

Operational Experience of the First Synchrophasor Pilot Project in Northern India

V. K. Agrawal*, P.K. Agrawal, R. K. Porwal, R. Kumar, Vivek Pandey
T. Muthukumar, Suruchi Jain
Power System Operation Corporation
*vkagrwal@ieee.org

Abstract

The Synchrophasor technology is considered as a major breakthrough in providing a time synchronized, dynamic visibility of the power system. In India, a pilot project has been taken up wherein Phasor Measurement Units have been commissioned at four locations and the phasor data has been made available at one of the Regional control centres through the high speed Optic Fibre communication. The objective of the pilot project was to gain a quick first-hand experience of synchrophasor based Wide Area Measurement Systems (WAMS) before its large scale deployment in India. This paper shares the experience gained during the first few months after the commissioning of the project.

1. Introduction

Increasing dependence of human society on electrical energy is associated with a desire for reliability of the highest order in power system. In this regard information on phase angle difference between two nodes has always been sought after by Power System Operators.

Phase angle measurement is commonly used in auto synchronization of generating stations and check synchronization relays used at substations for closing of lines as well as during three-phase auto-reclosing. All these applications are at the local level. At control centre level this analogue value is normally not considered as measurable in SCADA system and hence does not form a part of the database. However SCADA technology does provides an estimate of the relative phase angle difference (with respect to a reference bus) through the State Estimator. The State estimator uses the SCADA inputs (analogue and digital measurands) to estimate the system state viz. node voltage and angle.

Information about phase angle difference between two different nodes in a power system has also been calculated based on the real time power flow between the nodes, bus voltages and network reactance using standard equation $\delta = \sin^{-1} (P^*X/V_1^*V_2)$.

Another way in which the information on phase angle separation between strategic locations has been obtained is with the help of voltage or phase angle transducers

installed at strategic location and then having it telemetered through conventional SCADA system. [1]

However all the above methods of calculation of phase angle difference have limitations due to resolution, data latency, updation time and data skewedness. Update time in the SCADA system is considerably large for visualizing and controlling the dynamics of power system.

2. PMU pilot project in NR, India

A pilot project on WAMS has been taken up in India. The project comprised of installation of Phasor Measurement Unit (PMU) along with GPS clock at selected four 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 [2].

3. Selection of locations for installation of PMUs

Generally PMU placement can be done using several different criteria including security concerns, observability and improvement in state estimation [3]. Interfacing the PMU data with the existing EMS system is a highly involved task and requires modification in the State Estimation algorithm. However the primary objective of the WAMS pilot project in Northern Region (NR) was to comprehend the synchrophasor 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. The broad procedure for selection of PMU locations in Northern Region is described below:

(a) Locations separated by large geographical distance

Northern Region is spread across a vast geographical area having huge diversity in the nature of terrain, population density and land usage. A huge power system network comprising of generators and loads spread across the region. During system operation it is essential to gather a wider footprint of the grid from a very macro

level and therefore it was decided to place the PMUs at 400 kV substations in the grid.

(b) Locations with large phase angle separation

Nodes in the grid having large phase angle separation are generally considered vulnerable during system transients. In Northern Region there have been incidents where the grid was separated into subsystems. A steady state offline power flow simulation was therefore carried out for high hydro and low hydro conditions (two typical scenarios). The phase angle for each 400 kV node in the grid was tabulated considering 400 kV Dadri as the reference bus. A cluster of nodes having electrical proximity were formed. Each of these clusters had around 10 nodes.

(c) Locations near big generating stations / critical nodes

In Northern region major pit head stations are located in the South east part of Uttar Pradesh and the major hydro stations are located in North west areas of Uttarakhand, Himachal Pradesh and Jammu Kashmir. The load centres are in and around the National Capital Region. As a result Northern Region has huge network comprising of long EHV transmission lines. In order to observe the dynamic behaviour of the power system it was considered desirable to place PMUs at locations whose phasors can be considered as representative of that area. The representative nodes in the clusters identified in previous step were further shortlisted.

(d) Locations having broad band communication link with the control centre

Implementation time and cost in the WAMS project is generally dependent on the number of locations and the communication network between the PMU location and the control centre. Choosing PMU locations that did not have high speed communication network would have increased the overall costs and implementation time of the pilot project. Therefore the prospective nodes shortlisted in step (a), (b) and (c) above were further narrowed down by selecting the nodes having readily available Fibre Optic connectivity with the regional control centre.

(e) Locations considered important from point of view of operation and prospective power system augmentation

The nodes identified in the previous steps were further checked for their perceived importance for real-time operation in the present and in near future. Thus the past experience in real-time and the expected transmission augmentation in near future were also considered while finalizing the PMU locations.

4. Installation of PMUs

The locations that were finalized for installation of PMUs were 400kV North bus of HVDC Vindhyachal back-to-back, 400/220 kV Kanpur, 400kV bus of HVDC Dadri and 400/220 kV Moga. All these stations are vital from the grid operation perspective and they have connectivity with NRLDC through Optic fibre.

Vindhyachal HVDC back-to-back station is located near major pithead thermal generation complex comprising of Singrauli (2000 MW), Rihand (2000 MW), Anpara (1630 MW) and Obra (1300 MW) in the northern region. Vindhyachal back-to-back station is also close to the HVDC Rihand terminal of +500kV Rihand-Dadri Bipole. It also provides asynchronous interconnection with Western Regional power system and is geographically close to major pit head stations such as Vindhychal STPS (3260 MW), Korba STPS(2600 MW) and Sipat STPS(2320 MW) located in Western Region (WR). In the near future a 765 kV synchronous link interconnecting Vindhyachal in WR and Rihand in NR is also expected. Further the power order on Vindhyachal back-to-back is also varied in real time for security purposes.

400/220 kV Kanpur substation has connectivity with generation complex at one end and major load centre in National Capital Region of Delhi at the other end. It is also in the route of import of power from Eastern Region Thus it is a major transmission pooling station.

HVDC Dadri station is the inverter terminal of the ± 500 kV Rihand Dadri HVDC Bipole. Its position is very critical as it has close proximity to major load-centre and power stations of Dadri, Badarpur, Ropar, Bhatinda, Panipat, Khedar and Yamunanagar in the Northern Region. Dadri is also a part of the 400 kV ring around the national capital of Delhi and it is also close to the Bhiwadi terminal of the ± 500 kV HVDC Balia-Bhiwadi. In future ± 800 kV HVDC Vishwanath Chariyali-Agra would be commissioned and Dadri is near the Agra HVDC terminal as well as the 400 kV Agra substation which would be energised at 765 kV.

400/220 kV Moga is considered as the pooling station for the present and future hydro generating stations located in the Himalayan belt. In future Moga substation would be upgraded to 765 kV level and would thus get connected to the 765 kV UHV grid. Moga is also electrically adjacent to the Bhiwadi terminal of ± 500 kV HVDC Balia-Bhiwadi bipole.

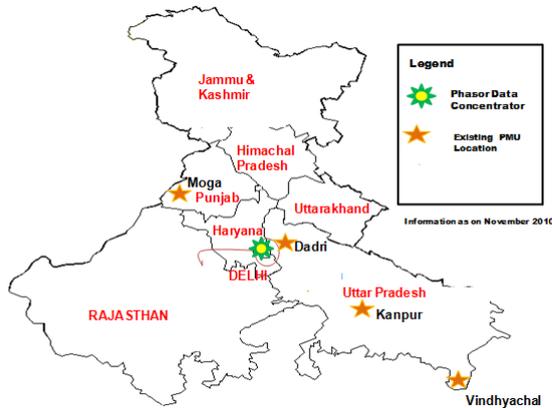


Figure 1: Location of PMU, PDC in India

5. Inputs to PMU and Synchrophasor data available at the control centre

The inputs that have been given to the PMU at the chosen substations are three phase voltage of one of the buses and three phase currents of one of the feeders at the chosen substations. Voltage inputs (V_r , V_y , V_b , V_n) have been provided from CVT/PT of one of the main buses of the substation while the line currents (I_r , I_y , I_b ,) have been given from the line CT.

Thus the 3-phase voltage of one of the buses of 400 kV Vindhya (north bus), 400 kV Kanpur, 400 kV Dadri and 400 kV Moga have been given as input to the PMU at the respective location. Likewise 3-phase currents given as input to the PMU at the respective location are 400 kV Vindhya Singrauli-I line current (to PMU at 400 kV Vindhya), 400 kV Kanpur-Ballabgarh-I line current (to PMU at 400 kV Kanpur), current in Interconnector between 400 kV Dadri_NTPC-HVDC Dadri (to PMU at 400 kV Dadri) and 400 kV Moga-Bhiwadi-I line current (to PMU at 400 kV Moga) .

The PMU takes time reference from the GPS clock installed at each of the PMU location and measures the voltage phasors, current phasors, frequency and rate of change of frequency for each location. The Phasor Data Concentrator (PDC) and associated equipments installed at NRLDC align the data sent by PMUs and display it on the operator console. The data available at the control centre are as under:

- GPS time
- Time synchronized voltage phasors i.e. magnitude and angle of each of the three phases from four locations (400 kV Vindhya (north bus), 400 kV Kanpur, 400 kV Dadri and 400 kV Moga)
- Time synchronized frequency from four locations
- Time synchronized rate of change of frequency from four locations

- Time synchronized current phasors i.e. magnitude and angle of line current of four lines- 400 kV Vindhya-Singrauli-I, 400 kV Kanpur-Ballabgarh-I, 400 kV Moga-Bhiwadi-I and Interconnector between 400 kV Dadri_NTPC-HVDC Dadri (at 400 kV Dadri)
- Time synchronized power flow (MW and MVar) of the four lines

All the above data is also archived and is available for retrieval through a historian. Data from historian is available to external database and spread sheet through ODBC (Open Database Connectivity) spreadsheet for further analysis. The Phasor Data Concentrator (PDC) has also been provided with OPC (Object Linking and Editing for Process Control) server in order to transfer real time phasor data to existing SCADA system. The data & data streaming of PMUs and PDCs follow IEEE C37.188 standard. [4, 5]

The data from historian is useful for post event analysis. The present set up has a capability for storing data from 20 PMUs up to one year. Thus the operator can see the archived data from the four PMUs for five years. Memory space is expandable with the help additional data cards.

6. Displays available at the operator console for visualization

The time aligned data from PDC is provided to operator console for visualization. Displays are configurable through the display editor. Few customized displays have been prepared for the operators. Displays are presently of two types- dial display and trend display.

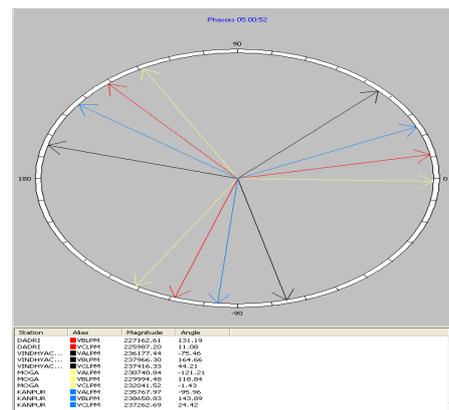


Figure 2: Voltage phasors from four locations

Dial display has been used to visualize the absolute and relative voltage phasors from the four locations. Trend displays (time series) have been used for absolute frequency, MW, MVar, relative frequency between the

four locations, $d\delta/dt$ (slip frequency) and df/dt . The synchrophasor data is available at every 40 milli seconds interval.

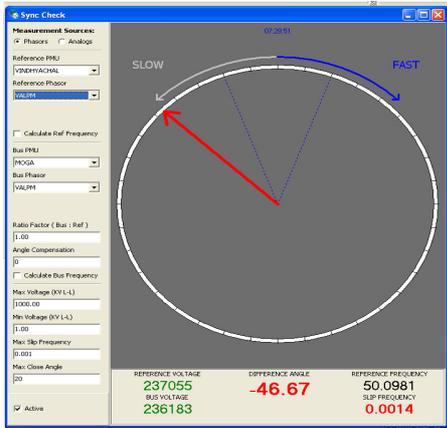


Figure 3: Display for phase angle difference

The voltage phasors from Vindhyachal, Kanpur Dadri and Moga can be seen simultaneously as in Figure 2. Due to deviation in frequency from the nominal value of 50 Hz, the phasors seen in the dial display does not remain stationary and they either move in the clock wise direction or anti clockwise direction, depending on the frequency. The speed of rotation depends on the deviation from the nominal frequency. The phase angle separation between any two chosen locations can also be monitored in the display shown at Figure 3.

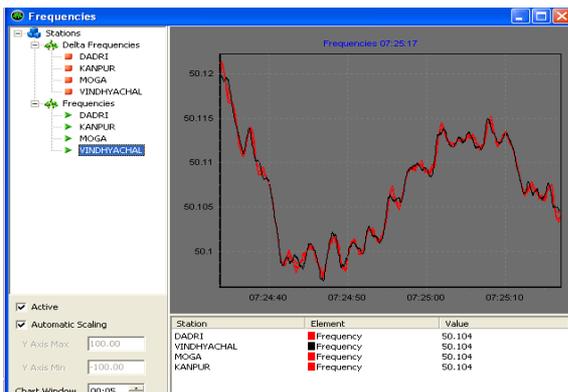


Figure 4: Display for absolute frequency

Figure 4 shows a very precise trend of the system frequency in the real time. In Figure 5 one can see the frequency difference between the four locations.

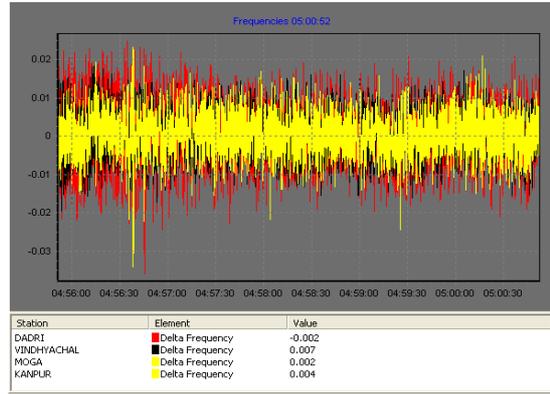


Figure 5: Display for frequency difference

7. Experience on the synchrophasor data

The data from synchrophasor is a huge leap from the data from SCADA system. Accurate measurements of voltage and current phasors for four locations in the grid is now available with a resolution of 40 ms. The precise relative phase angle separation can also be seen. Apart from these, additional information such as frequency and power flow is also available. Even the limited exposure with synchrophasor data has been a revelation in terms of its potential for future applications. The data is being examined closely for drawing inferences. Few of inferences have been shared in the paragraphs ahead.

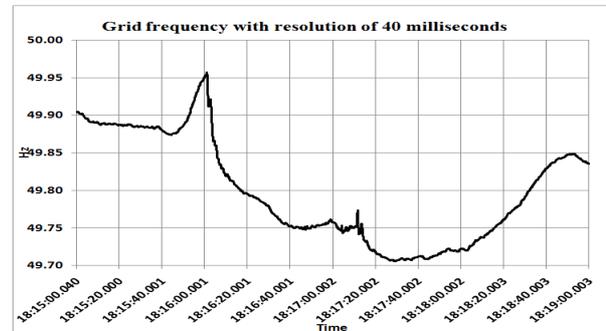


Figure 6: Typical Frequency plot

It has been found that even within the synchronous system there could be difference in frequency (few hundred microseconds) at various locations. This difference is pronounced during system transients such as tripping of generating units.

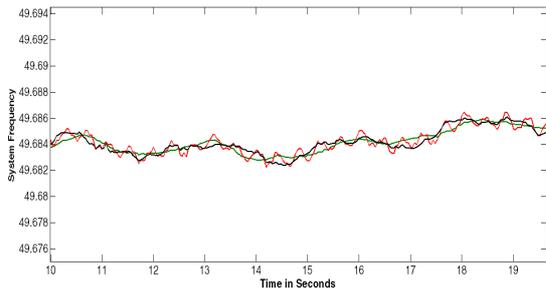


Figure 7: Frequency observed at different locations

The sags and swells in voltage [5] which were not observable in SCADA are now observable through Synchrophasor data. Likewise the imbalance in voltage and current between different phases can be clearly seen Figure 8 and 9.

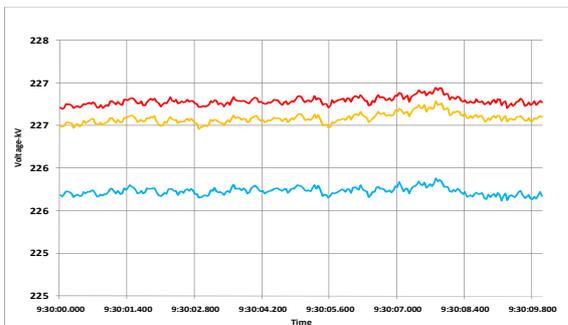


Figure 8: Imbalance in phase voltage

During grid events the operators are able to see the fault current, voltage, protection system response time, fault clearance time etc. The overall experience with synchrophasor data has been summarised in the form of a case study.

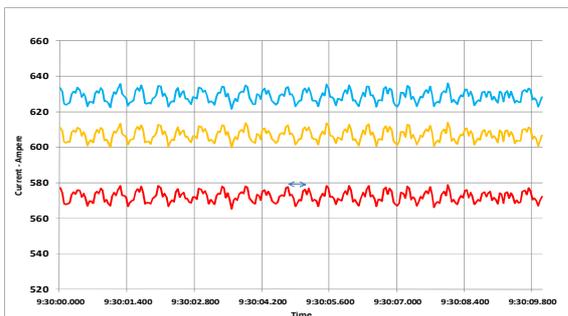


Figure 9: Imbalance in phase currents

8. Case Study

The data has been analysed for grid incidents like multiple element tripping, load through off and loss of generation. The case study discusses the loss of 2000

MW of generation at Rihand on 1st June 2010 as seen through Synchrophasor data.

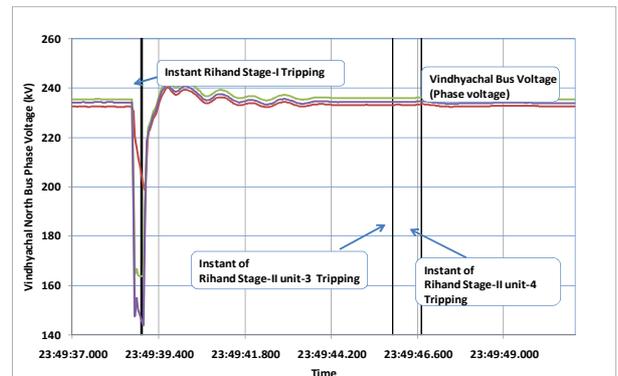


Figure 10: 400 kV Vindhyachal phase voltages during the incident

Rihand STPS stage I & II (4 X 500 MW) is a major pit head generating station near Vindhyachal in the South east part of the northern region. An incident of tripping of all the four units at Rihand Thermal Power Station occurred on 01st June 2010. Rihand stage-I units 1 & 2 tripped at 23:49:38:933hrs & 23:49:38:945 hrs respectively on pole slip caused due to fault in the system and then after a gap of 7 seconds Rihand stage-II units 3 & 4 tripped at 23:49:45:934 hrs & 23:49:46:727 hrs respectively on auxiliary supply failure. The phase voltage, the frequency as well as rate of change of frequency as captured by PMUs at 400 kV Vindhyachal, 400 kV Dadri and 400 kV Moga during the tripping can be seen in figures 10, 11, 12, 13, 14 & 15.

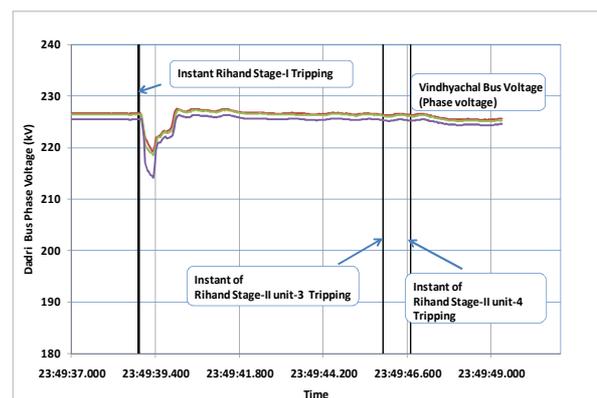


Figure 11: 400 kV Dadri voltage

From the frequency plots [Fig 13] it is clear that after the loss of 2000 MW generation the frequency observed at different locations oscillated differently for about 1 seconds before settling down to a common frequency. The amplitude of fluctuations in the frequency were maximum

near the fault location and it decreased as the distance from the fault location increased. Information about coherent group of generators can also be inferred from this frequency plot.

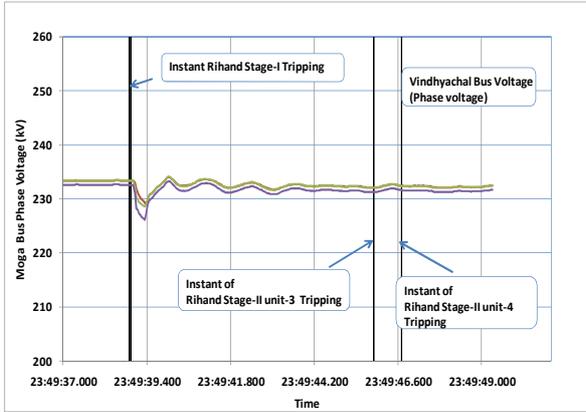


Figure 12: 400 kV Moga voltage

Similar to the absolute frequency, rate of change in frequency was maximum near the fault location and as the distance from the fault location increases the amplitude of df/dt reduces and can be seen in Figure 14. This plot also indicates that the initial df/dt is of the order of + 1 Hz / - 1.5 Hz, This needs to be explored further.

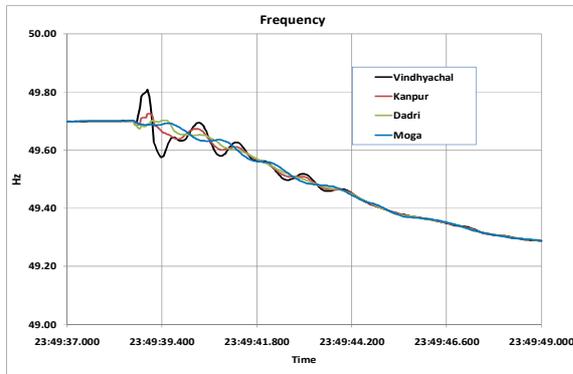


Figure 13: Absolute frequency

Analysis of several other grid incidents indicate that such high value of df/dt is observed during unbalanced faults. It is also observed that such high value of df/dt disappears after 100 to 120 milliseconds. Such a high value of df/dt may result into load shedding through df/dt relays during fault condition which may not be desirable.

In view of this, in the Protection Sub-committee of Northern Region Power Committee (NRPC), New Delhi a decision has been taken to introduce at least 8 to 10 cycle measurement time to avoid unnecessary load shedding by df/dt relays due to initial high value of df/dt . [7]. Further

the information on df/dt was used to determine the system inertia constant and it was found to be 6.4 seconds.

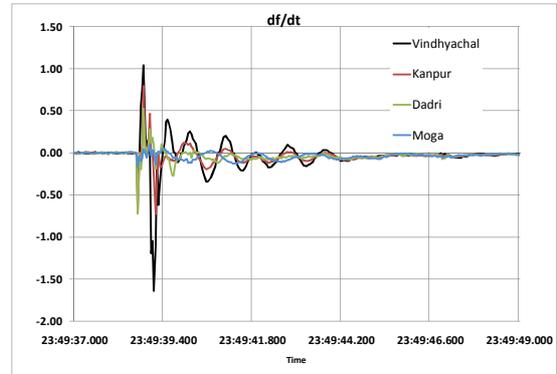


Figure 14: Rate of change of frequency

The plot of angular separation observed during the above incident is shown in figure 15. It can be observed that the amplitude of change in the angular separation between different locations was highest in case of 400 kV Vindhychal and 400 kV Kanpur and lowest in case of 400 kV Dadri and 400 kV Moga.

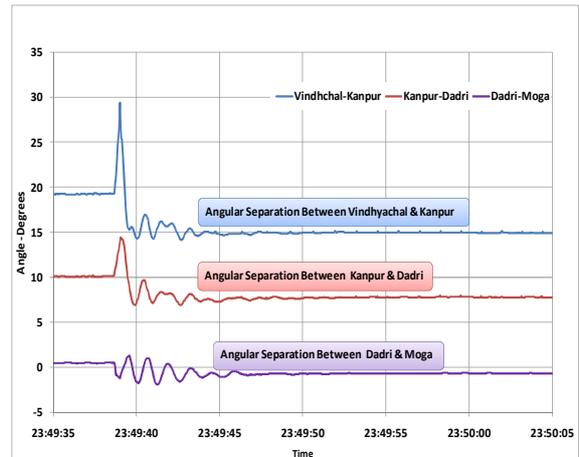


Figure 15: Angular separation between few locations during the incident

9. Conclusions and scope for further work

The Synchrophasor measurement is a new technology, and the commissioning and operation of pilot project in N.R has been an excellent learning experience for everyone. It has been established that synchrophasors can dramatically improve the visualization available at the control centres. The Synchrophasor data has been initialized in grid event analysis. It had helped in further understanding of the system behaviour during system transients. However there are immense possibilities and scope for further work [3, 5, 8].

Better displays for visualization of synchrophasor data need to be developed. For instance, data could be superimposed over the existing geographical power maps [8]. The synchrophasor display is presently visualized through a standalone system. Perhaps it would be better if it could be integrated within the available operator consoles [8]. 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 analysed thoroughly for drawing valid inferences for the Indian grids. There is a need to use signal processing techniques available in specialized software tools such as Matlab extensively. Analysis could also be done to compute the various power quality indices for the Indian power system.

10. References

- [1] Soonee S. K, et al, 'Application of phase angle measurement for real time security monitoring of Indian Electric Power System- An Experience', CIGRE, 2008
- [2] Agrawal V. K., et al, 'Smart Power Grid initiatives at Super Grid level in India', All India Seminar on Smart Grids, Hyderabad, 15th and 16th July 2009
- [3] Jun Zhu, Ali Abur, Mark J Rice, G. T. Heydt, Sakis Meliopoulos Enhanced State Estimators Final Project Report by, PSERC Publication, Nov 2006
- [4] IEEE Standard for Synchrophasors for Power System. **IEEE Std C37.118** – 2005
- [5] Phadke Arun and Thrope J.S., 'Synchronized Phasor Measurements and Their Application', Springer,2008
- [6] Ewald F. Fuchs, Mohammad A. S. Masoum, 'Power quality in Power System and Electrical Machines', Academic Press, 2008
- [7] Minutes of 12th Protection Sub-Committee of Northern Region Power Committee meeting dated 15-1-2010
- [8] CIGRE Working Group C4.601, 'Wide Area Monitoring and Control for Transmission Capability Enhancement', Technical Brochure-330, 2007

11. Acknowledgement

The authors acknowledge the support and encouragement given by the management of Power grid Corporation of India and Power System Operation Corporation. The authors also acknowledge the valuable contribution of colleagues and engineers for conducting black start exercises and providing inputs for documenting. Special thanks to Sh S.K. Soonee, CEO, POSOCO for his guidance on the subject of synchrophasor technology.

12. Disclaimer

The views expressed in the paper are the opinion of the authors and may or may not be that of the organization to which they belong.

Main Author

V. K. Agrawal
General Manager
Northern Regional Load Despatch Centre- POSOCO
18-A, Qutub Institutional Area,
New Delhi-110 016, INDIA

Coauthors

P. K. Agarwal: pkagarwal@ieee.org
R. K. Porwal: rajivporwal@ieee.org
Rajesh Kumar: kumar.rajesh@ieee.org
Vivek Pandey: vivek.pandey@nrlcd.org
Muthu Kumar: t_muthukumar80@yahoo.co.in
Suruchi Jain: suru.jain@gmail.com.