Performance Evaluation and Review of System Protection Schemes Using Synchrophasor Measurement

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***Abstract*—System Protection Schemes (SPS) are considered as an effective tool for enhancing the resilience of the power system towards rare contingencies. The validation of SPS is difficult by using conventional SCADA data due to its inherent low scan rate and skewedness. Under such condition, Synchrophasors has been found to be better suited for performance evaluation SPS and review of its design. This paper presents few case studies to illustrate the usage of Synchrophasors for evaluation and review of SPS in Indian Grid.**

***Index Terms*— Dependability, Indian grid, Reliability, Security, Selectivity, Sensitivity, Synchrophasor, System Protection Scheme.**

I. INTRODUCTION

Generation, transmission and distribution capacity is being augmented in a planned manner in Indian Grid. Occasionally there may be a mismatch in the commissioning of few segments of the network or variation between the forecasted and actual demand. This may cause skewed utilization of the network and transmission constraints. Under these scenarios, System Protection Schemes are being deployed in India for optimizing utilization of resources without compromising the system security. These schemes trigger automatic actions when the predesigned logic is satisfied [1].

As per CIGRE Task force 38.02.19, SPS is classified into various types like based on its input variables, its impact on Power System and its operating time [2]. These SPS includes under frequency load shedding (UFLS), under voltage load shedding (UVLS), fault condition that must be isolated and out of step (OOS) relaying. However, NERC definition of SPS excludes these and include only the schemes which act while detecting abnormal or predetermined system conditions [3]. Deployment of SPS may be a cost effective measure than building new infrastructure, however the risks associated with SPS are (1) risks of failure on demand and of inadvertent activation; (2) risk of interacting with other SPS in unintended ways and (3) increased management, maintenance, coordination requirements, and analysis complexity [4]. An SPS may fail to operate for several reasons, among which are (1) hardware failure; (2) faulty design logic; (3) software failure and (4) human error [3]. Recognizing the importance of SPS in any large grid, its mis-operation or failure would have a severe impact so, the SPS design first must address the following performance aspects [2]:

1. Dependability; which is a measure of certainty to operate when required [2].
2. Security; which is a measure of certainty that SPS will not operate when not required [2].
3. Selectivity; which is the ability to affect the least amount of action when performing its intended function [2].
4. Robustness; which is the ability to work correctly over the full range of expected steady state and dynamic system conditions [2].

As on date 129 SPS have been deployed in Indian Grid [5]. In line with NERC [6], these 129 SPS do not include UFLS, UVLS and OOS relaying. Out of these, 71 number of SPS are installed in the Western regional (WR) grid. These constitute of 34 wide impact SPS and 37 are local impact SPS [2].

Most of these SPS are designed to operate within milliseconds to few seconds for providing the automatic response during contingencies. Earlier the SPS operation could not be visualized or analyzed with the help of conventional SCADA system which is having scan rate of more than 10 seconds. However, Synchrophasor with their capability to provide synchronized and dynamic view of the system have been found to be better suited for performance evaluation and review of the SPS design due to high data rate. This paper discusses utilization of Synchrophasor measurements in Indian Grid for monitoring, evaluation and review of the SPS.

II. SPS PERFORMANCE EVALUATION

An SPS operation can be classified into four categories which are (1) Successful Operation; (2) Failure Operation; (3) Unsuccessful Operation and 4) Unnecessary Operation. Based on enumeration of above mentioned operations following three indices are defined in [7] to evaluate the performance of SPS.

$$\text{Effectiveness Index (EI)} = \frac{n_1}{n_1 + n_2 + n_3} \tag{1}$$

$$\text{Dependability Index (DI)} = \frac{n_1}{n_1 + n_2} \quad (2)$$

$$\text{Unnecessary Operation Rate (UOR)} = \frac{n_4}{n_y} \quad (3)$$

Where,
n_1- Number of Successful Operations;
n_2- Number of Failures;
n_3- Number of Unsuccessful Operations;
n_4- Number of Unnecessary Operations;
n_y- Number of Scheme - Years of Operation;

Based on above indices the performance of any SPS are calculated which provides the feedback regarding the efficiency as well the design review of the SPS. With the help of Synchrophasor data, the indices of SPS in Western Regional Grid have been calculated and presented in this paper.

However, before proceeding to calculation, there is need to further classify the type of SPS whose performance are being studied with these indices based on their control action [6]. Western Regional Grid SPS which amounts to number 71 is further classified based on type of control actions i.e. load/generation reduction, load and generation rejection and HVDC control etc. as given in table 1 and 2.

TABLE 1: WIDE IMPACT SPS IN WESTERN REGION IN INDIA

Type of SPS based on control action	Wide Impact SPS in WR Grid	
	Number of SPS	*Percentage of SPS*
Load Rejection	20	59 %
Generation Rejection	7	21 %
Load & Generation Rejection	6	18 %
HVDC Control	1	3 %

TABLE 2: LOCAL IMPACT SPS IN WESTERN REGION IN INDIA

Type of SPS based on control action	Local Impact SPS in WR Grid	
	Number of SPS	*Percentage of SPS*
Load Rejection	34	92 %
Generation Rejection	3	8 %

III. WAMS IN INDIAN GRID

In India, Synchrophasor initiative was started in the year 2010 [8]. It was started with five regional pilot projects wherein PMUs were placed at few of the strategic locations in the regional grids and the PMU measurements were integrated at the regional level. Subsequently the regional projects are integrated at the National level. At the beginning of the year 2015 there were 62 PMUs installed at 62 substations. After recognizing potential benefits of PMUs, two state utilities also came forward with their own Synchrophasor projects in the last one year. These State level projects have now been integrated with the National PDC via the regional PDC. By the end of year 2015, the population of PMUs grew to 154 covering 103 substations. The present WAMS network in Indian Grid is shown in figure 1. The next section provides an overview of how the Synchrophasor can be used for SPS monitoring and performance evaluation.

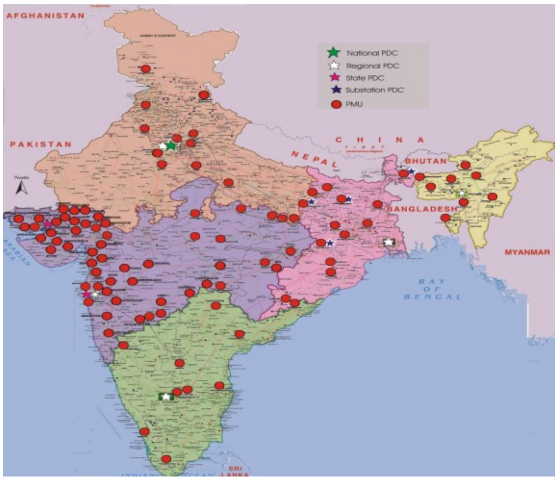

Figure 1. WAMS Network in India in 2016

IV. MONITORING OF SPS USING SYNCHROPHASORS

SPS are designed to detect the abnormal conditions in the system and take pre-planned, corrective actions to ensure system security [9]. After detection of abnormal system conditions, the SPS actions takes place in fraction of sub seconds. To monitor SPS actions and to evaluate its performance using conventional SCADA which takes long scan time of 2-10 seconds is of major concern. Synchrophasor measurements can be considered as perfect instrument for monitoring SPS actions and evaluating its performance as they monitor Power System states [10] in fraction of a second. Even though number of PMUs is limited measurements from these PMUs have helped in monitoring the performance of the deployed SPS. In many cases modification in the SPS were done to improve its performance. 286 numbers of SPS operation in Western region have been analyzed using Synchrophasors. The various indices like dependability, effectiveness and unnecessary operation were computed. The evaluation of SPS performance using Synchrophasors are illustrated using few case studies detailed in section V.

V. CASE STUDIES

The performance of SPS is evaluated in terms of its characteristics like Dependability, Security, Selectivity and Robustness. The case studies illustrated below evaluates one or other performance characteristics of SPS using Synchrophasor measurements.

Case Study I: This Case Study is about large generating station having six evacuating lines that are unevenly loaded as shown in figure 2. In order to secure the station under n-2 contingencies an SPS was deployed to runback generation or trip one of the units. The SPS successfully operated in several events. However, in one of the events there was a cascade failure of all evacuating lines. The station survived on house load with U#4, but later went into blackout.

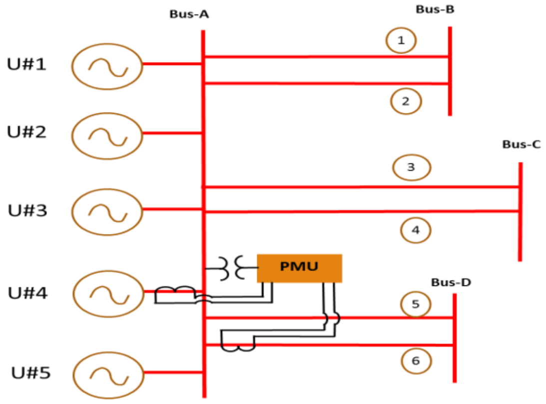

Figure 2. Generation Power Plant

Incidentally, as a part of the regional pilot project a PMU had been installed at this generating station having two current channels and one voltage channel. One of the current channels was connected to U#4 and other channel was connected to ckt 6. The performance of the SPS during the event was analyzed with the help of data from this PMU. The SPS logic is illustrated in figure 3.

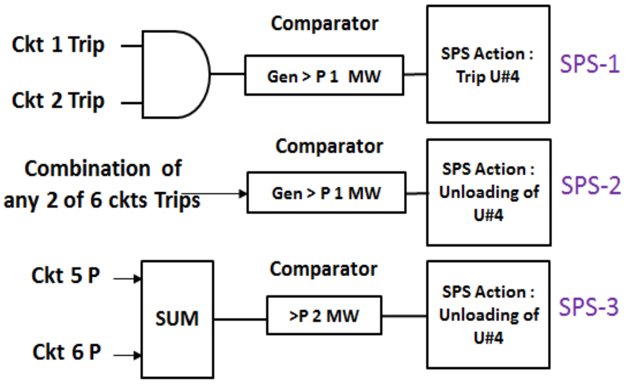

Figure 3. Local impact SPS scheme Implemented at the Generation plant

The event occurred at t=0 resulting in tripping of ckt 3. After t_1=11 min 13 sec 3 msec due to LBB action at Bus-C ckt 4 tripped. This resulted in overloading of the existing four lines Thus at time t_1 the criteria for SPS-2 was satisfied while at time t_2 the criteria for SPS-3 was satisfied. The generation reduction could have prevented cascade failure. The chronology of events is as follows:

- t=0: Occurrence of an event at bus C causing tripping of circuit 3.
- t_1=11 min 13 sec 3 msec: Tripping of circuit 4 satisfying SPS-2 criteria followed by envisaged action; U#4 unloading.
- t_2=11 min 13 sec 724 msec: Tripping of circuit 5 and 6 on power swing causing the station to island. Generating Units survived on house load. SPS-3 criteria also satisfied; U# 4 tripping.

The event was analyzed using Synchrophasors. The Synchrophasors measurements revealed that there was a delay in unloading of units as well as tripping of U# 4 as shown in figure 4. Simulations indicated that the station islanding could be avoided if Unit # 4 had tripped well before t_2. The cause for the delay was addressed by the Station and the SPS design was also reviewed.

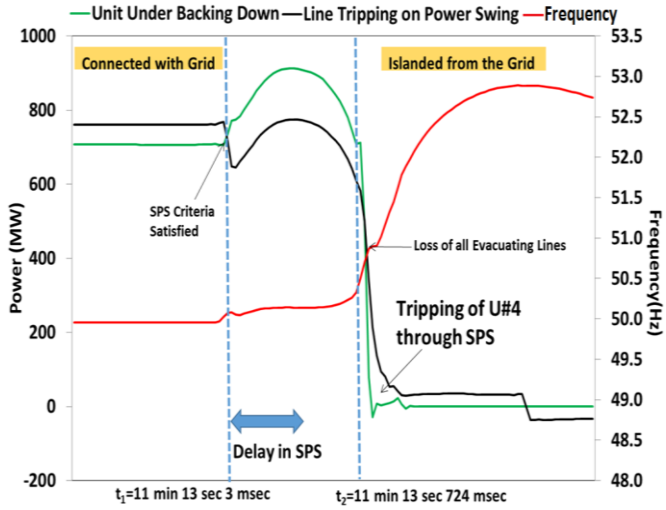

Figure 4. Plot of real power of unit, power flow on one of the line and frequency of the generating station bus from the PMU.

Modified SPS logic is shown in figure 5. The modified SPS considers contingencies of remote ckts also. After modification in SPS the performance of SPS was improved.

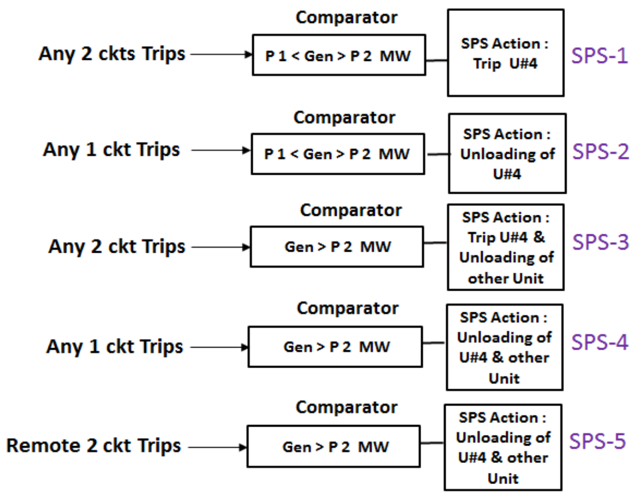

Figure 5. Modified wide impact SPS scheme Implemented at the power plant.

The modified SPS operated on 8 occasions out of which 7 were successful and only 1 failure occurred which was due to human error. The dependability index of modified SPS has which measures certainty to operate when required was 100 % for modified SPS.

Figure 6 shows SPS operations leading to U#4 unloading before SPS modification and after SPS modification. After SPS modification the time delay in unit unloading was reduced significantly. The Synchrophasor data assisted in removal of time delay associated with SPS scheme.

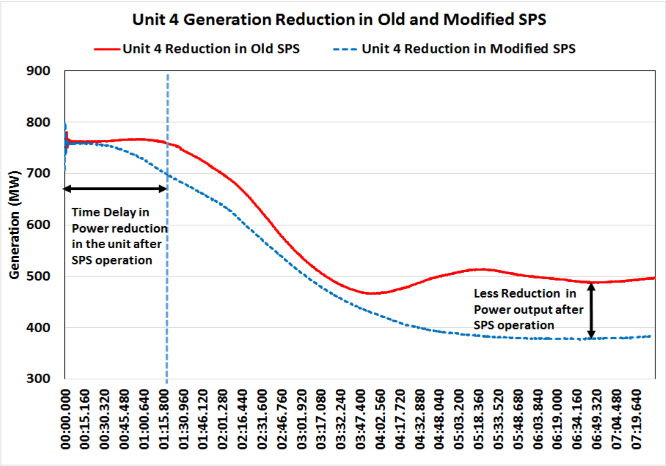

Figure 6. Plot of generation reduction on Old and modified SPS operation.

Case Study II: Case Study-I was a case of Local Impact SPS whereas this case study illustrates the application of Synchrophasors in assessing the performance of a wide impact SPS. Initially the two grids were connected through single 765 ckt. Grid 1 was of size 100 GW and Grid 2 was of 35 GW. Later on the network between Grid 1 and Grid 2 augmented with one more 765 kV ckt as shown in figure 7.

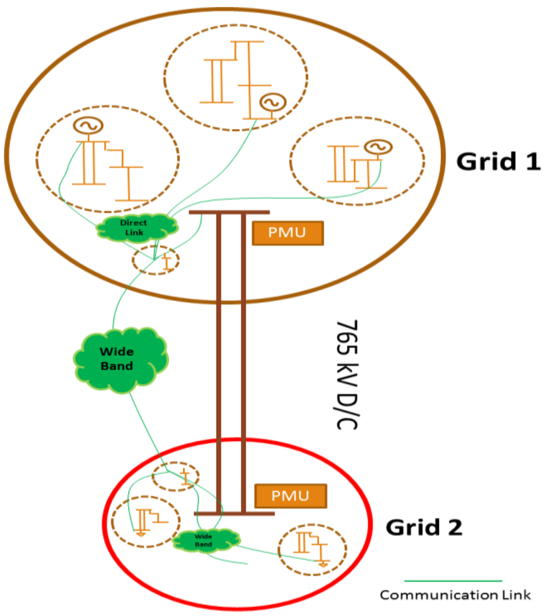

Figure 7. Wide Impact SPS scheme on the inter-regional tie lines.

Few SPS were designed to handle contingencies in either Grid 1 or Grid 2. One of the SPS logic is illustrated in figure 8. The SPS would trigger if flow on D/C is greater than or equal to 1500 MW for more than 2.5 sec or if flow on D/C is greater than 2000 MW. The SPS actions comprise of generation rejection in several generating stations located in Grid 1 and load rejection in Grid 2.

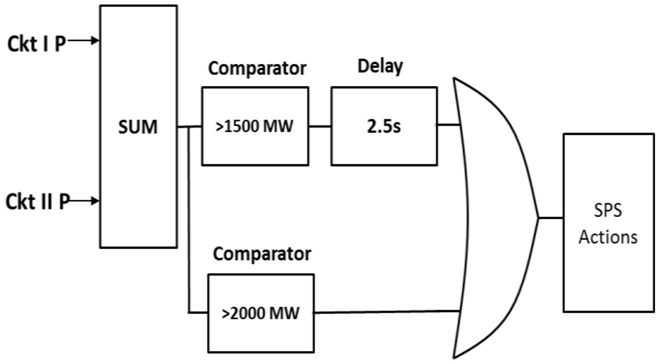

Figure 8. Wide impact SPS logic

Figure 9 shows MW measurements of D/C from PMU. Upon exceeding 1500 MW for 2.5 sec, the SPS was operated and generation rejection in Grid 1 and load rejection Grid 2 happened due to which the power flow on the ckts has come down. The delay of 2.5s helped in preventing frequent operation of SPS. This SPS has operated on 15 occasions with 100% dependability. There has been no unnecessary operation or insecure operation of this SPS which has led to its high effectiveness index and it has been validated using Synchrophasor measurements.

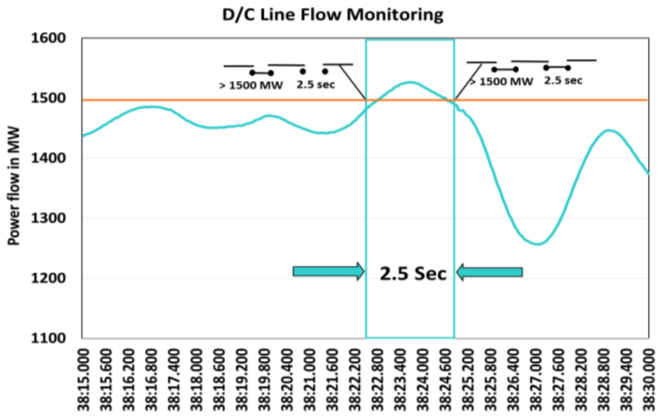

Figure 9. Plot of powerflow on the tie line showing the dependability of the SPS scheme.

Case Study III: This case study explains SPS logic when a single tie line is in service between Grid 1 and Grid 2 as shown in figure 7. This SPS operates when there is huge power flow from Grid 1 to Grid 2 during contingencies happening in either Grid 1 or Grid 2.

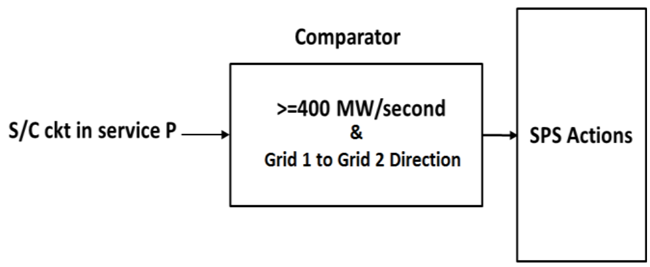

Figure 10. Wide impact SPS logic.

The implemented scheme is shown in figure 10. The SPS would operate when dp/dt exceeds 400 MW/sec in Grid 1 to Grid 2 direction. The desirable SPS operation is shown in figure 11. SPS got triggered correctly and was effective in damping the oscillations that seem to be growing in amplitude.

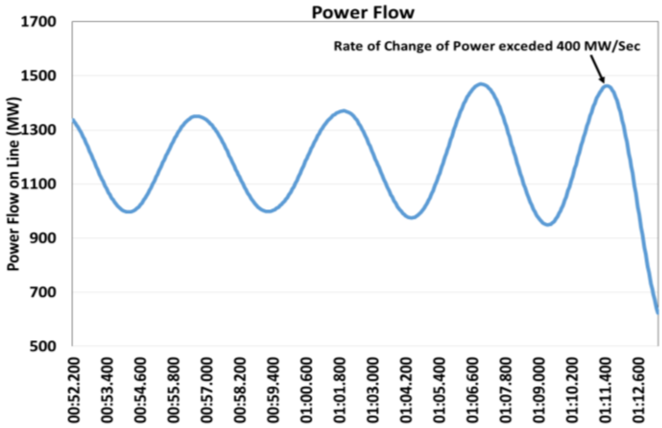

Figure 11. Plot of powerflow on the tie line indicating the correct operation of SPS.

It was observed that out of 24 operations, the SPS operated 21 times successfully while on two occasion's directionality condition was not satisfied and on one occasion the ramp rate condition was not satisfied as shown in figure 12. Due to triggering of SPS irrespective of the direction of power flow at occasions and the undesirable SPS operations this SPS was disarmed.

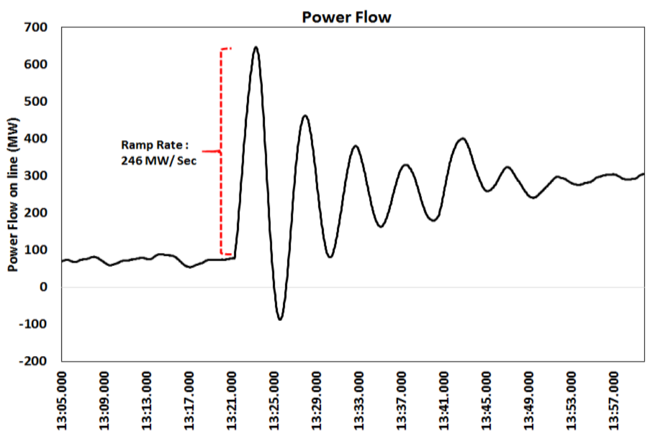

Figure 12. Plot of powerflow on the tie line indicating the undesirable operation of SPS.

Case Study IV: Apart from evaluating performance indices of SPS scheme, Synchrophasor measurements has also provided key input to the design of the SPS scheme. There is a generating station having units and evacuation lines connected at two different voltage levels (Bus B and C). It was observed that tripping of any one of these lines leading to power swing on other line and oscillations in the Grid. The generating plant connectivity and oscillations observed in the Grid using Synchrophasor measurements are shown in figure 13 and figure 14 respectively.

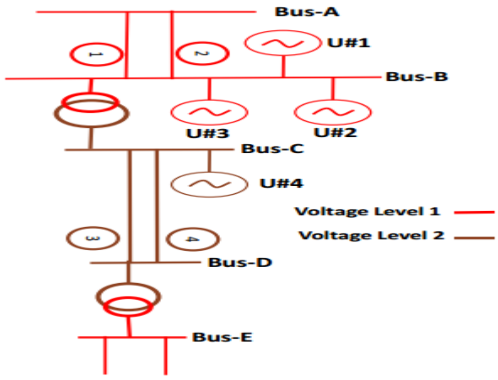

Figure 13. Generators connectivity at two different voltage levels

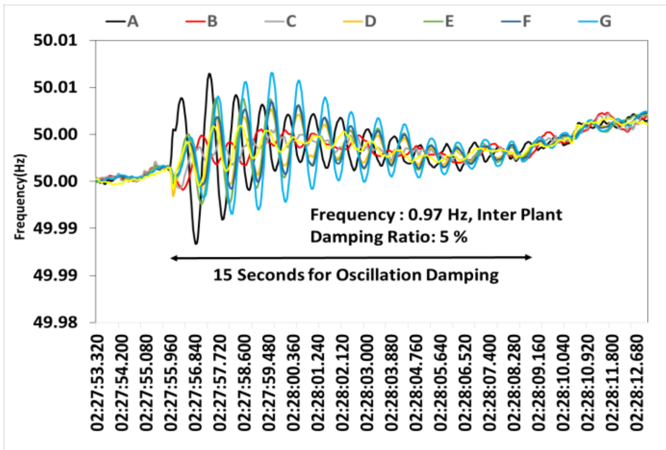

Figure 14. Plot of oscillation observed in frequencies near to sub-station due to tripping of evacuation line from Bus C and Bus D.

The oscillations in the Grid are due to tripping of one circuit resulted in tripping of other circuit in zone 1 Power swing. This has resulted in loss of evacuation lines from power plant. In order to improve system reliability, first the PSS tuning of generating station was carried out. After that, an SPS was designed in which detection of power swing was set as base criteria for SPS action. The SPS actions either trip or reduces generation as per the logic shown in figure 15.

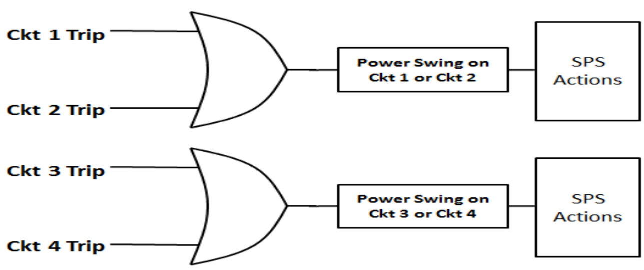

Figure 15. Scheme of SPS implemented at generating station based on detection of power swing and circuit tripping.

After PSS tuning and implementation of SPS based on power swing, reliability of system was improved. In an event due to tripping of one ckt the SPS has avoided tripping of other ckt on power swing and figure 16 illustrates that oscillations are reduced significantly after implementation of SPS.

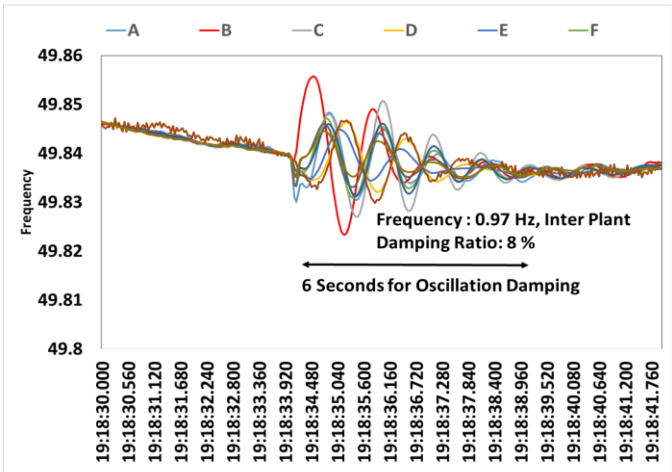

Figure 16. Plot of oscillation observed in frequencies near to sub-station due to tripping of evacuation line from Bus C and Bus D.

From these case studies, it can be seen that how the Synchrophasor data has helped in improving the design of SPS as well as designing a new SPS. Summary of performance indices of four case studies as calculated from Synchrophasor data are shown in table 3.

TABLE 3: PEFROMANCE INDICES OF SPS DISCUSSED IN CASE STUDIES

Sl.no	n_1	n_2	n_3	n_4	n_y	DI (%)	EI (%)	UOR (%)
Case Study I	7	0	1	0	69	100	88	0
Case Study II	15	0	0	0	69	100	100	0
Case Study III	21	0	3	0	69	100	88	0
Case Study IV	3	0	0	0	69	100	100	0

VI. CONCLUSION

The paper has illustrated various case studies that how Synchrophasor can help system operator in performance evaluation of SPS and its design improvement. Various indices measuring the efficacy of SPS dependability, security, effectiveness can be evaluated using Synchrophasors. These indices can be utilized for improving the operational performance of SPS. This paper has also show cased how Indian grid operator has utilized the data in extensive manner in improving the system performance under various contingencies and laid down the foundation for effective utilization of WAMS for evaluating SPS operation, modifying SPS design and designing as new SPS. The WAMS based SPS requires reliable communication, faster processing time, adaptive algorithm and redundancy in all the aspects prior to its implementation. The WAMS based SPS are also envisaged as a part of Unified Real Time Dynamic State Measurement (URTDSM) [11].

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REFERENCES

[1]. V. K. Agrawal et al, “Deployment of System Protection Schemes for enhancing reliability of power system: Operational experience of wide area SPS in Northern Regional Power System in India”, International Conference on Power and Energy Systems (ICPS), 22-24 Dec. 2011.

[2]. CIGRE 38.02.19, “System protection schemes in power networks”,June 2001

[3]. NERC, Special Protection Systems (SPS) / Remedial Action Schemes (RAS): Assessment of Definition, Regional Practices, and Application of Related Standards

[4]. PSERC Final Project Report, “System Protection Schemes: Limitations, Risks, and Management”, December 2010.

[5]. POSOCO, System Portection Schcme in Indian Grid, Internal report.

[6]. Weihui Fu et al, “Risk Assessment for Special Protection Systems”, IEEE Transactions on Power Systems, vol. 17, no. 1, February 2002.

[7]. Industry Experience with Special Protection Schemes, IEEE Transactions on Power Systems, Vol. 11, No. 3, August 1996.

[8]. POSOCO, “Synchrophasors Initiative in India”, New Delhi, Tech.Rep. July 2012, http://www.erldc.org/Other_Doc/synchrophasor_initiatives_in_india.pdf

[9]. P.M.Anderson, “Power System Protection”, IEEE Press, 1999, Chapter 21 page 902-909

[10]. Prabha Kundur et al, “Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions”, IEEE Transactions on Power Systems, vol. 19, no. 3, pp.1387-1401, Aug 2004.

[11]. POSOCO, “Synchrophasors Initiative in India”, New Delhi, Tech.Rep. December 2013, http://www.nldc.in/WebsiteData/Reports/OtherReports/Synchrophasors%20Initiatives%20in%20India%20Decmber%202013%20-%20Web.pdf