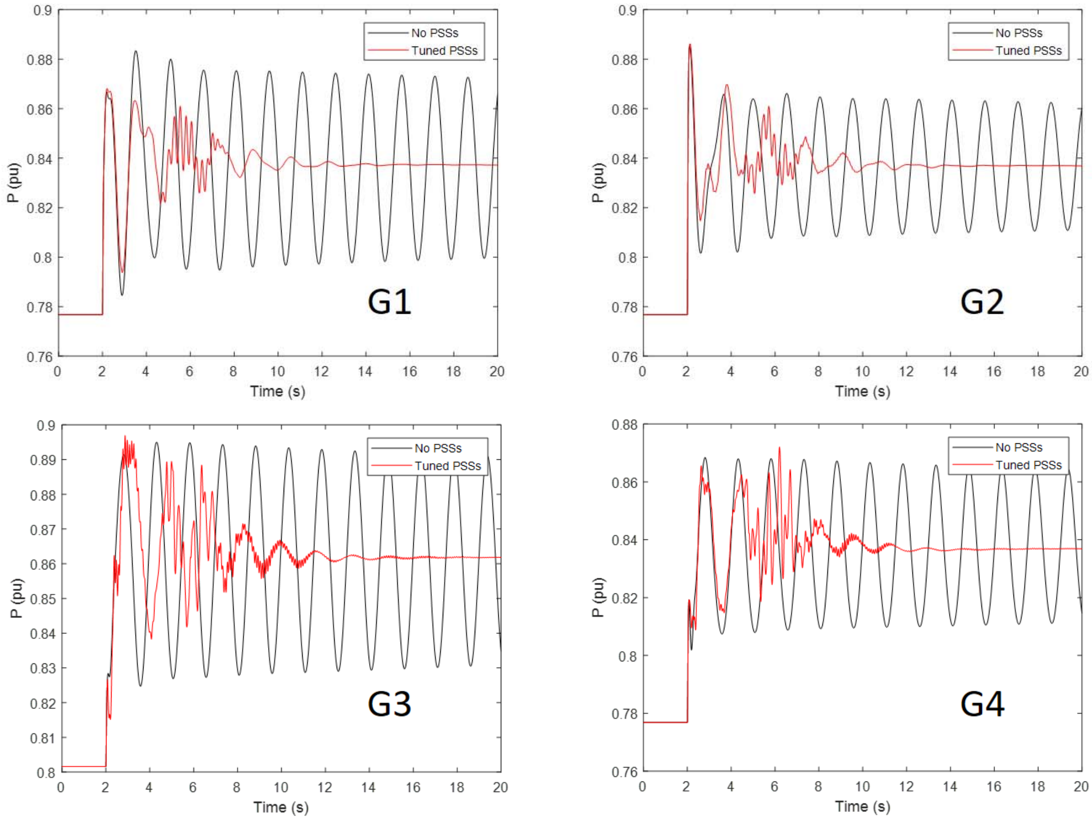


Fig 6. Generator active power responses for disturbance 1

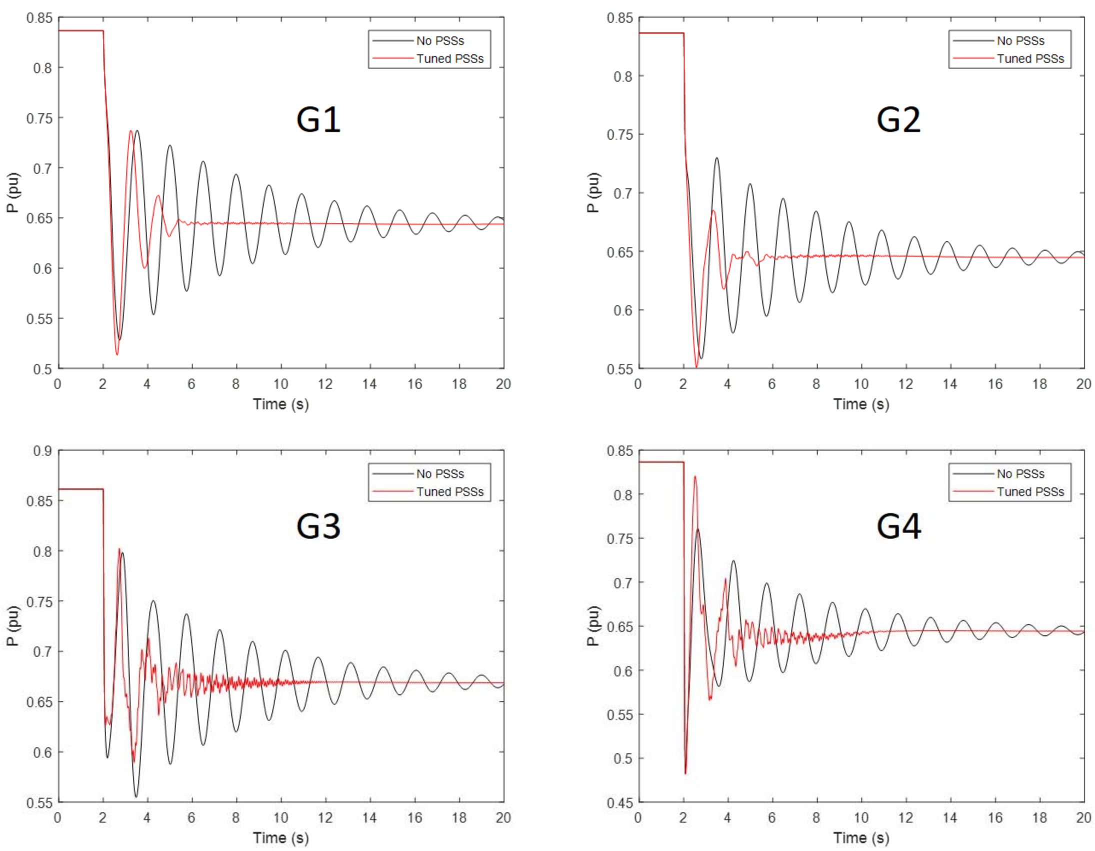


Fig 7. Generator active power responses for disturbance 2

TABLE I. FUZZY INPUTS IN TIME, FREQUENCY RESPONSES AND FUZZY OUTPUT SA INDEX

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ***Disturbance 1*** | | | | | | | | |
| | ***G1-NPSS*** | ***G1-TPSS*** | ***G2-NPSS*** | ***G2-TPSS*** | ***G3-NPSS*** | ***G3-TPSS*** | ***G4-NPSS*** | ***G4-TPSS*** |
| ***Overshoot (pu)*** | 0.76 | 0.51 | 0.80 | 0.82 | 0.55 | 0.58 | 0.52 | 0.58 |
| ***Settling Time (s)*** | 17.97 | 10.40 | 17.96 | 9.58 | 17.98 | 10.49 | 17.97 | 9.41 |
| ***D-Inter (pu)*** | 0.66 Hz 0.002 | 0.63Hz 0.127 | 0.66Hz 0.0016 | 0.62Hz 0.105 | 0.66Hz 0.0017 | 0.54Hz 0.111 | 0.66Hz 0.0019 | 0.57Hz 0.123 |
| ***D-Intra (pu)*** | 1.34Hz 0.049 | 1.04Hz 0.07 1.75Hz 0.106 | 1.14Hz 0.08 | 1.18Hz 0.08 1.56Hz 0.14 | 1.34HZ 0.015 | 1.25Hz 0.33 | 1.33Hz 0.0035 | 1.62Hz 0.08 |
| ***SA Index*** | 0.2107 | 0.5960 | 0.1714 | 0.5255 | 0.2886 | 0.5775 | 0.2350 | 0.5938 |
| ***Disturbance 2*** | | | | | | | | |
| ***Undershoot (pu)*** | 0.599 | 0.676 | 0.452 | 0.491 | 0.592 | 0.412 | 0.844 | 0.848 |
| ***Settling Time (s)*** | 17.30 | 3.45 | 17.22 | 3.41 | 17.30 | 7.88 | 17.21 | 7.90 |
| ***D-Inter (pu)*** | 0.67Hz 0.037 | 0.67Hz 0.23 | 0.67Hz 0.04 | 0.57Hz 0.40 | 0.67Hz 0.04 | 0.8Hz 0.08 | 0.67Hz 0.039 | 0.8Hz 0.106 |
| ***D-Intra (pu)*** | 1.33Hz 0.037 | 1.31Hz 0.174 | 1.33Hz 0.05 | 1.43Hz 0.03 | 1.32Hz 0.06 | 1.18Hz 0.09 | 1.54Hz 0.12 | 1.53Hz 0.14 |
| ***SA Index*** | 0.4010 | 0.8750 | 0.3113 | 0.7500 | 0.4000 | 0.7499 | 0.1849 | 0.7500 |

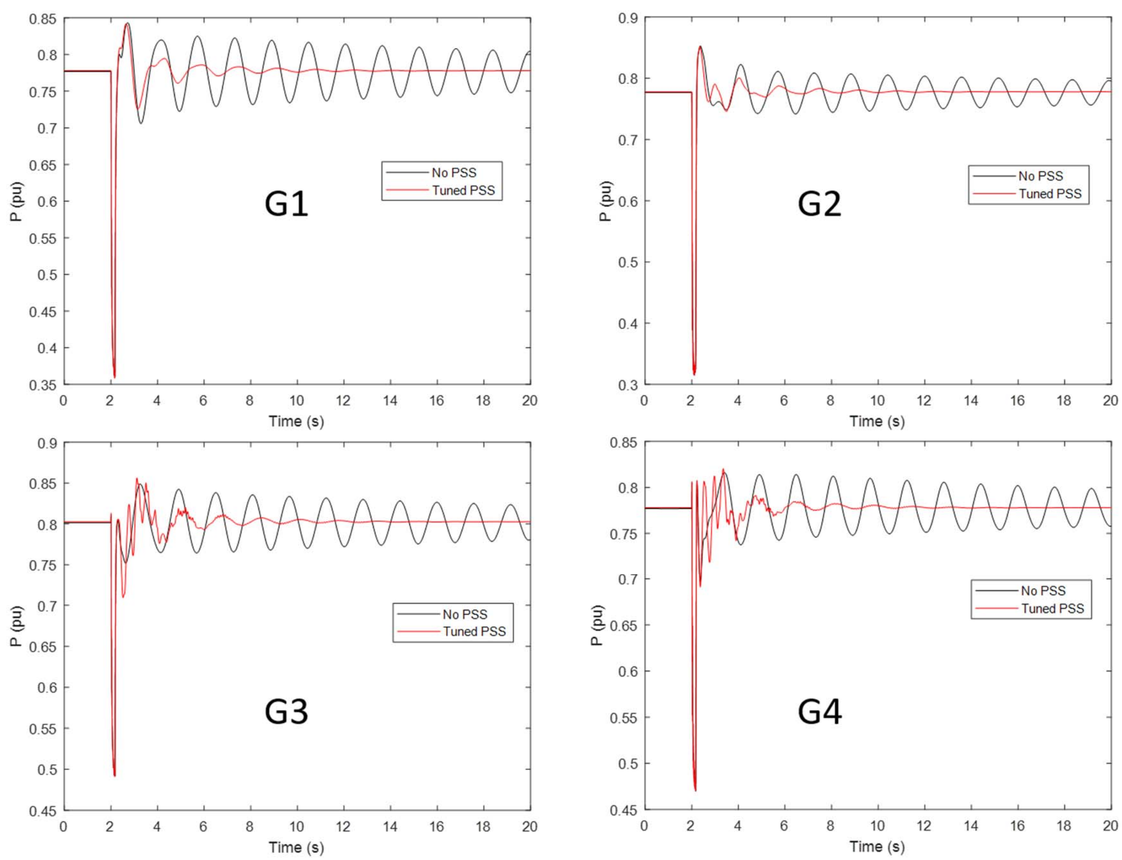


Fig 8. Generator responses for disturbance 3

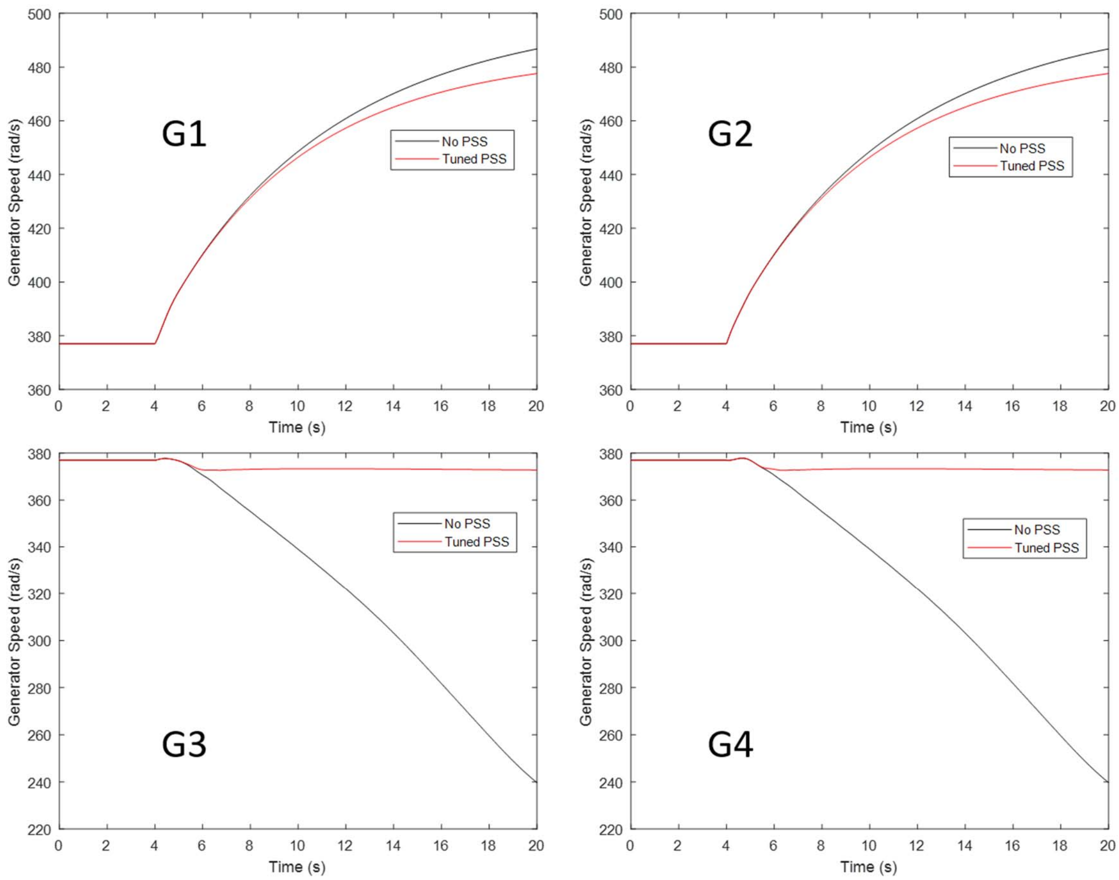


Fig 9. Generator responses for disturbance 4

## *C. Disturbance 3 – D3*

A 10 cycles duration three phase line to ground short circuit placed at bus 8 and the generator responses are shown in Fig. 8.

## *D. Disturbance 4 – D4*

A permanent line outage is simulated to study the first swing instability (FSI) of the system. Transmission line connecting bus 6 and 7 is tripped and the generator responses are shown in Fig. 9.

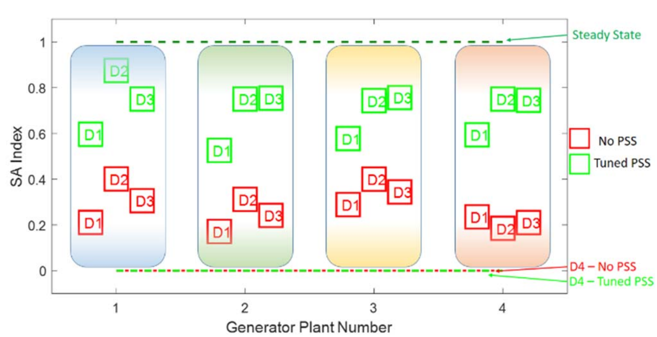


Fig 10. SA index of generators for different disturbances without PSSs and tuned PSSs

Fig.10 is the summary of SA index plot for all four generator plants for disturbances D1, D2, D3 and D4. System operating condition prior to these disturbances are summarized in Appendix.

# V. Conclusion

Poorly damped power system oscillations are detrimental to the security of the power system operation and it is required to damp as soon as possible. Synchronous generators equipped with power system stabilizers need to be monitored for improved reliability of the power system. Phasor measurement units based system-wide synchronized measurements are received at energy control centers for monitoring and control purposes. PMU measurements on system disturbance data is analyzed to get the PSS performances in time response and frequency response. A fuzzy logic system is designed to combine the time response and frequency response metrics and it provides a situational awareness on PSS performance on synchronous generator's oscillation(s). This proposed method is applied on a two-area four-machine benchmark power system simulated on a real-time digital simulator platform. It is validated with system disturbance data collected for different cases including a load change, short circuit fault and first swing instability. An improved situational awareness index is obtained with tuned PSSs. SA index of PSS performance interprets the severity of the system disturbance to the control center operator. Monitoring SA on PSS performance at the control center will enhance the power system operation more stable and secure.

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# Appendix

Power System Operating Condition prior to System Disturbance

| | | D1 | D2 | D3 | D4 |
|---|---|---|---|---|---|
| ***Generating Plant 1*** | ***P1(MW)*** | 700.10 | 738.60 | 700.10 | 700.10 |
| | ***Q1(MVAR)*** | 177.60 | 190.80 | 177.60 | 177.60 |
| | ***V1(pu)*** | 1.03 | 1.03 | 1.03 | 1.03 |
| ***Generating Plant 2*** | ***P2(MW)*** | 700.10 | 738.60 | 700.10 | 700.10 |
| | ***Q2(MVAR)*** | 217.90 | 232.10 | 217.90 | 217.90 |
| | ***V2(pu)*** | 1.01 | 1.01 | 1.01 | 1.01 |
| ***Generating Plant 3*** | ***P3(MW)*** | 722.40 | 761.00 | 722.40 | 722.40 |
| | ***Q3(MVAR)*** | 169.90 | 179.90 | 169.90 | 169.90 |
| | ***V3(pu)*** | 1.03 | 1.03 | 1.03 | 1.03 |
| ***Generating Plant 4*** | ***P4(MW)*** | 700.10 | 738.70 | 700.10 | 700.10 |
| | ***Q4(MVAR)*** | 186.60 | 192.70 | 186.60 | 186.60 |
| | ***V4(pu)*** | 1.01 | 1.01 | 1.01 | 1.01 |
| ***L7(MW)*** | | 967.00 | 1120.00 | 967.00 | 967.00 |
| ***L9(MW)*** | | 1767.00 | 1767.00 | 1767.00 | 1767.00 |
| ***Tie-Line Power (MW)*** | | 400.00 | 316.60 | 400.00 | 400.00 |