

Chapter 16

Validation and Tuning of Remedial Action Schemes in Indian Grid Operations Using Synchrophasor Technology



P. K. Agarwal and Chandan Kumar

16.1 Introduction

Generation, transmission, and distribution capacity is being augmented in a planned manner in the 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 result in skewed utilization of the network and cause transmission and generation constraints. Under these scenarios, System Protection Schemes (SPSs) are being deployed in Indian Power System for optimizing the utilization of resources without compromising the system security and reliability. These schemes trigger automatic actions when the predesigned logic is satisfied and provide adequate action to bring back the system to normalcy [1]. Apart from these, with the large size and increased complexity of the Indian power grid, it is also subjected to situations such as congestion, over/under frequency, over/under voltage, system load adjustment, power swings. To detect and take preventive/protective actions for these conditions, System Protection Schemes are developed to address in order to bring the system back to equilibrium and under Normal State of operation from any Alert or Emergency State. Apart from these, Indian Power System has been designed with N-1 and N-1-1 criteria, and if under N-1-1 criteria system parameters are going above stability limits, System Protection Scheme has to be provided in order to enhance the optimum utilization of available resources along with keeping the grid reliability as paramount importance.

As per CIGRE Task force 38.02.19, SPS is classified into various types based on its input variables, its impact on power system and operating time [2].

P. K. Agarwal (✉) · C. Kumar

Power System Operation Corporation Ltd, New Delhi 11016, India
e-mail: pkagarwal@posoco.in

C. Kumar

e-mail: chandan@posoco.in

This SPS definition 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 includes only the schemes which act while detecting abnormal or predetermined system conditions [3]. In Indian Power System also, the SPS has been discussed in terms of scheme separate from the UFLS, UVLS, and OOS.

A System Protection System is different in concept and implementation from a conventional protection scheme which is being used in substations (transformer load trimming scheme, line loading-based load trimming scheme) as these schemes are intended to provide a safety net for the electrical grid during unplanned/extreme/N-1-1 contingency conditions or when system or operating constraints could not allow meeting the optimum resource utilization. Deployment of SPS may be a cost-effective measure than building new infrastructure (constriction of new transmission lines may cause non-optimum utilization); however, the risks associated with SPS are as follows:

1. Risk of failure on demand and of inadvertent activation;
2. Risk of interacting with other SPS in unintended ways;
3. Increased management, maintenance, coordination requirements, and analysis complexity [4]; and
4. Improper implementation of envisaged automated action.

The SPS may fail to operate for several reasons, among which prominent ones 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. Because of this, 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 SPSs have been deployed in Indian Grid [5]. In line with NERC [6], these 129 SPSs do not include UFLS, UVLS, and OOS relaying. Out of these, 71 SPSs are installed in the Western Regional (WR) Grid in India. These constitute of 34 Wide Impact SPSs, and 37 are Local Impact SPSs [2]. Wide Impact SPSs are those where action envisaged occurs at various locations far away from each other

at the same time when its associated SPS acts. While in the Local Impact SPS, the action is localized in nature to provide immediate relief.

Most of these SPSs 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 s. However, Synchrophasor measurements of power system with their capability to provide a 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 their high data rate. This chapter discusses utilization of Synchrophasor measurements in the Indian Grid for monitoring, evaluation, and review of the System Protection Scheme.

16.2 SPS Performance Evaluation

In order to ensure the optimum performance of designed and implemented SPS scheme in the grid, there is always a need to evaluate its performance during its actual operation. In order to find the performance level, it has to be classified into various categories. An SPS operation can be classified into basically four categories which are as quoted below:

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.

$$\text{Effectiveness Index (EI)} = \frac{n_1}{n_1 + n_2 + n_3} \quad (16.1)$$

$$\text{Dependability Index (DI)} = \frac{n_1}{n_1 + n_2} \quad (16.2)$$

$$\text{Unnecessary Operation Rate (UOR)} = \frac{n_4}{n_y} \quad (16.3)$$

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;

Table 16.1 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 and generation rejection	6	18
HVDC control	1	3

Table 16.2 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

Based on the above indices, the performance of any SPS is calculated which provides the feedback regarding the efficiency as well as 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 chapter.

However, before proceeding to calculation, there is a need to further classify the type of SPS whose performance is 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, as given in Tables 16.1 and 16.2.

16.3 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 have also come forward with their own Synchrophasor projects in the last two years. These state-level projects have now been integrated with the National PDC via the regional PDC. By the end of the year 2015, the population of PMUs grew to 154 covering 103 substations. The WAMS network (as in 2016) in Indian Grid is as shown in Fig. 16.1. The next section provides an overview of how the Synchrophasor can be used for SPS monitoring and performance evaluation.

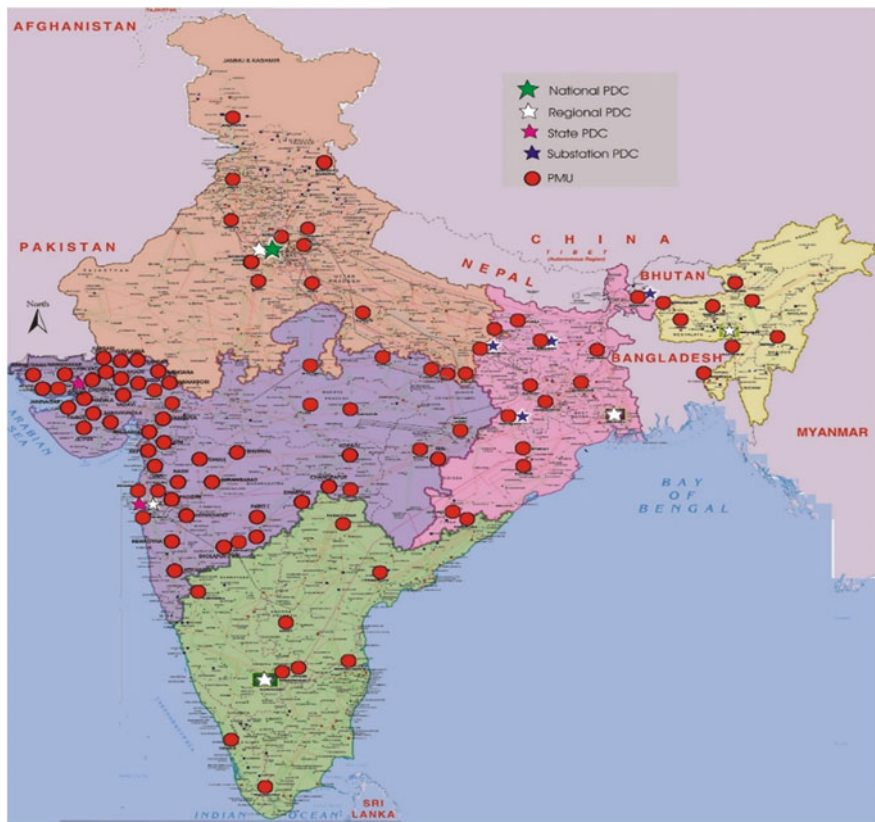


Fig. 16.1 WAMS network in India in 2016

16.4 Monitoring of SPS Using Synchrophasors

SPSs are designed to detect the abnormal conditions in the system and take pre-planned automated corrective actions to ensure system security and reliability [9]. After detection of abnormal system conditions, the SPS actions take place in fraction of sub-seconds in order to ensure that system parameter is not outside the permissible limit for large duration of time and enter transient instability zone. To monitor SPS actions and to evaluate its performance using conventional SCADA which takes long scan time of 2–14 s 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 the Indian Power System with their suitable installation at selected substations. In many cases, modifications in the SPS were done to improve its performance for better reliability

and security. Until 2015, around 286 SPS operations 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 is illustrated using few case studies detailed in next sections in this chapter.

16.5 Case Studies

The performance of SPS is evaluated in terms of its characteristics like Dependability, Security, Selectivity, and Robustness. The case studies illustrated below evaluate one or other performance characteristics of SPS using Synchrophasor measurements in the Indian Power System. These case studies have been used in various papers published by the authors in order to spread the utilization aspect of Synchrophasor measurement in this area [11, 12].

Case Study I: This case study is about large generating station having six evacuating lines that are unevenly loaded as shown in Fig. 16.2. In order to secure the station under n-2 contingencies, an SPS was deployed to runback generation or trip one of the units so that the system remains stable under transient stability. The SPS has 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.

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 another channel was connected to circuit/Line 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 Fig. 16.3.

The event occurred at $t = 0$ resulting in tripping of circuit 3. After $t_1 = 11 \text{ min } 13 \text{ s } 3 \text{ ms}$ due to local breaker backup (LBB) action at Bus C, circuit 4 tripped. This resulted in overloading of the existing four lines. Thus at time t_1 , the criteria for SPS-2 were satisfied while at time t_2 ($t_2 = 11 \text{ min, } 13 \text{ s, } 724 \text{ ms}$) the criteria for SPS-3 were satisfied. The generation reduction could have prevented cascade failure. The chronology of events is as follows:

1. $t = 0$: Occurrence of an event at Bus C causing tripping of circuit 3.
2. $t_1 = 11 \text{ min } 13 \text{ s } 3 \text{ ms}$: Tripping of circuit 4 satisfying SPS-2 criteria followed by envisaged action; U #4 unloading.
3. $t_2 = 11 \text{ min } 13 \text{ s } 724 \text{ ms}$: Tripping of circuit 1, 2, 5 and 6 on power swing causing the station to island. Generating Units survived on house load. SPS-3 criteria also satisfied for U #4 tripping.

The event was analyzed using Synchrophasors. The Synchrophasors measurements revealed that there was a delay in the unloading of units as well as tripping of U #4 as shown in Fig. 16.4. Simulations indicated that the station islanding could

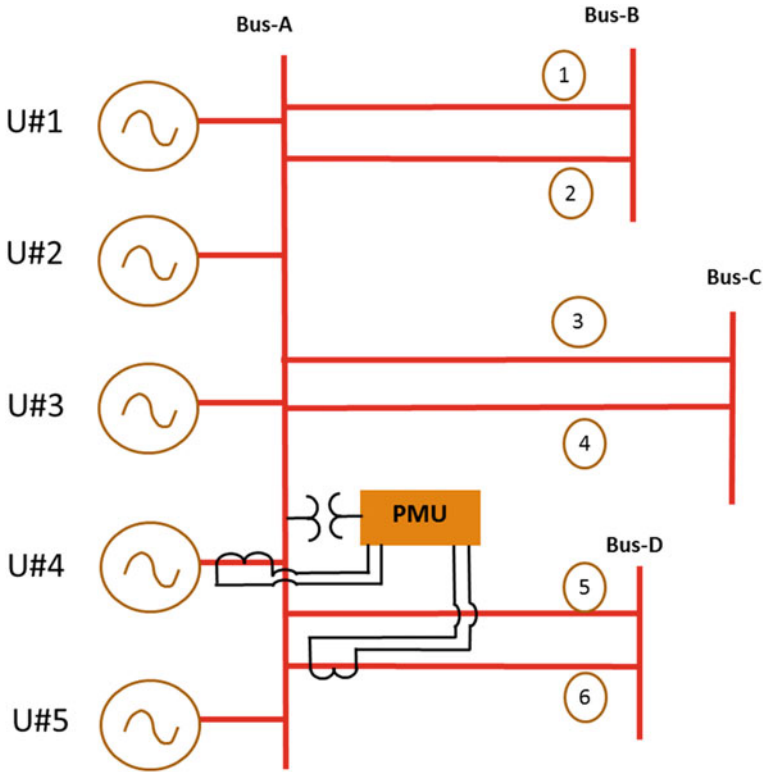


Fig. 16.2 Generation power plant

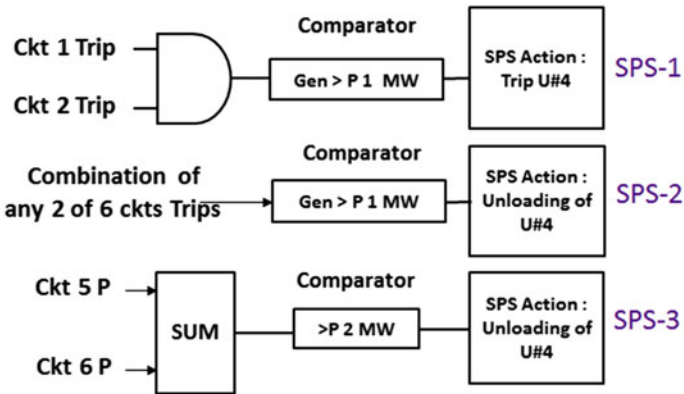


Fig. 16.3 Local Impact SPS scheme implemented at the generation plant

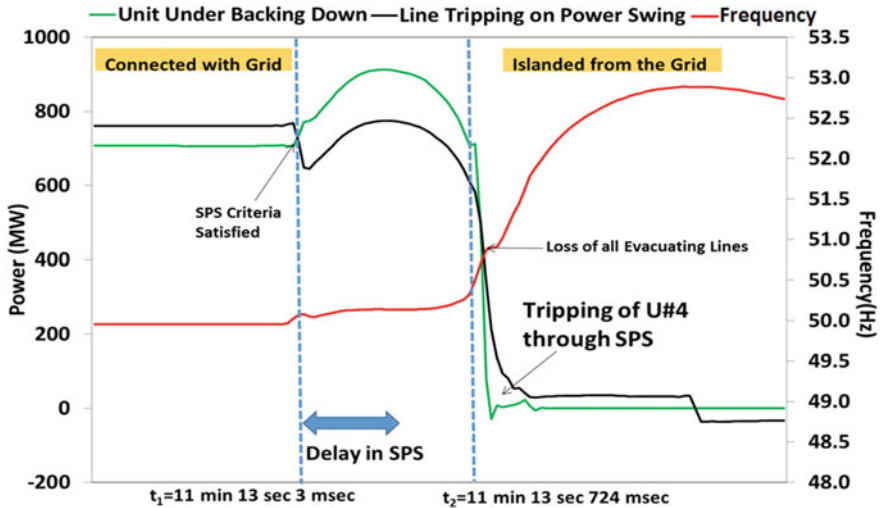


Fig. 16.4 Plot of real power of unit, power flow on one of the lines, and frequency of the generating station bus from the PMU

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.

Modified SPS logic is shown in Fig. 16.5. The modified SPS considers contingencies of remote circuits also. After modification in SPS, the performance of SPS was improved.

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 which measures certainty to operate when required was 88% for the modified SPS.

Figure 16.6 shows SPS operations leading to Unit #4 unloading before SPS modification and after SPS modification. After SPS modification, the time delay in unit unloading was reduced significantly. This has impacted the transient stability of the system and helping it to recover from any contingency. The Synchrophasor data assisted in the removal of time delay associated with SPS scheme and generation runback scheme at the plant.

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 transmission circuit. Grid 1 was of size 100 GW and Grid 2 was of 35 GW. Later on, the network between Grid 1 and Grid 2 is augmented with one more 765 kV circuit as shown in Fig. 16.7.

Few SPSs were designed to handle contingencies in either Grid 1 or Grid 2. One of the SPS logic is illustrated in Fig. 16.8. The SPS would trigger if flow on D/C is greater than or equal to 1500 MW for more than 2.5 s or if flow on D/C is greater

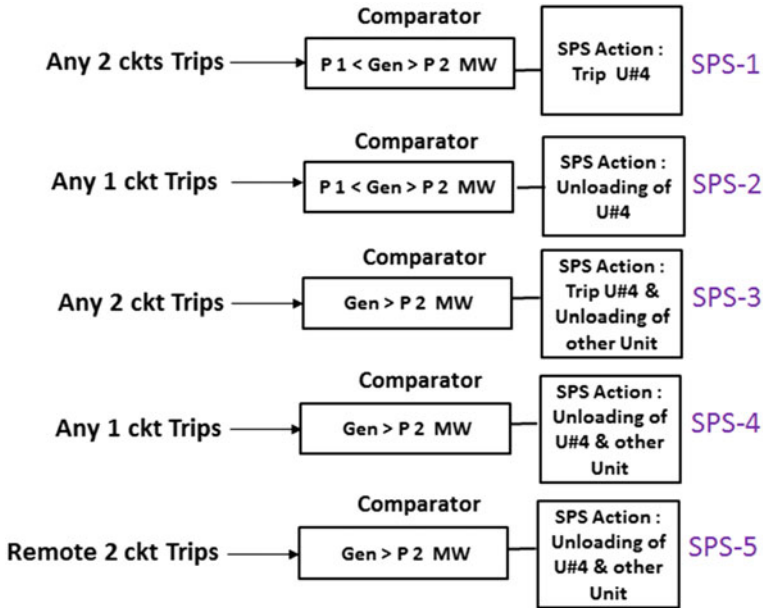


Fig. 16.5 Modified Wide Impact SPS scheme implemented at the power plant

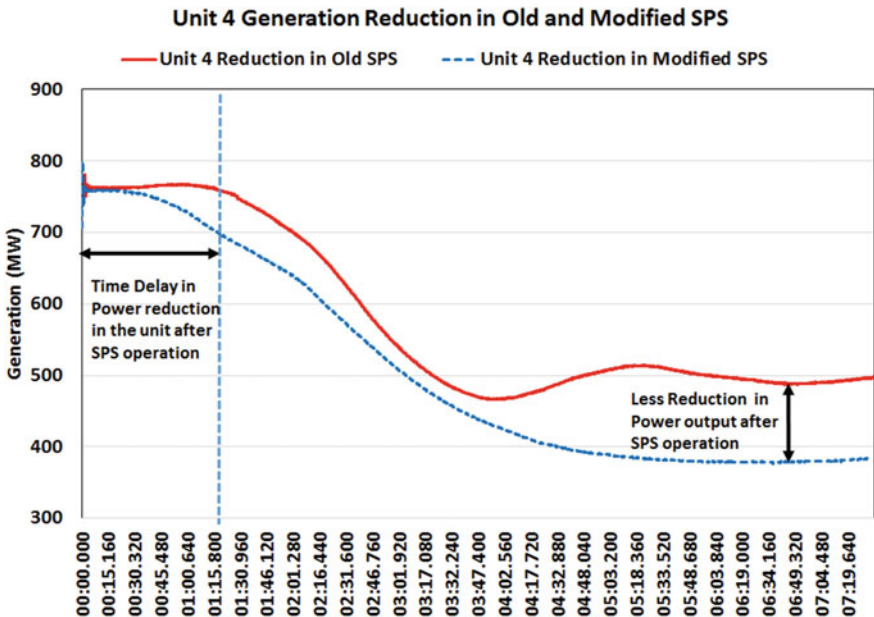


Fig. 16.6 Plot of generation reduction on old and modified SPS operation

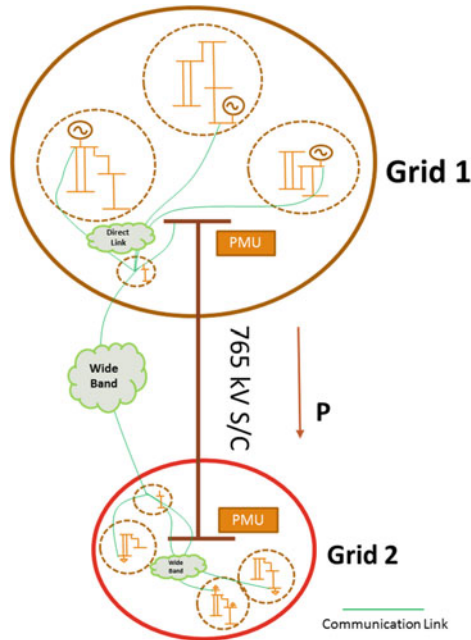


Fig. 16.7 Wide Impact SPS scheme on the inter-regional tie lines

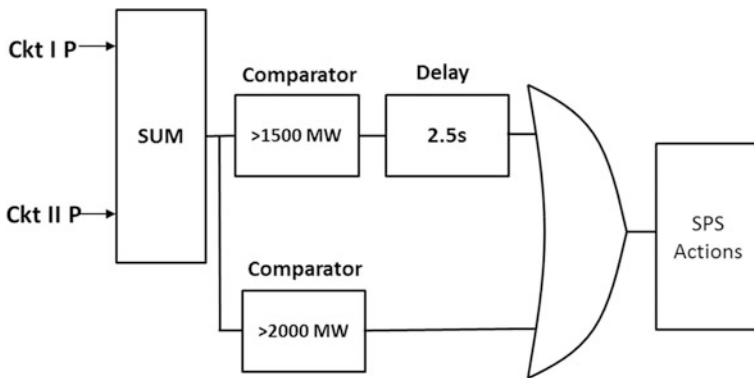


Fig. 16.8 Wide Impact SPS logic in the case study II

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 16.9 shows MW measurements of D/C from PMU. Upon exceeding 1500 MW for 2.5 s, the SPS has operated and generation rejection in Grid 1 and load rejection Grid 2 happened due to which the power flow on the circuits has come down. The delay of 2.5 s has helped in preventing frequent operation of SPS.

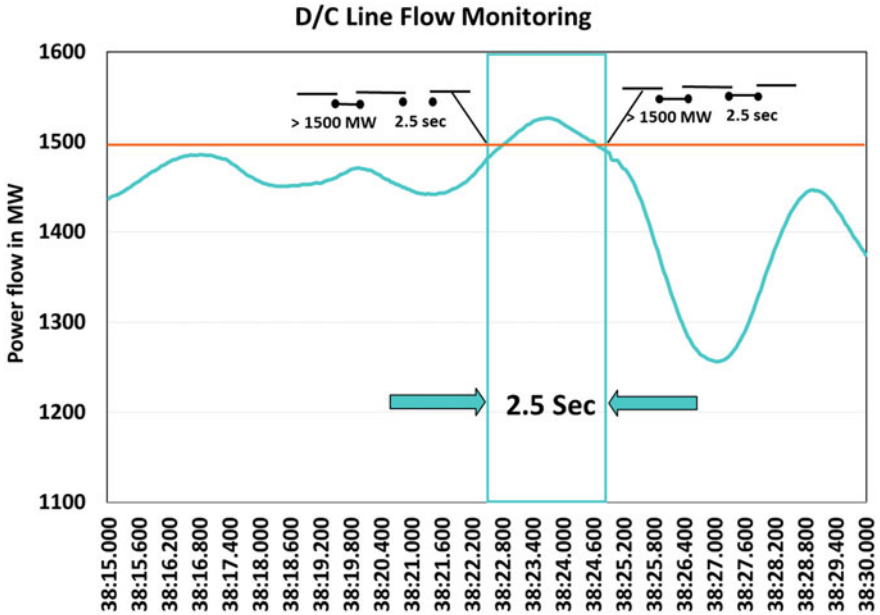


Fig. 16.9 Plot of power flow on the tie line showing the dependability of the SPS scheme

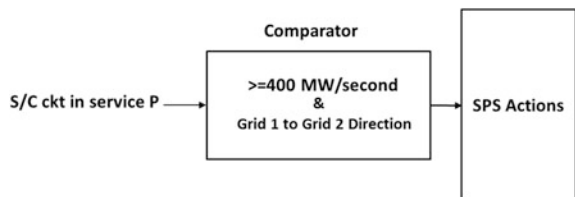
This SPS has operated on 15 occasions with 100% dependability. There has been no unnecessary operation or insecure operation of this SPS which has led to its high effectiveness index, and it has been validated using Synchrophasor measurements.

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 Fig. 16.7. 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.

The implemented scheme is shown in Fig. 16.10. The SPS would operate when dp/dt exceeds 400 MW/s in Grid 1 to Grid 2 direction. The desirable SPS operation is shown in Fig. 16.11. SPS got triggered correctly and was effective in damping the oscillations that seem to be growing in amplitude.

It was observed that out of 24 operations, the SPS operated 21 times successfully while on two occasions directionality condition was not satisfied and on one occasion the ramp rate condition was not satisfied as shown in Fig. 16.12. Due to

Fig. 16.10 Wide Impact SPS logic in case study III



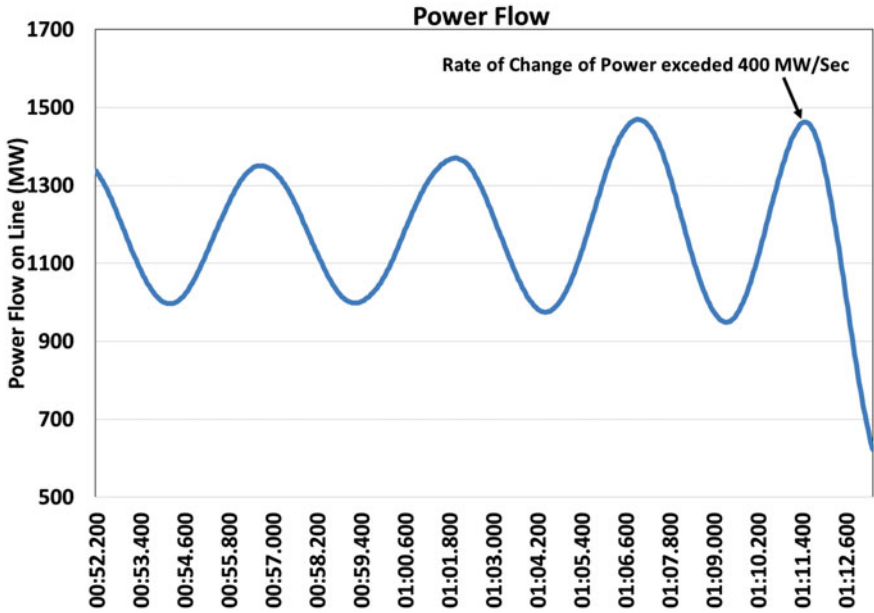


Fig. 16.11 Plot of power flow on the tie line indicating the correct operation of SPS

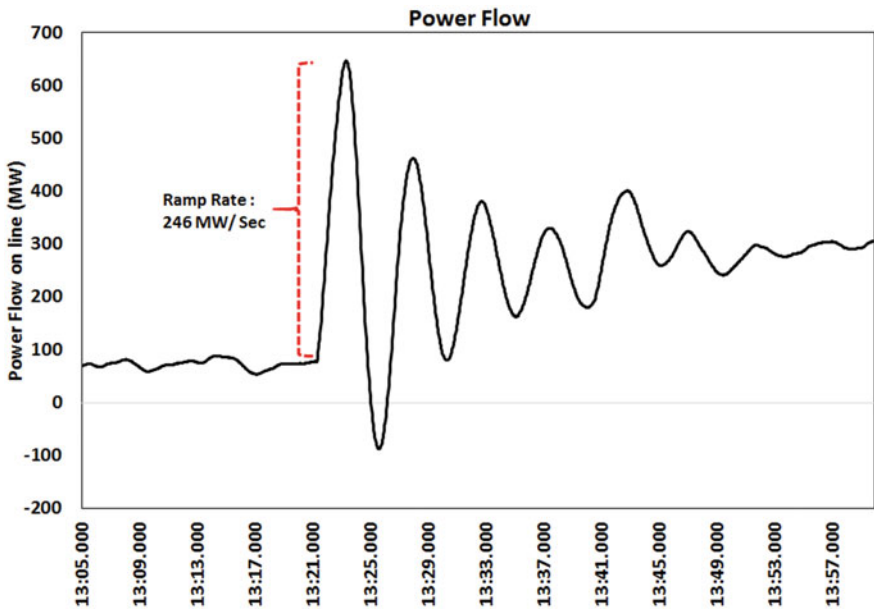
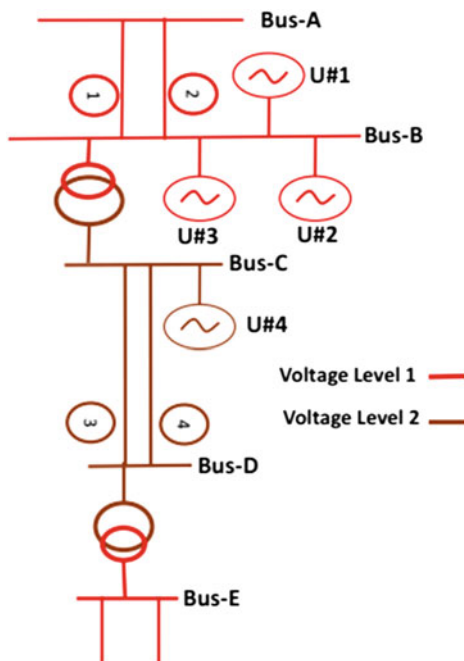


Fig. 16.12 Plot of power flow on the tie line indicating the undesirable operation of SPS

Fig. 16.13 Generators connectivity at two different voltage levels



triggering of SPS irrespective of the direction of power flow at occasions and the undesirable SPS operations, this SPS was disarmed.

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 leads to power swing on other line and low-frequency oscillations in the grid. The generating plant connectivity and oscillations observed in the grid using Synchrophasor measurements are shown in Fig. 16.13 and Fig. 16.14, respectively. The oscillations observed were of inter-plant nature and associated with generators and its connectivity with the rest of the network.

The oscillations in the grid are due to tripping of one circuit which further resulted in tripping of other circuit in Zone 1 power swing. This has resulted in the loss of evacuation lines from the power plant. In order to improve system reliability and transient stability, 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 action either trip or reduce generation as per the logic shown in Fig. 16.15.

After PSS tuning and implementation of SPS based on power swing, reliability of the system has improved. In an event due to the tripping of one circuit, the SPS has avoided tripping of other circuit on power swing and Fig. 16.16 illustrates that oscillations are reduced significantly after implementation of SPS.

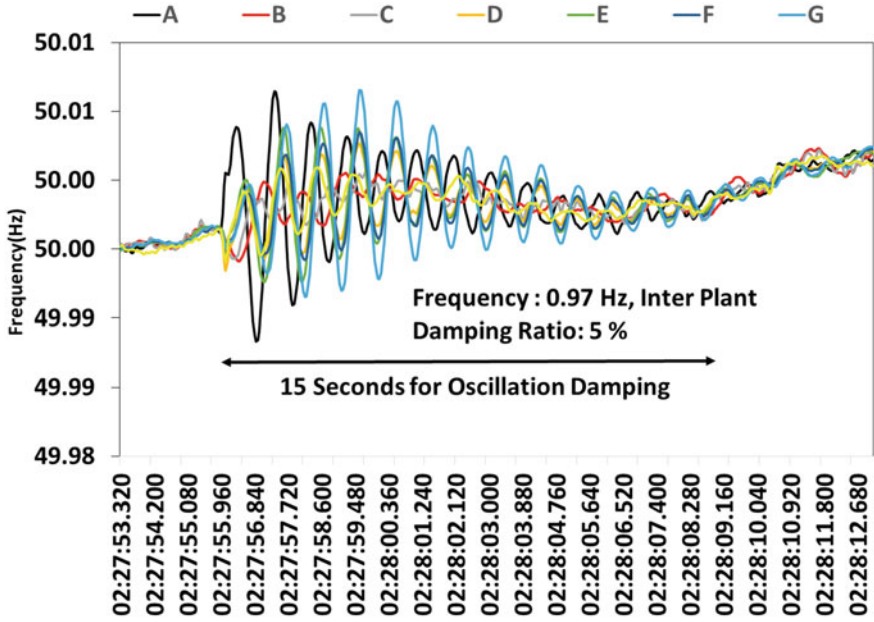


Fig. 16.14 Plot of oscillation observed in frequencies near to substation due to tripping of evacuation line from Bus C and Bus D

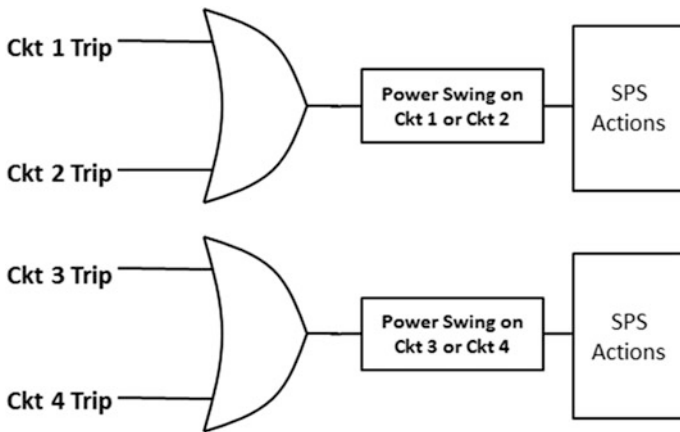


Fig. 16.15 Scheme of SPS implemented at generating station based on detection of power swing and circuit tripping

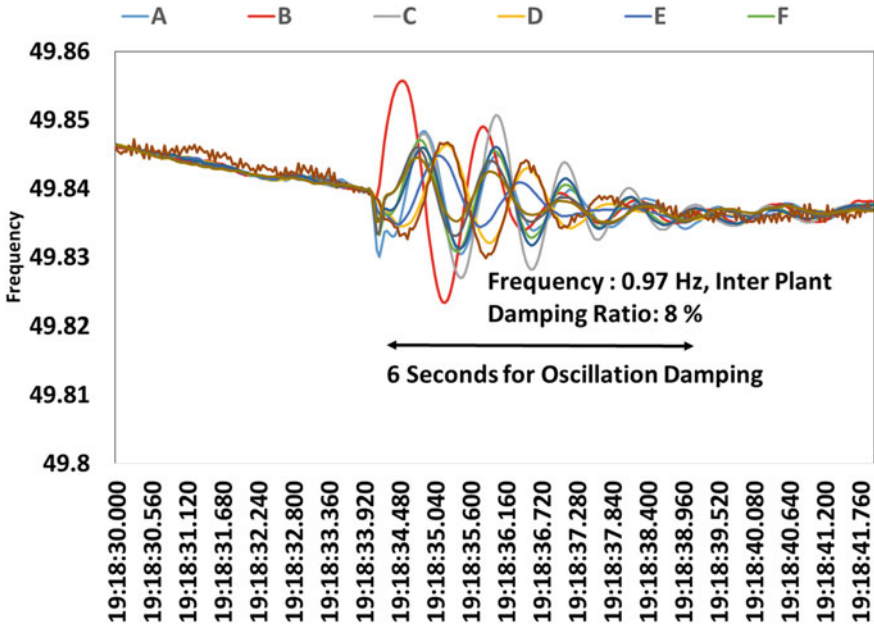


Fig. 16.16 Plot of oscillation observed in frequencies near to substation due to tripping of evacuation line from Bus C and Bus D

Table 16.3 Performance 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	1	0	0	71	88	88	0
Case study II	15	0	0	0	71	100	100	0
Case study III	21	0	3	3	71	100	100	4
Case study IV	3	0	0	0	71	100	100	0

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 is shown in Table 16.3.

16.6 Conclusion

This chapter has illustrated through various case studies how Synchrophasor technology can help system operators in performance evaluation of SPS and provide guidance in improving its design. These have helped in averting major grid

disturbance and economizing the resource utilization along with the benefit of system reliability and security. 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 chapter also showcased how Indian Grid operator has utilized the Synchrophasor measurement 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 a 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 SPSs are also envisaged as a part of Unified Real Time Dynamic State Measurement (URTDSM) [13]. However, several other issues such as reliability of the Synchrophasor measurement under various conditions, dynamic performance of Synchrophasor units, loss of time synchronization, loss of data, latency impact have to be studied in detail. Efforts are in progress to address these issues [14, 15].

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