

Application of PMU Based Information in Improving the Performance of Indian Electricity Grid

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Abstract—SCADA/EMS system has been the most commonly used tool for real time power system operation and control throughout the world. This system has been found to be very useful in steady state analysis of the power system. The ever-increasing dependence of human society and country's economy on electrical energy calls for reliable power delivery. In order to meet these expectations, engineers across the globe have been exploring for new technologies that can improve upon the limitations of SCADA and provide dynamic visibility of the power system. A breakthrough has now been achieved in the form of Synchrophasor technology. Synchrophasor measurements using PMU deployed over wide-area, facilitate dynamic state measurement and visualization of power system which are useful in monitoring safety and security of the grid

The Power System Operation Corporation (POSOCO) has taken up initiative and implemented its first pilot project in NR wherein nine Phasor Measurement Units (PMUs) along with one Phasor Data Concentrator (PDC) were commissioned. The primary objective of this pilot project was to comprehend the Synchrophasor technology and its applications in Power System operation. The data received and information derived from pilot project have been found very useful and helped in improving the performance of the grid operation in several ways. The pilot project is operational since last 2 years. Meanwhile other initiatives have been taken up and pilot/demo projects are being implemented in other regions also by Power System Operation Corporation. This paper detailed out the utilization of data collected from these pilot/demo projects and application of the data towards improvement in operation of the Indian electricity grid.

Keywords- Phasor Measurement Units (PMU), Synchrophasors, Wide Area Monitoring System (WAMS), Oscillations, PSS Tuning.

I. INTRODUCTION

Electricity energy being the most basic raw material for any activity of human being and its ever increasing role in country's economy must be delivered with security and high reliability. Until now, Supervisory Control and Data Acquisition system is very humbly discharging the duty of managing power grid efficiently by providing the static view of the grid to the grid operators. But integration of widely dissimilar generating resources, increases in demand of more power flow on limited transmission resource have resulted in exponential increase in the complicity of the grid operation. At

the same time, industrialization and automation is putting more pressure on secure, reliable and environment friendly delivery of electrical energy. In order to meet these expectations under ever increasing risk, new technologies that can improve upon the limitations of SCADA are being explored. A breakthrough has now been achieved in the form of Synchrophasor technology which has capability to provide time synchronized, dynamic visibility of the power system

Utilities in several countries are experimenting with Synchrophasors and trying to utilize the data that would assist the System Operators in real-time as well as post dispatch. The Power System Corporation has implemented a pilot project wherein nine PMUs have been deployed for acquiring phasor data from widely dispersed locations in Northern India.. In the project, time synchronized data is telemetered at high speed from phasor measurement units (PMUs) at high speed through Optic Fiber communication and at Phasor data concentrator located at northern Region Load Despatch Center (NRLDC). The objective of the pilot project was to gain a first-hand experience of synchrophasors based Wide Area Measurement Systems (WAMS) before its large scale deployment in India. Since the commissioning of this project, POSOCO is utilizing the information acquired from synchrophasors data in improvement of grid performance in several ways. Some of these are as mentioned below:-

- Enhancing situational awareness in real-time.
- Setting of df/dt relays.
- Forensic analysis of faults/Disturbance analysis / determining the exact instant of fault and fault clearing time.
- Detection and analysis of oscillations in the power system.
- Angular separation value observed through the PMU also helps in validating the network model in the SCADA as well as offline simulation packages.
- Validation and determining the need of Special Protection Schemes

It has been found that that synchrophasors can dramatically improve the performance of grid operation and monitoring in several ways. Several other initiatives have also been taken up by POSOCO in the form of pilot projects in other regions i.e

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Western Region, Southern Region, Eastern Region and Southern Region. All the pilot projects will finally be integrated in National Level pilot project under implementation as extension of NR pilot project. By the end of December 2012, a National Level pilot project will be available with about 53 PMUs located all over of India. This paper deals with experiences and improvements carried out to Indian power grid from the real time as well as historical data obtained from synchrophasors pilot projects. The paper elaborates upon the details of the pilot project implemented in Northern Region and also includes the case studies detailing the applications of the information obtained from the pilot project.

II. PILOT PROJECT IN NORTHERN REGION

The NR project comprised of Phasor Measurement Unit (PMU) along with GPS clock at strategically selected nine substations in the Northern Region. Phasor Data Concentrator (PDC) and other associated equipment have been installed at Northern Regional Load Despatch Center (NRLDC), New Delhi [1].

The primary objective of the WAMS pilot project in Northern Region (NR) was to comprehend the WAMS technology and its applications for Power System Operation. Further, it was also understood that the PMU commissioned at a substation could be relocated very quickly in case the earlier selection of location was not found appropriate. Therefore, a heuristic approach was adopted for faster implementation. Since, the number of PMUs were small in comparison to the total number of buses in Northern Region, PMU locations were selected strategically rather than optimally. **Figure-1** shows the locations existing Phasor Measurement Units in Northern Region. The broad criteria used for selection of PMU locations in Northern Region are:

- Locations separated by large geographical distance.
- Locations with large load angle separation.
- Locations near large Generating Stations / Critical Nodes.
- Locations having fiber optic communication link with the control center
- Locations important from point of view of operation and prospective power system augmentation.

In order to implement the project in minimum possible time, initially only 4 PMUs and one data concentrator were installed in May 2010. Facility of data storage along with easy data exchange with other system was also provided, in order to analyze the data in commercially off the self (COTS) available software like Microsoft Excel, Matlab etc. After gaining the experience and realizing the significance of phasor measurement, subsequently, five more PMUs were added to the project in Jan 2011. The phasor LAN of the project was also integrated with the existing SCADA LAN to transfer real

time phasor data to SCADA visualization for displaying the load angle values between various points of the Northern Grid.

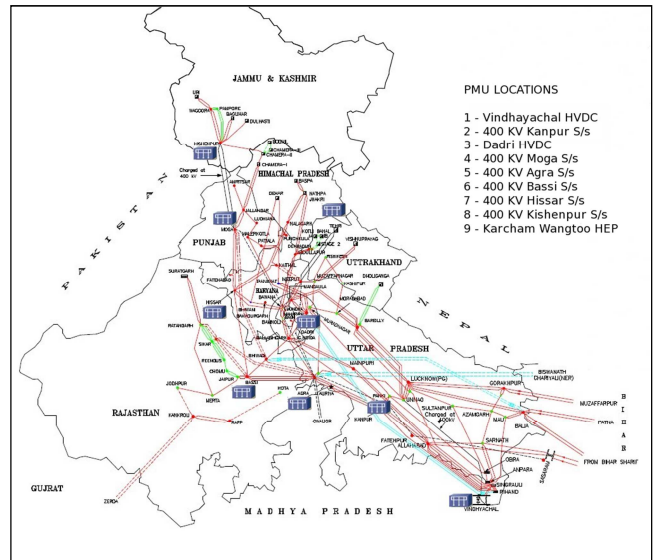


Figure 1

As on date Fourteen (14) PMUs have been installed under different pilot projects out of which nine are installed in Northern Region, two in Western region and three in Southern region. The three Phasor Data Concentrators (PDC) have also been installed at the respective Regional Load Despatch Centers (RLDCs) located in New Delhi, Mumbai and Bengaluru. Placement of PMUs/PDCs at few more locations in India has been envisaged under the pilot projects taken up by the RLDCs. The existing WAMS in Western and Southern Region are demonstration projects, while in the Northern Region it is was a pilot project. **Figure-2** shows the locations existing Phasor Measurement Units in India.

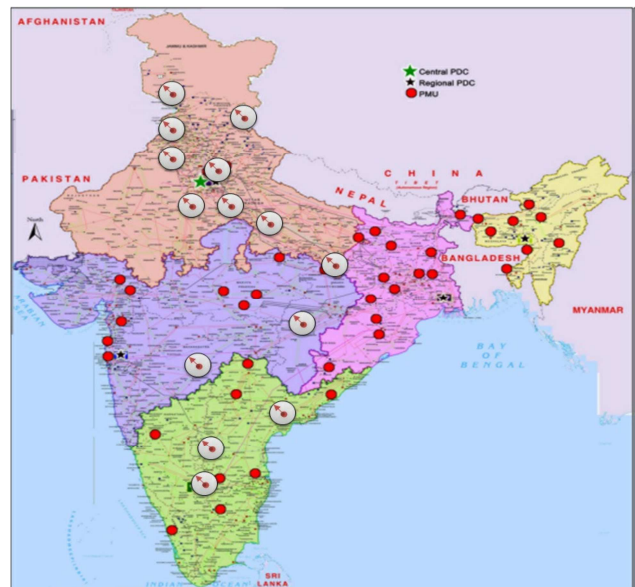


Figure 2

III. SYNCHROPHASORS APPLICATION WORLDWIDE

Worldwide many utilities from North America, Europe, China, Russia and Brazil have started using/developing the new PMU applications to harness the potential benefits of this emerging technology in operating very large electrical grids. In 2006, China's Wide Area Monitoring Systems (WAMS) for its six (6) grids had 300 PMUs installed mainly at 500kV and 330kV substations and power plants. Presently China has installed more than 1000 PMUs in their Grid. By 2012, China plans to have PMUs at all 500kV substations and all power plants of 300MW and above. In U.S there are ten(10) synchrophasor projects underway involving 57 utilities and grid operators across the country and installing about 850 networked PMUs. By 2013, the devices will be operating in nearly all regions of the country. The Eastern Interconnect Phasor Project (EIPP) (now known as the North American Synchrophasor Initiative, or NASPI www.naspi.org/), has over 40 connected phasor measurement units collecting data into a "Super Phasor Data Concentrator" system centered at Tennessee Valley Authority (TVA). Southern California Edison (<http://www.sce.com/PowerandEnvironment>) is successfully using synchrophasors today to trigger some automated grid protection functions on their System. [2]

Oklahoma Gas & Electric Co.(OG&E), USA (<http://www.oge.com>) uses synchrophasor technology as a practical tool to locate and solve real-world operating problems. The utility has added more than 100 PMUs to the system, which provided monitoring almost 30% of its transmission grid. From the synchrophasor data, OG&E can determine if a disturbance is cleared by high-speed or step-distance (delayed) tripping. The data is being used to locate the source of event disturbance and proceed with an investigation. Another valuable use of synchrophasor data is the detection of equipment failure, most of which is not detectable by SCADA system. System stability assessment is being carried out using synchrophasor data especially capturing the intricacies of an interconnected system like low frequency oscillations due to generation control problem or other reasons. The benefit of PMU measurements at the point of wind farm interconnection facilitates customer to receive clean power (in terms of voltage fluctuation/flicker) while maintaining the level of system stability necessary for reliable power system operation. Apart from above nations, other countries like South Africa, Brazil, USSR, Western Electricity Coordinating Council (WECC)(<http://www.wecc.biz>) whose service territory extends from Canada to Mexico and some European countries have deployed/ planning to deploy a large no. of PMUs in their system [3].

IV. APPLICATIONS OF SYNCHROPHASORS DATA

When the first commercial PMUs became available, post-event monitoring was the only application due to the low availability and high cost of communications channels required for real-time monitoring, control, and protection applications [4]. New information and communication technologies enabled synchrophasors to be processed in real

time [5]. Utilities and vendors in several countries are striving hard to utilize phasor measurement data in real time applications from early warning and improving operator's situational awareness to wide area control and protection. Since, pilot project in NR, was implemented with a minimalist approach, no real time applications was acquired with the project. PMU data from the project is being utilized for forensic analysis of faults; post-dispatch analysis of grid performance and; detection and analysis of oscillations in the power system. During the period of last 2 years, several event analysis were carried out successfully with the help of data from the PMU. Information from the project were found useful in taking decisions at various instant of time at the control center by increasing the visualization depth to the grid operators which helped in improving the performance of the Indian electric grid. Rest of the section of this paper will describes some of the such applications of PMU data and information used in different regions. However, an overview of the applications of synchrophasors data used in different regions in real-time and offline have also been summarized.

V. UTILIZATION OF SYNCHROPHASORS IN REAL TIME

The synchrophasor data is currently being used in different regions for the following applications in grid operation:

- i). Improving Situational awareness through real time monitoring of frequency, df/dt , angular separation.
- ii). Occurrence of transmission line tripping/ revival within a flowgate by observing
 - Step change in angular separation.
 - Step change in line current (MW & MVAR)
- iii). Occurrence of generator tripping by observing:
 - Frequency decline
 - Increase in df/dt
 - Change in angular separation
 - Decrease in voltage magnitude
- iv). Occurrence of auto reclosure by change in df/dt .
- v). Occurrence of load crash/ load throw off by observing
 - Sustained High frequency
 - Sustained abnormal phase angle separation
 - Sustained High voltage
- vi). Help in subsystem synchronization during restoration by using standing phase angle separation and phase sequence

VI. UTILISATION OF SYNCHROPHASORS DATA IN OFFLINE

Synchrophasors data is being used in grid operation at various instances of off line applications as listed below:-

- Visualization of power system dynamics with the help of State measurements.
- Visualization of phasors, sequence components, angular separation, inter area oscillations, df/dt , voltage dip during fault, voltage recovery after clearance of fault, synchro-check etc.

- Extensive utilization for post event (forensic) analysis. It helped in detection of type of fault (phases involved), Identification of the phase in which fault has occurred, Fault clearing time Protection mis-operation detection.
- Detection of various modes in low frequency oscillation using techniques like Prony Analysis, Fast Fourier Transform etc.
- Detection of inter area/local mode oscillations
- Validation of operation of under frequency and df/dt relays due to availability of high resolution frequency data at the control center.
- Used in computation of Frequency Response Characteristic
- Delay of 8 cycles was introduced in the df/dt relays in Northern Region to reduce spurious operations.
- Identification of coherent group of generators during grid event
- Observing SVC response during grid events
- Validation of operation time of SPS used for inter tripping generating units at Karchan Wangtoo after tripping of evacuation lines
- Validation of Transfer Capability for evacuation of Karcham Wangtoo generation; Oscillations were visible when the actual power flow crossed the prescribed limits
- Validation of Steady state network model in SCADA/EMS
- Validation of fault level as reported by Disturbance Recorder and as computed from offline studies

VII. CASE STUDIES OF APPLICATIONS OF SYNCHROPHASORS DATA

Synchrophasors data from the pilot projects implemented by POSOCO, have been utilized in several ways like incidence analysis, detection of oscillations, validation of operations of special protection scheme (SPS), fine turning of SPS etc. POSOCO has published a report titled “Synchrophasors Initiative in India” comprising about 38 case studies. The report can be downloaded from the website of NLDC and RLDCs. Important case studies have been analyzed here.

A. Incidence Analysis

First encounter of significance of information from synchrophasors were very exciting and revealing. Initial project was completed in the month of May 2010. In June 2010, a event took place at Rihand Super Thermal Power Station (Rihand STPS) (Stage 1 with 2x500 MW and Stage II with 2x500 MW units) located in the lower right part of the Northern Region. Rihand STPS switchyard has one & half breaker scheme. One of the tie circuit breaker, at Rihand STPS switch yard, went under lockout due to low air pressure in the breaker. While carrying out the switching operation to isolate the locked out breaker, Rihand STPS stage-I units tripped on pole slipping. And after 7 seconds Rihand Stage-II

unit 3 tripped on FD Fan off and Unit-4 tripped on loss of fuel supply.

The event sequence could not be ascertained in NRLDC control room only with SCADA data. However, when data from the pilot project’s historian was analyzed and a very clear analysis of the event could be achieved. It was found that the cause of tripping was occurrence of some fault and not the switching operation and envisaged initially. During this analysis, we could gain the experience of actual visualization of df/dt and oscillations in the power system. During the loss of complete power station a decrease of 10 degree in the angular separation between Vindhyachal and Moga was also observed. The comprehensive plot of the measurements from PMU located in the vicinity of Rihand STPS has been shown in **figure-3** which is self-explanatory.

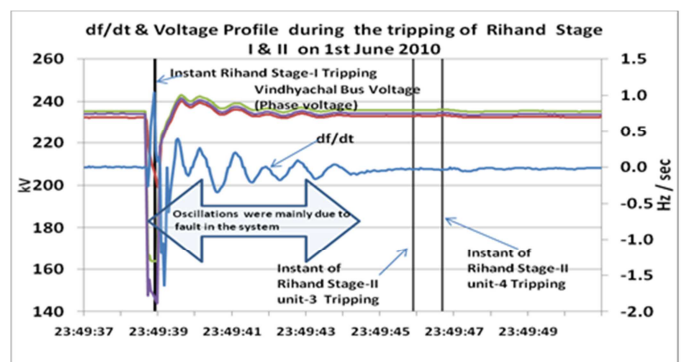


Figure 3

B. Improved Grid Stress Indication

Most significance measurement from a Phasor Measurement Unit is angular separation. The angular separation between two nodes within a synchronous system is primarily a function of the voltage at the two nodes; Impedance between the two nodes and the power flow between the nodes. Therefore the angular separation between the two nodes is sensitive to the variation in one or more of these variables. The difference of the phase angles between any two buses in the power grid gives accurate indication of the grid stress. Higher the value of this angle, higher the stress of the grid. This phenomena has been used in Indian power grid very successfully even much before the implementation of WAMS pilot project. The phase angle difference across different nodes is a measure of static stress across the grid and its proximity to instability and therefore can be monitored with respect to predetermined stability threshold limits. These threshold limits are being put based on the past experiences of the system separation and offline simulations [6].

On 22nd October 2006, Northern Region, Northeastern Region, Bhutan system and parts of Eastern Region separated from rest of the N-E-W (synchronized North, Easy and West grid) grid due to the tripping of a transmission line. Both the systems survived and they were quickly synchronized back. It was observed that the export from Northern Region to rest of the grid continued to increase along with the angular

separation between Vindhyachal North bus and West bus till

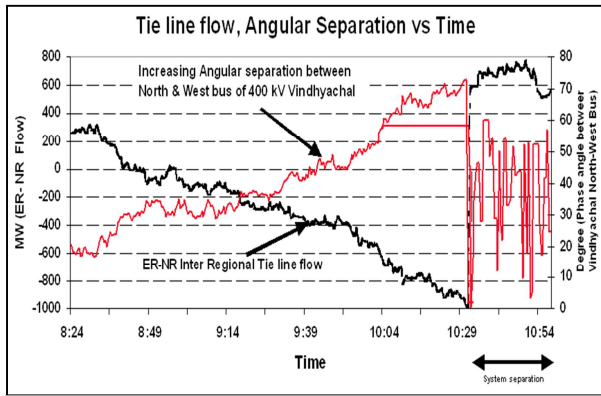


Figure 5

the tripping point was reached [6]. The phase angle measurement was being done by phase angle transducer in installed at Vindhyachal. **Figure-4** depicts the whole incidence. After installation of phasor measurement units the phase angle measurement are now more accurate, more fast and available form more number of locations. This has resulted in improved visualization of grid stress and improved situational awareness to the grid operator.

C. Detection of oscillations and validation of transfer capability

Assessment of transfer capability is required for estimating the permissible quantum of power flow through a flow gate. Over assessment may lead to insecure operation while under assessment may lead to under-utilization of the transmission network or throttling of generation.

Tehri Hydro Electric Power Plant having 1000 MW capacity is located in north of Northern Region. There are four 765 KV transmission lines emanating from this plant for evacuation of power generated. These all four lines are charged at 400 KV presently. Tehri power station has informed the experiences of oscillation in the system. An exercise was carried out to examine the oscillation phenomena and ascertain the loadability of the line. Test was performed by keeping only two out of four lines in service (refer **figure-5**) and generation at Tehri HEP was increased in controlled manner.

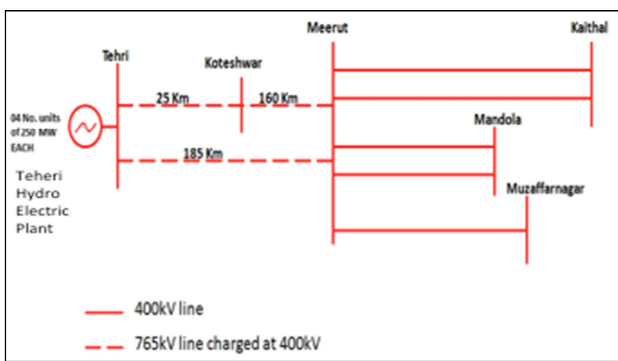


Figure 4

The oscillation were observed in the system as visualized from the plots of frequency from the data collected from PMUs installed under the pilot project as shown in **figure-6**. It was observed that magnitude of oscillations are more at Moga sub station, which is nearest to the Tehri. Hence it was concluded that source of oscillation is Tehri power station. Subsequently, PSS tuning of Tehri power station was carried out and after this no oscillations had been observed again. By this issue of line loadability / transfer capability could be resolved with the help of synchrophasors.

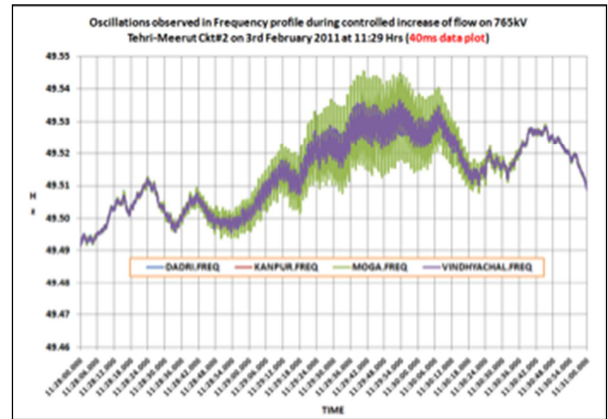


Figure 6

D. Setting of df/dt relays

Rate of change of frequency (df/dt) relays have been provided to arrest the large drop in grid frequency subsequent to a large generation loss. These relays are set to initiate automatic load shedding whenever the frequency declines at a rate higher than 0.1 Hz/second. Until the availability of data from PMUs of pilot project, concept of df/dt was a parameter on paper only. Grid operators in India were not able to visualize it in real time. Moreover, it was never thought that values and of df/dt may be different at different locations especially in case of disturbance. Relays operated by the df/dt signals are being used in India for islanding operation in case of fast ramp down of grid frequency in order to save certain important area of grid. Placement criteria of df/dt relays was being done based on the premises that df/dt is same at all places in case of disturbance. But visualizations of df/dt trends during disturbances (as shown in **figure-7**) caused the demise of this premise. Now, placement of df/dt is also considering the different values at different locations.

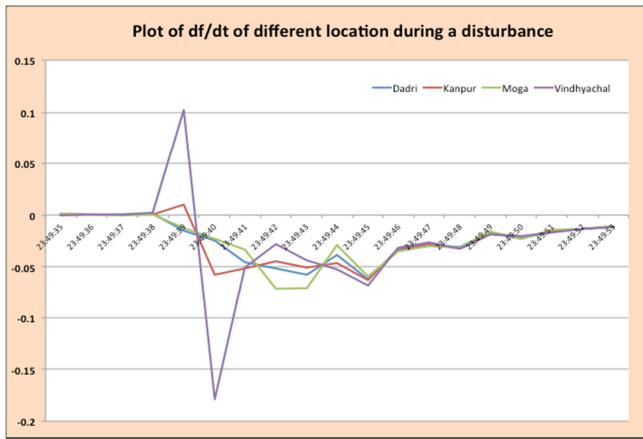


Figure 7

On several occasions it was also found that the relays had operated even when no generation loss had occurred. The df/dt data recorded by synchrophasor during various grid incidents was examined. It was observed that df/dt during the initial 40 ms was significantly high in comparison to the df/dt recorded after 100 ms. The problem was discussed with experts. It was learnt that the measurement of df/dt during the transient condition (within the first few milliseconds of the fault) may be erroneous due to the inherent algorithm used for computation and is not dependable. Subsequently some delay was provided in df/dt relay in order to prevent falls tripping.

E. Validation and determining the need of Special Protection

A hydroelectric power station Karcham Wangtoo has been constructed by a IPP in the north of Northern India having capacity of 500 MW (2x250 MW). Two dedicated transmission circuit were planned from this power station to nearby pooling station at Abdullapur (figure-8).

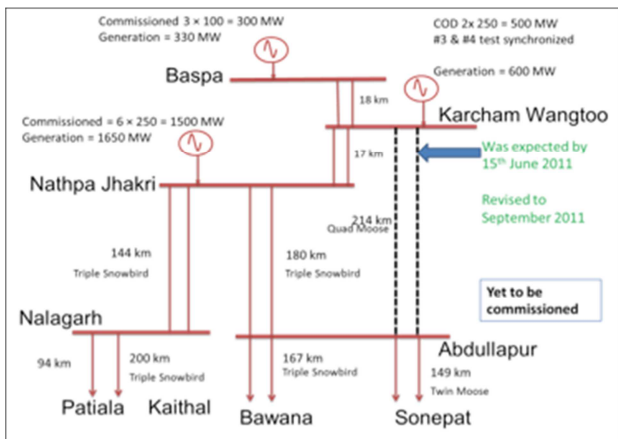


Figure 8

Due to some reason the commissioning of these lines got delayed but plant was ready to generate in its full capacity. In order to save the loss of generation, studies were carried for exploring the possibilities of evacuation of the generation through transmission lines through nearby power station Naptha Jhakri. Since, evacuation of more generation without

security of grid during any n-1 contingency may lead to cascading of tripping; a special protection scheme was implemented. SPS should trip the machines at Karcham Wangtoo in case of outage of any of the evacuation link and line loading of any of the remaining lines increases more than 800 MW load. However, during the operation of SPS at the incidence, system wide oscillations were observed from the plot of PMU data. On investigation, it was found that there was an unintentional delay of about 10 seconds in the tripping of unit through the operation of SPS as shown in figure-9. The delay was unknowing introduced, and it was removed later on. After this oscillations were not observed again.

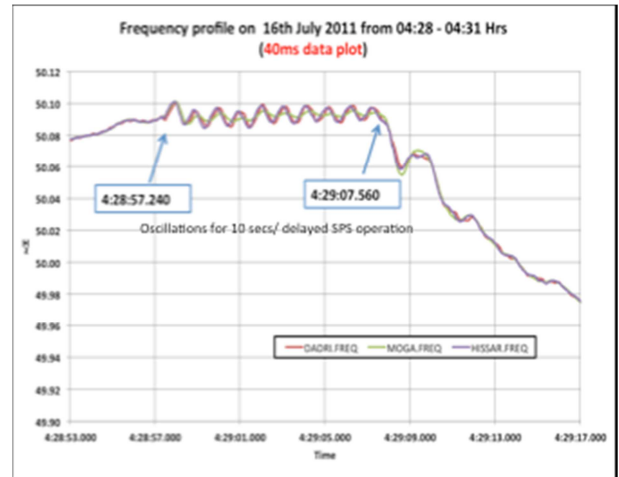


Figure 9

F. Validation of Auto-reclosure of EHV line

Single phase auto reclosure has been provided in 400 kV lines for transient faults. The operation of single phase auto-reclosure gets recorded in the Disturbance Recorder and Event log in the transmission substations. At the Regional/State Load Despatch Centre the Auto reclosure operation is recorded in the Sequence of Events available through the SCADA system. The synchrophasors data available at every 40 ms has enabled visualization and validations of the auto reclosure operation in the Load Despatch Centre. At many incidences it was found that opening and closing time of circuit breaker recorded in SOE received from SCADA system is matching with PMU data.

VIII. CONCLUSION

The synchrophasor technology has brought about a paradigm shift from state estimation to state measurement. The experience with synchrophasor pilot projects in India has been enriching and highly rewarding. Though the application of synchrophasor data is still in a nascent stage in India, it has facilitated building an understanding of the technology. It has been established that synchrophasors can dramatically improve the visualization available at the control centers. Huge volume of synchrophasor data is being received and stored at the control center. It is difficult to comprehend the

data due to limited availability of real time and offline applications. Hence there are immense possibilities and scope for further work on real time applications, customized real time and offline displays for better visualization of power system, integration of PMU data with SCADA/EMS system. Wide area applications for improving the stability in the grid by initiating action through System Protection could be explored. The wealth of information available in the historian needs to be analyzed thoroughly for drawing valid inferences for the Indian grids. Challenges in regard to storage of huge volume of PMU data have also been faced; this also requires developing mechanism to store these data. Currently limited analysis has been done only with the help of Micro Soft Excel. There is a need to use signal processing techniques available in specialized software tools such as Matlab.

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