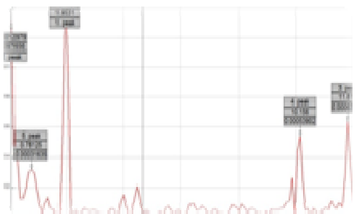
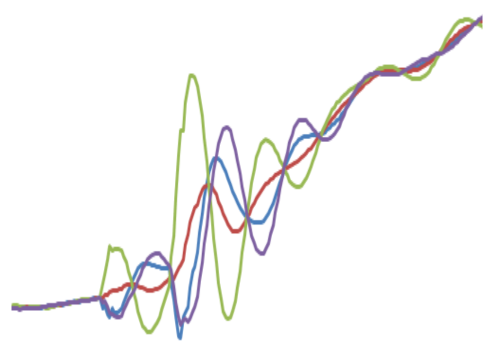
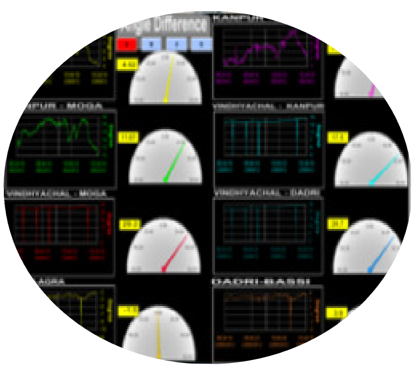
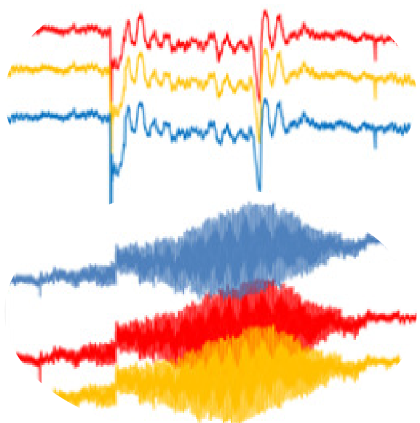
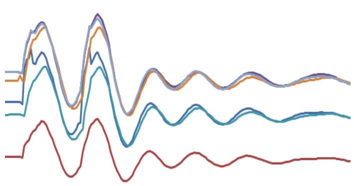
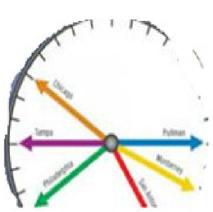
SYNCHROPHASORS
INITIATIVE IN INDIA

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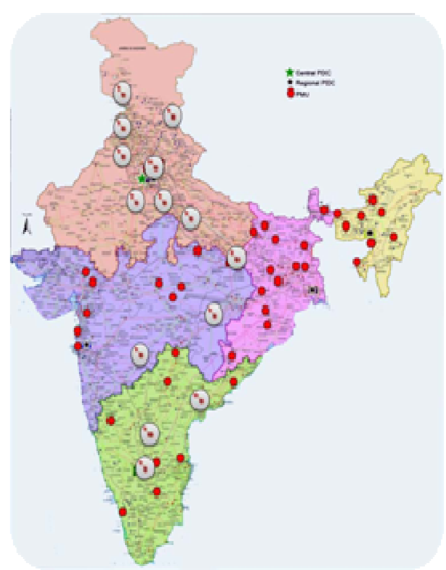

POWER SYSTEM OPERATION CORPORATION LIMITED
(A wholly owned subsidiary of Power Grid Corporation of India Limited)

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EXECUTIVE SUMMARY

The power system operation in India is being coordinated by the State, Regional and National Load Despatch Centres (SLDCs/ RLDCs/ NLDC). The Electricity Act 2003 mandates that the Load Despatch Centres shall exercise supervision and control over the transmission system and ensure integrated operation of the power system within their jurisdiction. They are expected to maintain vigil against threats and vulnerabilities in the system and take preventive measures to avoid failures. In the event of failures, it is desired that the system is restored to its normal state quickly.

The challenges in power system operation in India are increasing manifold day by day as a result of enlarged system size; brisk pace of capacity addition; long distance power flows; multiple players; increasing competition in the electricity market; emphasis on pan India optimization; climate change; large scale integration of renewable energy sources in certain pockets; and increasing customer expectations. The ability of the system operators to take decisions in real-time is dependent on their 'situational awareness' derived from the data/information available with them in real-time.

Conventionally the analog & digital information related to the power system, such as circuit breaker status, frequency, voltage and power flow (MW/MVAr) measured at the substation level is presented in the Load Despatch Centre through the Supervisory Control and Data Acquisition/Energy Management System (SCADA/EMS). In India, there is a hierarchical architecture through which the information is routed and updated (every 10 seconds) at the respective Load Despatch Centre.

Angular separation between coherent groups of generators within a synchronous grid is representative of the grid stress. The angular separation between adjacent nodes may be available at the substation synchronizing trolley during synchronizing the tie lines. However, the measurement of angular separation and its telemetry at the control centre level in SCADA/EMS has limitations. Therefore, the load angle is either 'estimated' from the available SCADA data or the angular separation between a pair of substations is derived offline with the help of power flow on the line, impedance of the line and respective terminal voltages. Both these methods have their limitations due to data latency, skewdness and inaccuracies inherent in SCADA/EMS.

The synchrophasor technology along with the high speed wideband communication infrastructure from substation to control centre has now overcome the above limitation. These schemes based on synchrophasor technology are also known as Wide Area Measurement System (WAMS). With the help of WAMS it is now possible to monitor the phase angles at the control centre. In addition this technology enables visualization of magnitude and angle of each phase of the three phase voltage/current, frequency, rate of change of frequency and angular separation at every few millisecond interval (say 40 milliseconds) in the Load Despatch Centre. Thus the transient / dynamic behavior of the power system can be observed in near real-time at the control centre which hitherto was possible only in offline mode in the form of substation Disturbance Records or through offline dynamic simulations performed on network models.

The Phasor Measurement Unit (PMU) is the basic building block of Wide Area Measurement System (WAMS). The PMU measures the system state viz. voltage and angle of a particular location at a rate of multiple samples per second (say 25 samples per second). This data is time stamped through a common reference and transmitted to the Phasor Data Concentrator (PDC) installed at a nodal point, through high speed wideband communication medium (such as Optical Fibre). The PDC aligns the time synchronized data and presents it to the User/Historian. The Historian archives the data for retrieval and post-dispatch analysis of any grid.

World over the synchrophasor technology is increasingly being used for supplementing the conventional SCADA / EMS for providing a wide area visibility and enhancing situational awareness at the control centre. In India, pilot/ demo projects have been taken up or envisaged in all the five regions. This report enumerates the features available in the synchrophasor pilot/demo projects taken up in India since May 2010. It provides a compilation of case studies describing various real-time and offline application of the synchrophasors data. The report highlights the major challenges encountered in the tenure of the past two years. The report concludes with the proposed suggestions, future scope and probable roadmap for further exploitation of synchrophasors technology in India.

Overview of the synchrophasor initiative in India

In India, fourteen (14) Phasor Measurement Units (PMUs) have been commissioned as on 31st May 2012. In the Northern Region, the PMUs have been placed at nine 400 kV substations viz. Vindhyachal (HVDC back-to-back station), Kanpur (with SVC), Dadri (HVDC inverter terminal), Moga, Kishenpur, Agra, Bassi, Hisar and Karcham Wangtoo. In Western Region PMUs have been placed at two 400 kV substations viz. Raipur and Bhadravati. In Southern Region, they have been placed at three 400 kV substations viz. Salem, Hyderabad and Bengaluru. The three Phasor Data Concentrators (PDC) have been installed at the respective Regional Load Despatch Centres (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 WAMS in Western and Southern Region are demonstration projects, while in the Northern Region the expenditure under the pilot project was approved by the Honourable Central Electricity Regulatory Commission (CERC) and funded from the Unscheduled Interchange Pool Account.

Application of synchrophasor data available through the pilot project

Though the synchrophasors data is presently available only from a few locations in the Indian grid, yet it has dramatically raised visualization and the level of understanding of the power system at the control centres within few months of its commissioning. It has enhanced situational awareness in real-time. In the offline mode the synchrophasors data is being utilized for forensic analysis of faults; post-dispatch analysis of grid performance and; detection and analysis of oscillations in the power system. An overview of the application of synchrophasors data in real-time and offline is presented in the table below:

Table 1: Application of Synchrophasors in India

Time frame	Application	Description	Case Study No.
Real-time	Enhancing situational awareness	Visualization of - Magnitude, angle of all three voltage/current phasor - Sequence components of voltage/current phasor - Frequency & Frequency difference - Rate of change of frequency - Angular separation between pair of nodes - 1-phase auto reclosing in EHV transmission line	Case Study-1 to 5
Off-line	Forensic analysis of faults/grid incidents	Detection of - Grid events within / other region - Type of fault viz. LG, LL, LLG, LLL, LLLG - Nature of fault (Dead short circuit or high resistance) - Time of the fault and sequence of events - Fault clearance time, probable location of fault - Summary of element on fault or otherwise - Voltage recovery post fault clearance - Possible protection operation / misoperation - 1-phase auto reclosing in EHV transmission line	Case Study-6 to 19
	Post-dispatch analysis of grid operation	Validation of - Steady state network model - Transfer Capability declaration - Simulated short circuit current - Substation disturbance record - Substation event log - Performance / utility of System Protection Scheme - Measurement cycle used in df/dt relay	Case Study-20 to 29
		Computation of - System inertia constant (H) using df/dt - Frequency Response Characteristics (in MW/Hz)	Case Study-38 to 39
	Detection and analysis of oscillations in the power system	Detection of - Time, duration, amplitude, frequency of oscillations - Type of oscillation viz. inter area or local - Nature of oscillations viz. damped or un-damped - Modes present, their amplitude and damping factor - Coherent group of generators	Case Study-30 to 37

Challenges faced

The journey with synchrophasors has been a roller-coaster ride full of exhilaration and excitement. The pilot project has revealed several challenges that need to be addressed during subsequent initiatives. The areas where major challenges were faced are stated below:

- Philosophy for placement of PMUs – strategic vis-a-vis optimal
- Validation of the accuracy/quality of synchrophasor data
- Adequacy of communication infrastructure
- Customization of real-time and offline displays
- Intelligent alarms for alerting the operator against grid events in real-time
- Real time tools to further enhance the situational awareness in control centre
- Innovative tools to tag grid events to the synchrophasor data
- Seamless integration of synchrophasor data in SCADA/EMS displays
- Data retention/storage policy for Indian conditions (Trigger based or 100%storage)
- Data retrieval from the historian
- Analytical tools for performing in depth post dispatch analysis
- Interaction between utility, academia and application developers

Suggestions and scope for future work

Few suggestions with regard to scope for future work are listed below:

- Ramp up all activities related to synchrophasor initiative
    - Integrate regional pilot projects at the national level
    - Identify possible solutions to suitably address the challenges faced
    - Formulate policy for retention and storage of synchrophasor data
    - Ensure compliance to relevant standards
    - Deploy Common Information Model
    - Establish Quality of Service (QoS) norms for Indian conditions
    - Develop tailor made displays and customized applications for real-time and offline to facilitate comprehension of high speed, voluminous data
    - Determine thresholds and operating limits from historical data
    - Develop intelligent alarms to alert the operators in real-time

- Explore application of synchrophasor data in
  - Adaptive protection and control
  - Dynamic model validation
  - Tuning of Power System Stabilisers (PSS)
  - Real time dynamic stability analysis
  - Enhanced state estimation
  - Transmission planning and generation siting
  - Calibration of instrument transformers
- Capacity building for improving comprehension/interpretation of synchrophasors
  - Create a library of grid incidents and events characterized in phasor data
  - Establish a policy / mechanism for sharing synchrophasor data
  - Institutional mechanism for collaboration between industry and academia

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. The gestation and payback period of investment in synchrophasors very small compared to the benefits. It is desirable that adequate PMUs are installed to capture the information from each and every bay in an EHV substation. The possibility of installing PMUs at the LV side of generators and FACTS devices may be explored because it might facilitate monitoring the performance of generating units and FACTS controllers under system dynamics. In fact PMUs could become a part of the total substation package.

The population of Phasor Measurement Units is likely to grow. Considering the technological future innovations it would be important to take care of issues related to scalability and interoperability. Customized applications of synchrophasors in the operation and well as planning domain need to be quickly developed. Based on the historical information of load angles, the operational limits in respect of line loadability and angular separation of 30 degree between adjacent substations as specified in transmission planning criteria could be reviewed. All-India load angle contour could be used as an input for planning transmission line between two areas or siting a generating station. In the operational time domain, there is a need for developing customized applications to realize the potential of the technology particularly in view of its utility for large scale integration of renewable energy sources and reliable operation of the large synchronous pan India/SAARC grid.

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ACKNOWLEDGEMENTS

The motivation, encouragement and support provided by Ministry of Power, Government of India, in deployment of synchrophasors technology in India are gratefully acknowledged.

POSOCO is indebted to the Central Electricity Regulatory Commission for its pioneering role in recognizing the need for synchrophasors and being considerate in approving and providing funds for the synchrophasor pilot project in India.

The technical assistance and guidance provided by the Central Electricity Authority and Power Grid Corporation of India Limited, particularly during finalization of the technical specifications of the synchrophasor pilot project, are duly acknowledged. POSOCO is also thankful to the management and operating personnel of the all the concerned grid sub-stations in the different regions for providing necessary support during the commissioning of PMUs at their substations. Wide band communication plays a very important role in making any synchrophasor project operational and availability of communication channels at the desired nodes was one of the deciding factors for PMU placement in India. With the concerted support of the Regional Transmission Groups and Telecommunication department of POWERGRID, the communication channels between some of the critical nodes could be arranged and these are also duly acknowledged.

Cooperation and support extended by all the esteemed members of the Regional Power Committees and other stakeholders is also gratefully acknowledged.

POSOCO would like to thank researchers, scientists, engineers and institutions working on Synchrophasors/Smart Grid across the globe. The technical literature developed by them provided a solid foundation for the initiatives taken in India. Special thanks to Prof. Arun Phadke (Virginia Tech University), Dr. Ken Martin (EPG), Mr. Mahendra Patel (PJM), Prof. Anjan Bose (Washington State University), Prof Venkatasubramanian (Washington State University), Dr N. D. R. Sarma (ERCOT, Texas), Prof A.M. Kulkarni (IIT-Bombay), Prof S. Soman (IIT-Bombay), Prof S.C. Srivastav (IIT-Kanpur), and Dr. Nilanjan Senroy (IIT-Delhi) for sharing their knowledge and experience during various interactions with power system operators.

The herculean efforts put in by all the persons/engineers, vendors and application developers involved in conceptualizing, commissioning, designing applications and utilizing the synchrophasor technology as well as in documenting the experience in different phases is acknowledged.

This report is a culmination of collective efforts and contribution of a large number of engineers within POSOCO / POWERGRID. The valuable contribution by each and every one of them is highly appreciated and acknowledged.

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CHAPTER 1: INTRODUCTION

1.1 System Operation through load angle

Maintaining angular separation between coherent groups of generators within the acceptable limits is a fundamental need for maintaining system stability in a synchronous interconnection under various system conditions. The power flow (MW / MVAr) on any transmission line / or inter connecting transformers can be also be derived if the time synchronized voltage phasors of the two ends are known (along with the line impedance). During synchronization of energized AC systems, it is crucial to match “the voltage magnitude”, “the frequency”, and “the phase angle difference” to prevent equipment damage or grid disturbance in the process. Thus load angle is an important variable in power system operation.

In the conventional SCADA / EMS system, the voltage magnitude, frequency, MW, MVAr and the circuit breaker status are available at the control centre through direct measurements (using transducers) while the load angle of the buses are estimated (by the State Estimator). Alternatively, the angular separation between adjacent nodes could be derived from the power flow on the line connecting them, impedance of the line and the voltage magnitude at the two ends. These angular separations could be algebraically added up along the path to obtain the angular separation between any coherent groups of generators/ pair of nodes.

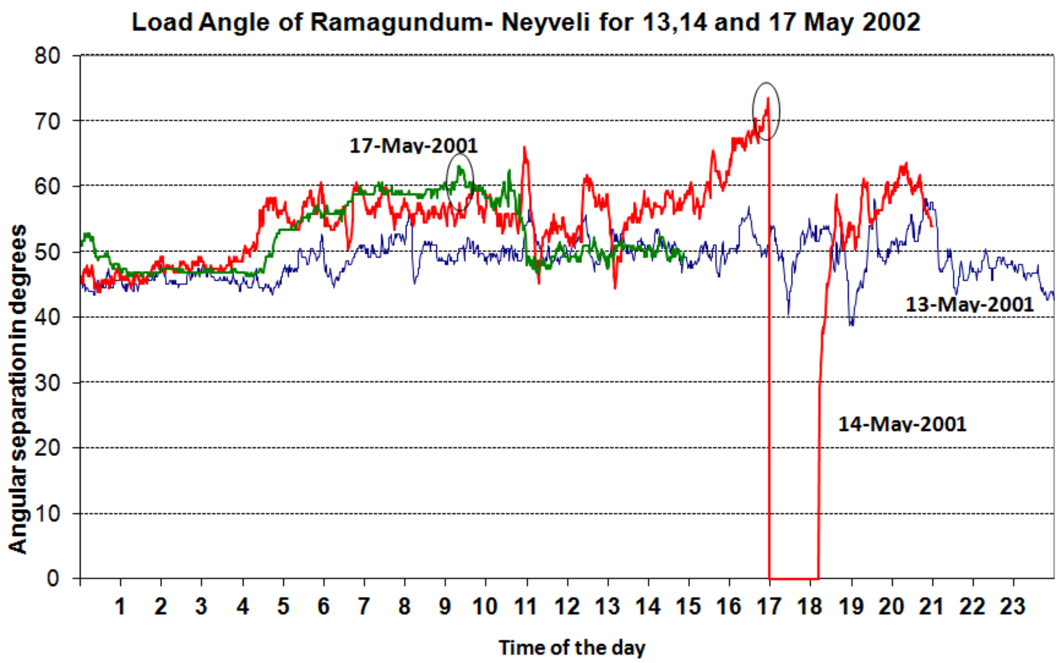


Figure 1: Load angle between Ramagundam and Neyvelli for 13, 14 and 17 May 2002

In the Southern Regional power system, analysis of several grid disturbances [Reference 1] that occurred in 2002 revealed that that the disturbance had occurred whenever the angular separation between 400 kV Ramagundam (generation complex) and 400 kV Neyveli (load centre) generally exceeded 60 degrees (Refer figure: 1).

Likewise in the Northern Region, the experience of several incidents of separation of the Eastern (pit head generation pocket) and Western part (load centre) of the Northern Region revealed that the angular separation between 400 kV Rihand (in South eastern part) and 400 kV Dadri (in the Western part) and the power flow across the East-West transmission corridor was required to be maintained within 40 degrees and 3500 MW respectively (Refer figure 2).

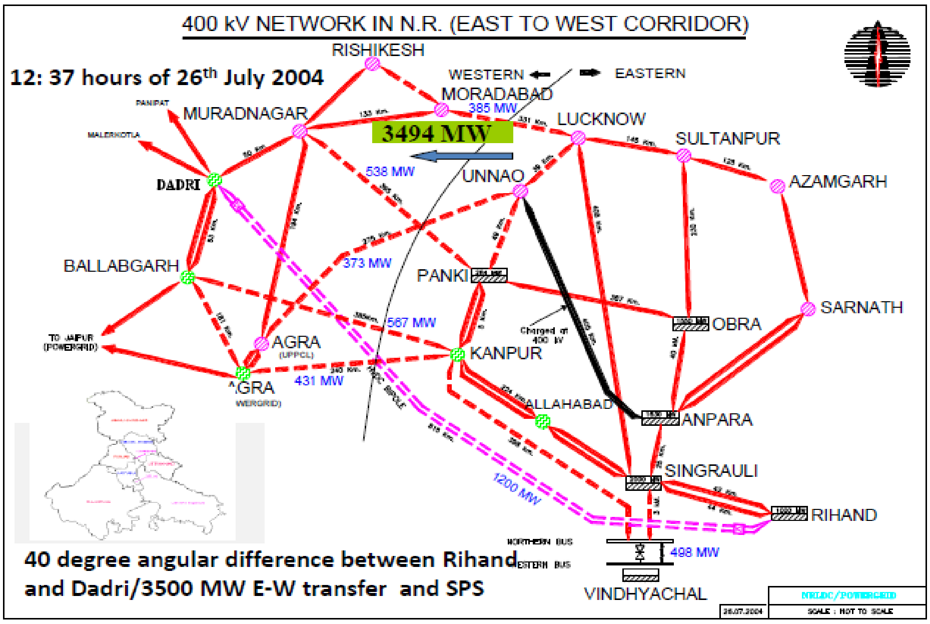


Figure 2: Angular separation between Rihand and Dadri on 26-July-2004

The above two experiences established that the angular separation between different nodes in the grid is an indicator of the stress in the grid and the need for monitoring it in real-time was felt. However, since the direct measurement of phase angles was not available through SCADA, the angular separation across the HVDC Rihand-Dadri bipole was computed externally and made available to the operator (refer figure 3).

Thereafter, an experiment with telemetry of measured phase angle separation between the adjacent 400 kV buses of an HVDC Vindhyachal back to back station within the synchronous system was carried out in 2007. Initially a voltage transducer was placed at HVDC Vindhyachal back-to-back station and the 400 kV R-phase voltage of the Vindhyachal North bus and Vindhyachal West bus was given as input. The vector difference of the two voltages was telemetered (through existing SCADA) at the Northern Regional Load Despatch Centre and the angular separation was locally computed using the cosine formula. Subsequently the phase angle separation between the two buses was measured using phase angle transducer (+/- 60 degrees) and telemetered (through the existing SCADA). The above angular separation was plotted and began to be monitored in real-time.

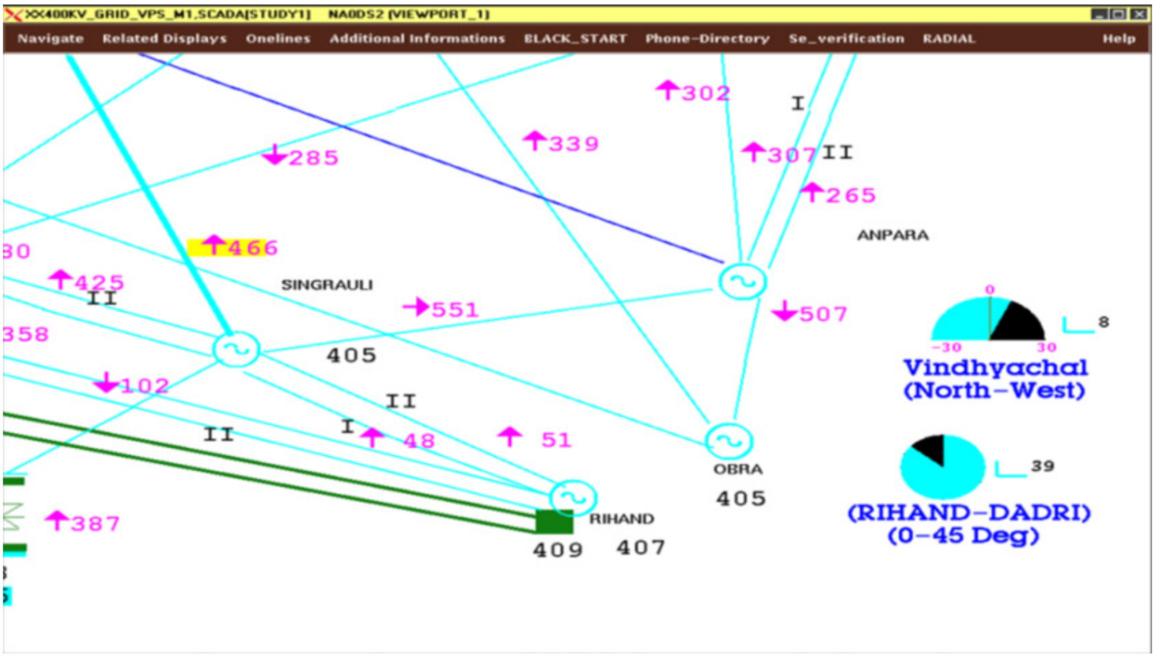


Figure 3: Monitoring of angular separation between Rihand and Dadri

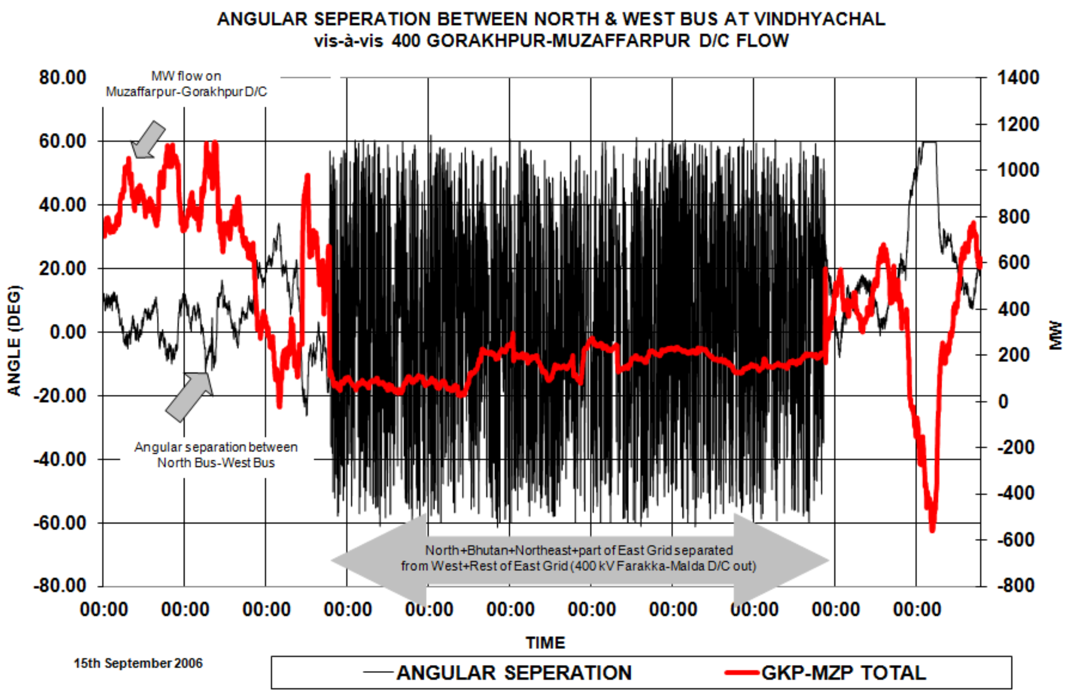


Figure 4: Detection of islanding in a synchronous grid (15-Sep-2006)

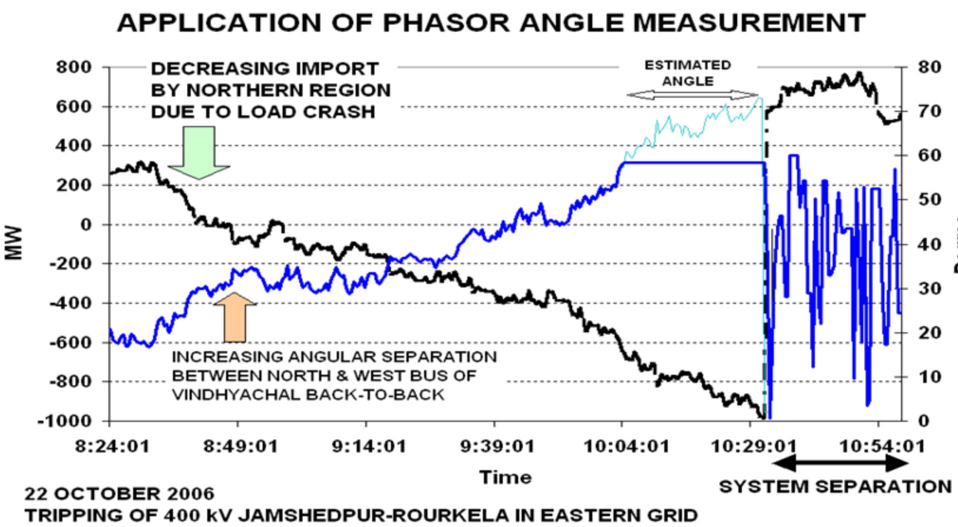


Figure 5: Detection of exceptional operating condition (22-Oct-2006)

Analysis revealed that the plot of the angular separation could be used for detecting major grid events within the same region or in neighboring regions; detecting islands and tagging exceptional grid operating conditions such as load crash. It was evident that the angular separation could provide valuable insights into the health of the synchronous interconnection [Reference-2].

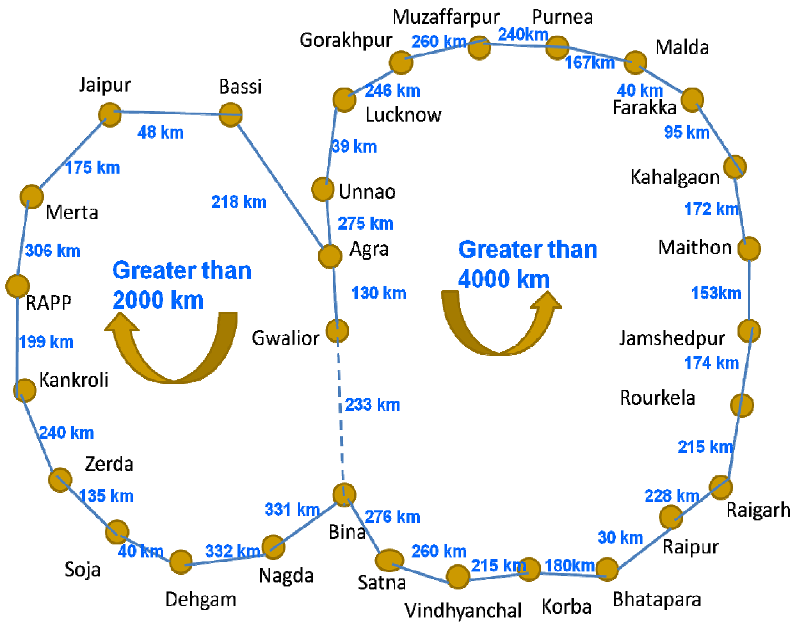


Figure 6: Diversion of power after tripping of 400 kV Bina-Gwalior (28-Nov-2009)

Open Access in inter State Transmission System was introduced in India in May 2004 by Central Electricity Regulatory Commission (CERC). The transmission licensees and National/Regional/State Load Despatch Centres were mandated to facilitate trade by determining the operational margins in the existing transmission system in line with the Electricity Act 2003 and subsequent National Electricity Policy and Tariff Policy by the Government of India. Therefore, RLDCs/NLDC started assessing and declaring the inter regional import/export transfer capability for facilitating Open Access as well as managing system security. On 28th November, 2009, at 13:26 Hrs tripping of a major transmission line in the Western Region (400 kV Bina-Gwalior S/C) carrying around 1000 MW resulted in cascade tripping of few other inter regional tie lines between the Western and Northern Region (Refer figure 6). The power was diverted on the remaining tie lines causing heavy line loadings and sharp dip in system voltages across the grid. The system could however survive on account of well meshed transmission network, support from generators and quick operator action. Offline simulation of the event revealed that the angular difference between Vindhyachal West and North bus swung from 37^{O} to 83^{O}. This event again emphasized the importance of real-time monitoring of phase angles in large grids [Reference-3].

Fundamentally, the state of power system can be determined if one has the voltage and angle of every bus in the interconnected power system. These measurements are carried out and used in check synchronization relays at substation level. However, the visibility of phase angle measurements at control centre was constrained due to limitations in communication and SCADA/EMS technology. Besides, there are other issues in utility of phase angle data from SCADA/EMS. The State Estimator runs periodically or on change of circuit breaker status. In a rapidly growing power system the SE results are often inaccurate and unreliable due to limited network observability and bad data.

Recent breakthrough in synchrophasor technology has overcome the limitations with respect to state measurement and its telemetry at the control centre. Synchrophasors are precise measurements of the state of the system available from Phasor Measurement Units (PMUs). Each measurement is time-stamped according to a common time reference. Time stamping allows measurements from PMUs to be time-aligned (or “synchronized”) and combined together providing a signature of the power system. It has been established that synchrophasors enable a better indication of grid stress, and may be used to trigger corrective actions to maintain reliability. Deployment of the synchrophasor technology for real time and offline applications is being studied worldwide. Thus based on experience in different regions derived from monitoring angular separations and considering the possibilities in synchrophasor technology, exploratory studies in the form of pilot project were carried out in India. These studies have yielded encouraging results and have ushered the transition from “state estimation” to “state measurements” in Indian power system.

1.2 Objectives of the Report

The synchrophasor technology at inter-state level was first introduced in India in 2010-11 through a pilot project in Northern Region. Subsequently PMUs have also been placed in some selected stations in Southern and Western Region. The PMUs installed in different regions are presently being utilized for certain real time and post dispatch applications.

A task force was formed by POSOCO for compilation of the experience with synchrophasors. The task force comprised of members from Regional/National Load Despatch Centre namely Shri Vivek Pandey, (NRLDC), Shri S.K. Saha, (WRLDC), Shri. T. Muthukumar (NRLDC), Shri Nripen Mishra (NLDC) and Shri Abdullah Siddiqui (SRLDC). The office order regarding formation of the task force is attached as Annex I.

This report of the task force attempts to compile the experience of the pilot/demo/complementary projects undertaken in Northern, Western and Southern Regional power system in India. This report covers the following aspects:

- Enumerate the features available in the present projects installed in different regions
- Identify the applications available and used in real time as well as offline analysis
- Itemize the case studies for each application
- Recommend further analytics that would be required
- Suggest a roadmap for the future

CHAPTER 2: OVERVIEW

2.1 Project Details

The first pilot project on Wide Area Measurement System at inter-state level in India was taken up in Northern Region. It was envisaged to install 26 Phasor Measurement Units and two Phasor Data Concentrators in three stages.

Table 2: Project details

S No.	Description	Details pertaining to		
		Northern Region	Western Region	Southern Region
1	Project Type	Pilot	Demo	Demo
2	Funded from	UI Pool surplus	Demo	Demo
3	Consultant / Partner	POWERGRID LD&C	M/S Infosys Ltd.	M/S Kalkitech , National Instrument
4	Number of Substations (PMU locations)	Phase-I: 4 Phase-II: 4 + 1	Demo Phase I: 2	3
5	Number of PMUs installed	9 Phase-I: 4 Phase-II: 4+1	Demo Phase I: 2	3
6	PMU Location	Vindhyachal, Kanpur, Moga, Hisar, Dadri, Bassi, Agra, Kishenpur, Karcham Wangtoo	Raipur, Bhadrawati	Salem, Hyderabad Somanahalli
7	Number of PDCs	Phase-I: 1 Phase-II: 0	Demo Phase I: 1	1
8	Location of PDC	Phase-I&II: NRLDC-Delhi	WRLDC- Mumbai	SRLDC-Bengaluru

After completion of the first two phases of the project total eight PMUs and one PDC has been installed and are functional. In the Western Region two PMUs and one PDC has been installed while in the Southern Region three PMUs and one PDC has been installed as a demo. The pilot project in NR was approved by the Central Electricity Regulatory and funded from the surplus fund available in the Unscheduled Interchange pool account while the installations in Western and Southern Region are demonstration projects. The other details of the project taken up in the three regions have been summarized in Table 2.

2.2 Location of Phasor Measurement Units

The primary objective of the pilot/demo projects 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 is described below:

i. Locations separated by large geographical distance
ii. Locations with large phase angle separation estimated from steady state load flow studies for different anticipated scenario
iii. Locations near large generation complex
iv. Locations having broadband communication link with NRLDC (location of the PDC)
v. Locations perceived to be critical based on operator experience

In the phase-I of the pilot project taken up in Northern Region, the PMUs were placed at four locations viz. 400 kV side of Vindhyachal HVDC back to back station; 400 kV Dadri; 400 kV Kanpur and 400 kV Moga substations. The PDC was placed at the Northern Regional Load Despatch Centre (NRLDC). In the phase-II the PMUs were placed at 400 kV Hisar, 400 kV Bassi, 400 kV Agra and 400 kV Kishenpur. Later an additional PMU was installed at the 400 kV Karcham Wangtoo HEP by Jaiprakash Power Ventures Ltd.

In the Western Region, the PMUs are located in 400 kV Bhadravati and 400 kV Raipur substations.

In the Southern Region the three PMUs are located in 400 kV Salem, 400 kV Bengaluru and 400 kV Hyderabad.

The geographical position may be referred in figure 7, 8 9, and the general architecture of the installation is shown as figure 10.

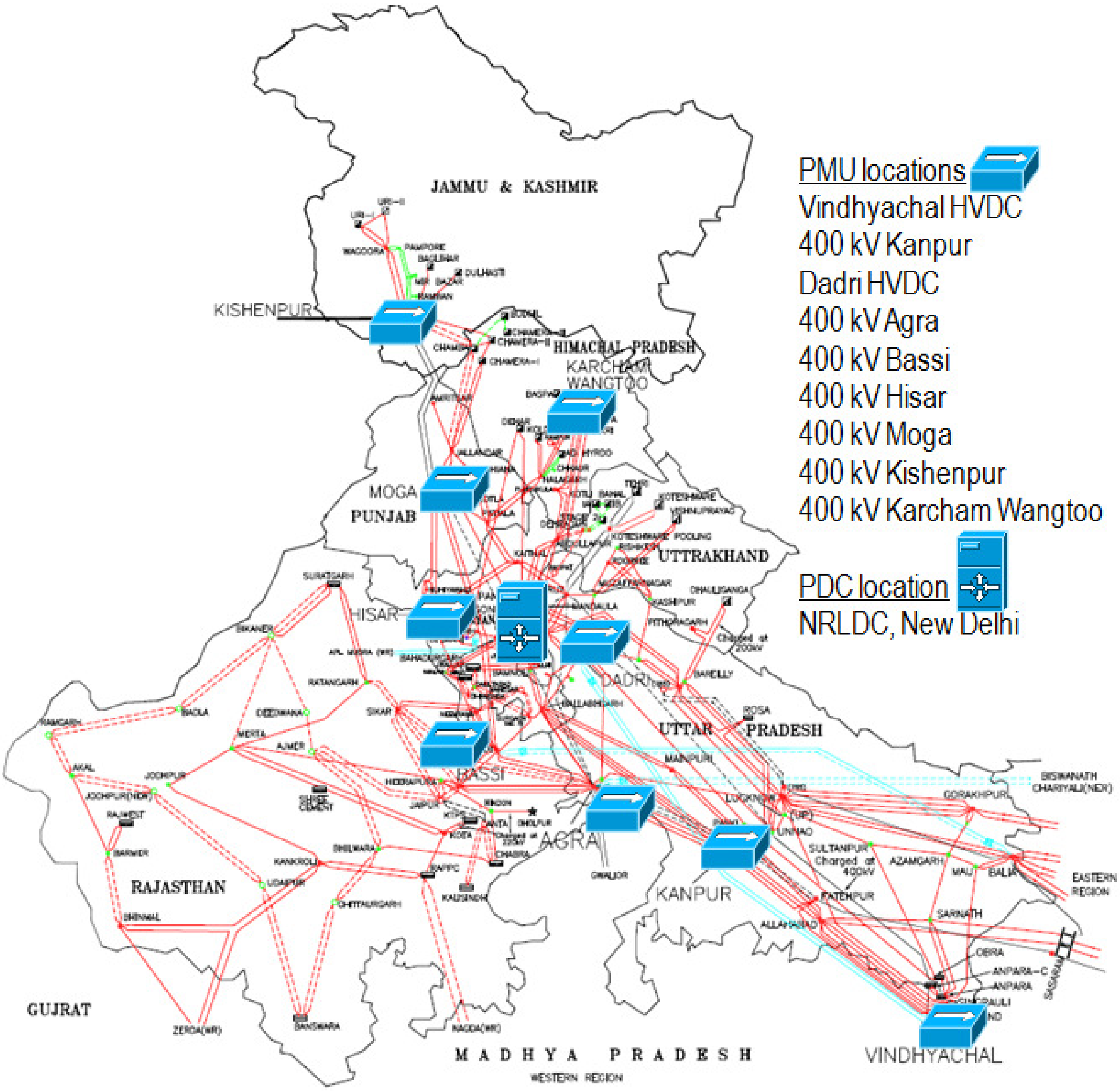


Figure 7: Geographical Location of PMUs and PDC in Northern Region

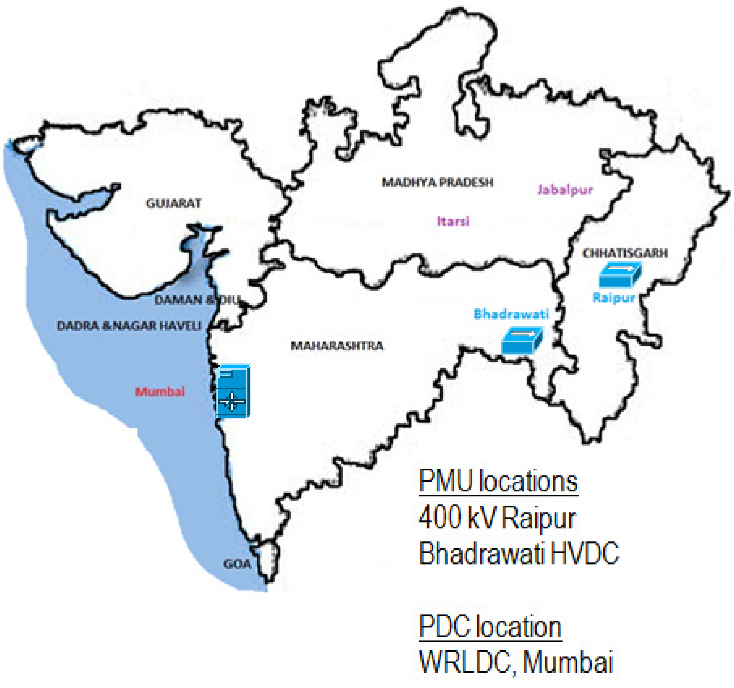


Figure 8: Geographical Location of PMUs and PDC in Western Region

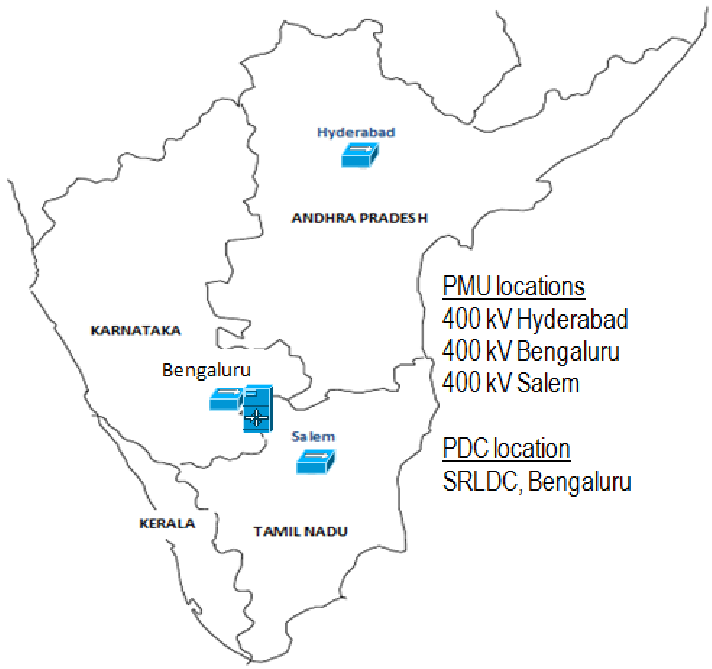


Figure 9: Geographical Location of PMUs and PDC in Southern Region

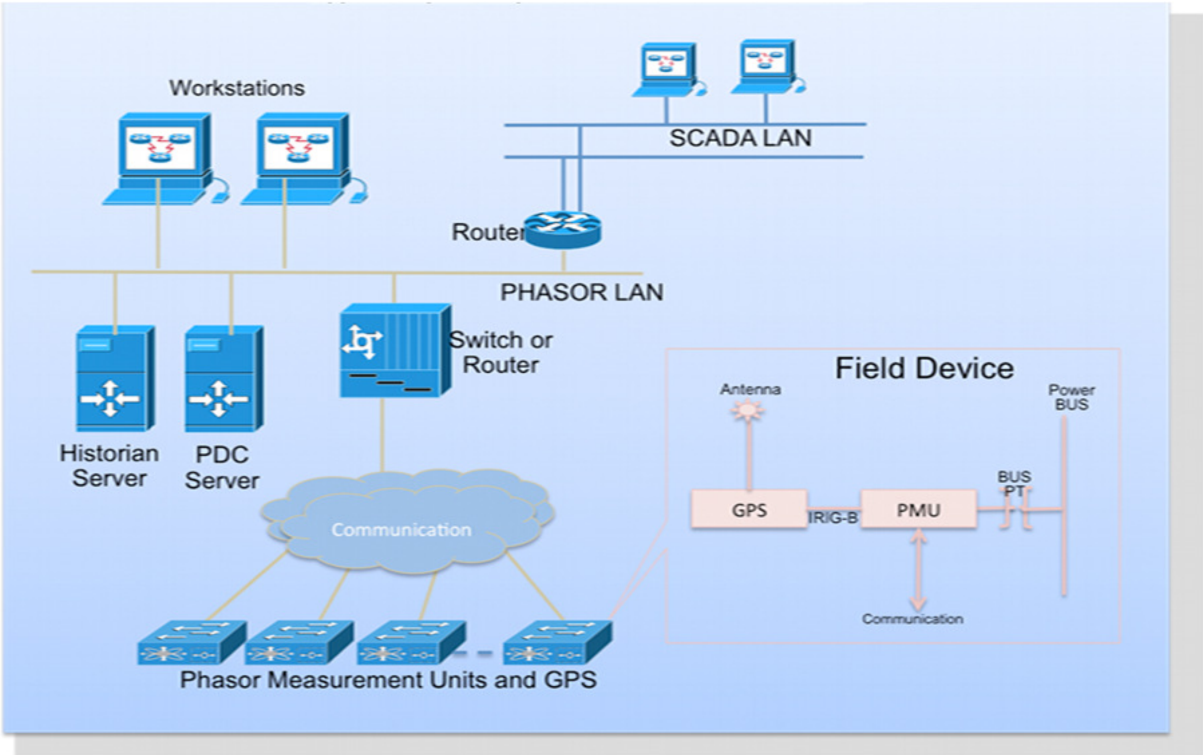


Figure 10: General architecture of a Synchrophasor project

2.3 Phasor Measurement Units: Technical Specifications

The Phasor Measurement Unit is the basic device for measurement of phasors. The inputs that are given to the PMU at the chosen substations are three phase voltage provided from CVT/PT and currents from one or more line CTs. The other technical specifications of the PMUs are summarized as Table-3. In the PMUs installed in the three regions, the 400 kV bus voltages available from the bus CVT of the respective substation has been given as input. The current input has been given from the line CT of the following lines:

A. Northern Region Phase-I

i. 400 kV Vindhyachal-Singrauli-I

ii. 400 kV Kanpur-Ballabgarh-I

iii. 400 kV Moga-Bhiwadi-I

iv. 400 kV Dadri_NTPC – Dadri_HVDC interconnector-I

B. Northern Region Phase-II

i. 400 kV Gwalior Agra-I and 400 kV Agra-Gwalior-II

ii. 400 kV Agra-Bassi-I and 400 kV Agra-Bassi-II

iii. 400 kV Hisar-Bawana

iv. 400 kV Kishenpur-Moga-I and 400 kV Kishenpur-Moga-II

C. Western Region

i. 400 kV Raipur-Bhadrawati-I

D. Southern Region

i. 400 kV Hyderabad-Ramagundam

ii. 400 kV Bengaluru-Kolar

iii. 400 kV Salem-Hosur

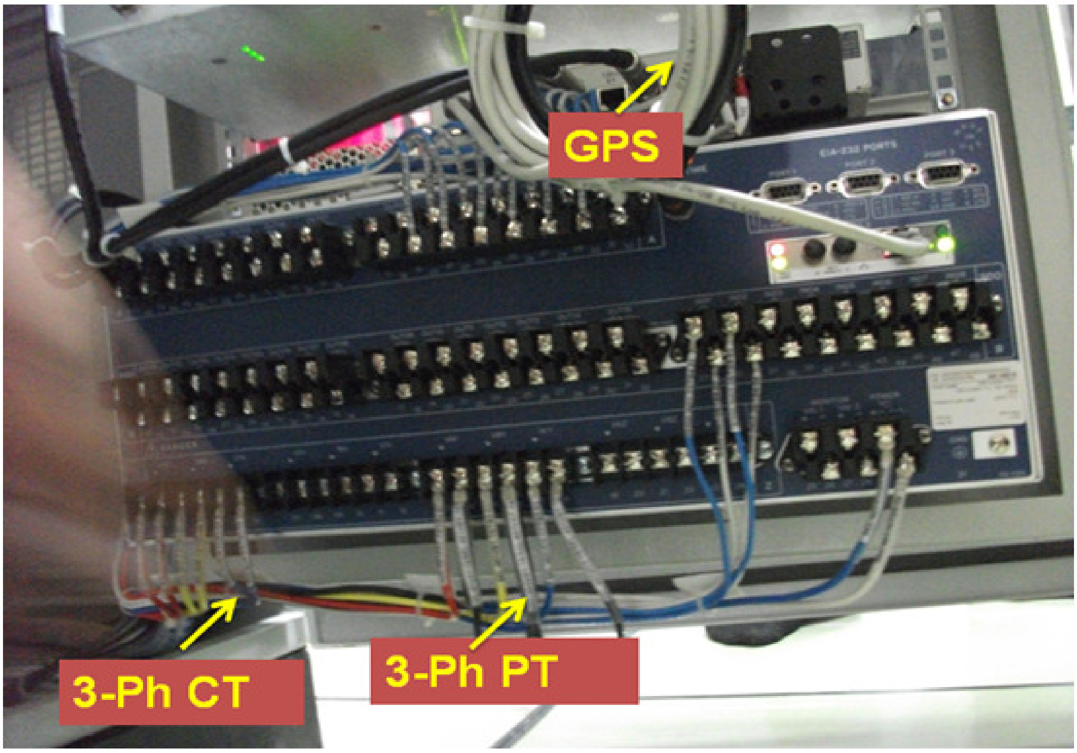


Figure 11: Inputs to Phasor Measurement Unit

The PMUs provide time stamped synchronized Phasor measurements which are then transmitted through high speed communication media to the Phasor Data Concentrator installed at the centralized location.

Table 3: Specifications-Phasor Measurement Units

S No.	Description	Details pertaining to		
		Northern Region	Western Region	Southern Region
1	Make	SEL 451	NIcRIO9012	National Instruments CR 10 2525
2	AC current input (CT Secondary circuit)	1 A or 5 A Nominal	1 A or 5 A Nominal	1 A or 5 A Nominal
3	AC voltage input (PT Secondary input)	300 V phase-to-neutral wye configuration PT inputs	300 V phase-to-neutral wye configuration PT inputs	400:110
4	Number of digital inputs	Phase-I: 8 Phase-II: 8	8	12
5	Analogue inputs	Phase-I: 1 set of 3 ph V & I Phase-II: 2 sets of 3-ph V & I	1 set of 3 ph V & I	MW, MVAR, PF
6	Communication protocol	IEEE C37.118 (2005)	IEEE C37.118 (2005)	IEEE C37.118 (2005)
7	Signal Sampling rate	8 kHz	50 kHz	50 kHz
8	Data reporting rate	25 samples per second	25 samples per second	25 Samples/Sec
9	Time reference source	IRIG B interface of GPS	MCX Interface of GPS	GPS
10	Accuracy of GPS	± 100 ns average	± 100 ns average	± 100 ns average
11	Local data display	Yes	No	Yes
12	Local data storage	Yes	No	Yes
13	Data transmission medium	Optical Fibre through IP WAN	Optical Fibre through IP WAN	Optical Fibre through IP WAN
14	Bandwidth used	64 kbps / 2 MBPS	2 MBPS	64 kbps

2.4 Phasor Data Concentrator: Technical Specifications

The Phasor Data Concentrator receives the data from PMUs. It aligns the data and forwards it to various client applications. The major features of Phase Data Concentrator installed in Northern Region are as under:

i. Supports serial or Ethernet communications to collect synchrophasor data

ii. Can take input from as many as 16 PMU's, using IEEE C37.118-2005 protocol

iii. Can process synchrophasor data at speeds upto 60 messages per second

iv. Can concentrate synchrophasor data at speeds upto 60 messages per second

v. Can concentrate synchrophasor data and transmits time alingned data to six external clients and one internal client in less than 2 ms

vi. Can issue control common, based on synchrophasor measurements, to external devices in less than 8 ms.

vii. Can combine predefined function blocks with standard IEC 61131-3 logic to build a synchrophasor –based monitoring, protection, automation and control system.

viii. Can create synchrophasor super packets, using data from relays for multitier applications.

ix. Can generate user defined synchrophasor messages to test synchrophasor systems or to provide data to upper tier applications

Table 4: Specifications-Phasor Data Concentrator

S No.	Description	Details pertaining to		
		Northern Region	**Western Region**	**Southern Region**
1	Make	SEL 3378	Open PDC	Kalkitech
2	Type	Hardware	Software	Hardware
3	No of PMUs that can be integrated(Processing Capacity)	16	100	25
4	Processing time (in ms)	4 ms	6 ms	5 ms
5	Communication Ports	Serial Ports-16 Ethernet Ports- 2	Ethernet	Ethernet Ports- 2
6	Data Input Format	IEEE 37.118-2005 (Ethernet & Serial) SEL Synchrophasor Fast Message(Ethernet & Serial)	IEEE 37.118-2005 IEEE 1344, Macrodyne & Virginia Tech F-Net protocols	IEEE 37.118-2005
7	Data output format	IEEE 37.118-2005 (Ethernet) & Object linking and embedding for Process Control (OPC)	IEEE 37.118-2005	Provides data in ODBC interface and coverts to multiple protocols

2.5 Historian: Technical Specifications

The historian archives the synchrophasor data for retrieval and analysis. The features available in the historian installed at different region are tabulated below.

Table 5: Specifications- Historian

S No.	Description	Details pertaining to		
		Northern Region	**Western Region**	**Southern Region**
1	Make	GE Funuc- GE proficy portal	Open PDC	EDNA INSTEP software
2	Data available	Frequency Voltage Phasors Current Phasors Sequence Voltages Sequence Currents Angle difference df/dt, MW, MVAr Slip frequency	Frequency Voltage Phasors Current Phasors Sequence Voltages Sequence Currents df/dt, MW, MVAr	Frequency Voltage Phasors Current Phasors Sequence Voltages Sequence Currents Angle difference df/dt, MW, MVAr pf
3	Data storage medium	Server (DELL)	HardDisk-Local PC	Server (DELL)
4	Data storage capability	Data from 10 PMUs for 12 months transfer to Storage Area Network (SAN)	Data from 2 PMUs for 1 week, transfer to secondary storage without any compression	Data from 3 PMUs for 6 months
5	Data exchange format for further analysis	via network through Open Database Connectivity in spreadsheet & Visual Basic	Data extraction from historian playback utility in csv format	via network through Open Database Connectivity in spreadsheet
6	Self visualization	Yes (Web based)	Yes (Playback mode)	Yes (web based)
7	Data visualization type	Tabular, Trend (with zoom/Pan)	Trend	Tabular, Trend (with zoom/Pan)

2.6 Operator Dashboard

Features of operator dashboard in different regions are given in table 6.

Table 6: Specifications- Operator Dashboard

S No.	Description	Details pertaining to		
		Northern Region	Western Region	Southern Region
1	Make	Synchrowave Software- SEL 5078	Open PDC	Kalki Visualization Software
2	Frequency	Trend display	Trend display	Trend display
3	Frequency difference between two locations	Trend display	Trend display	Trend display
4	Rate of change of frequency (df/dt)	Trend display	Trend display	Trend display
5	Phasor magnitude (Voltage and Current)	Polar display Trend display	Trend display	Polar display Trend display
6	Phasor Angle (Voltage & Current)	Polar display Trend display	Trend display	Polar display Trend display
7	Sequence components	Trend display (Positive Seq)	Trend display(+/- 0)	Trend display (Positive Seq)
8	Angular separation	Polar display	Trend display	Polar display Trend Display
9	MW	Trend display	Trend display	Trend display
10	MVAR	Trend display	Trend display	Trend display

2.7 Overview of next stage of the pilot project

Two stages of the synchrophasor pilot project undertaken by NRLDC with 8+1 PMU and 1 PDC have been completed. In the third phase 18 PMUs, 1 PDC and 1 Historian at the National Load Despatch Centre have been planned. The proposed architecture is shown as figure 12.

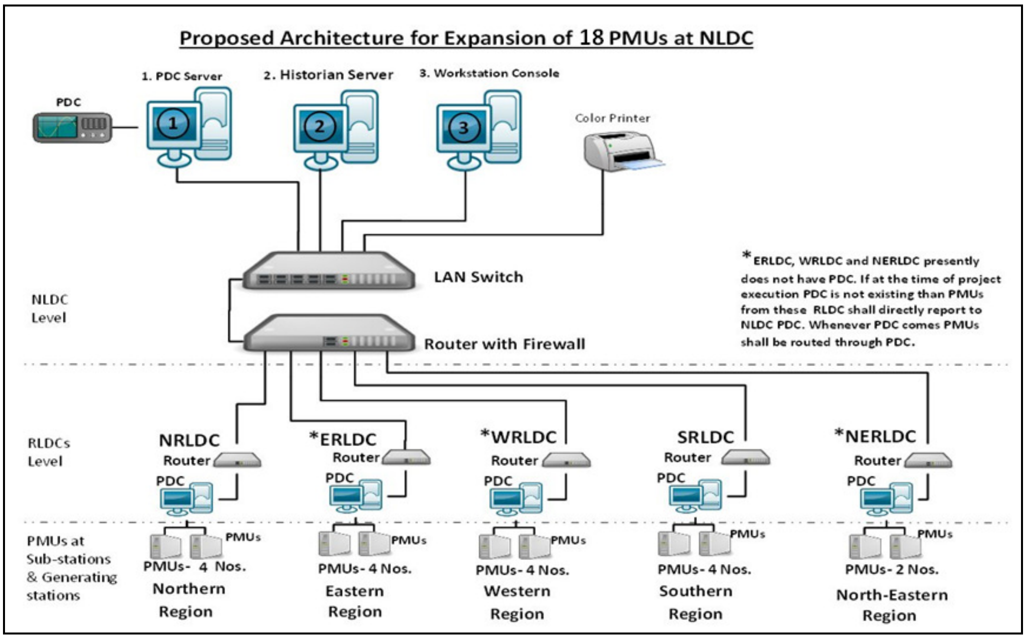


Figure 12: Proposed architecture for Phase-III of PMU pilot project in NR

In addition to the above, pilot projects have been envisaged by other Regional Load Despatch Centres for their respective regions. Under these projects 26 PMUs and 4 PDCs are envisaged to be installed (Refer figure 13).

Southern Region	North-eastern Region	Eastern Region	Western Region
6 PMUs + 1 PDC	6 PMUs + 1 PDC	8 PMUs + 1 PDC	6 PMU + 1 PDC
PMUs at	PMUs at –	PMUs at –	PMUs at –
1. Vijaywada	1. Bongoigon	1. Jamshedpur	1. Satna
2. Ramagundam	2. Balipara	2. Ranchi	2. Parli
3. Sriperumbudur	3. Imphal	3. Jayepore	3. Itarsai
4. Smonhalli	4. Sarusajai	4. Binaguri	4. Dehgam
5. Trichur	5. Nehu	5. Biharshariff	5. Boisar
6. Narendra	6. Agartala	6. Patana	6. Raipur
		7. Sasaram	
		8. Rengalli	
PDC at SRLDC-Bangalore	PDC at NERLDC-Shillong	PDC at ERLDC Kolkata	PDC at WRLDC, Mumbai

Figure 13: Pilot projects being undertaken by other RLDCs

Thus after completion of all the pilot projects, there would be 53 PMUs and 6 PDCs in India (without considering the demo PMUs in Western and Southern Region). The final architecture may be referred in figure 14.

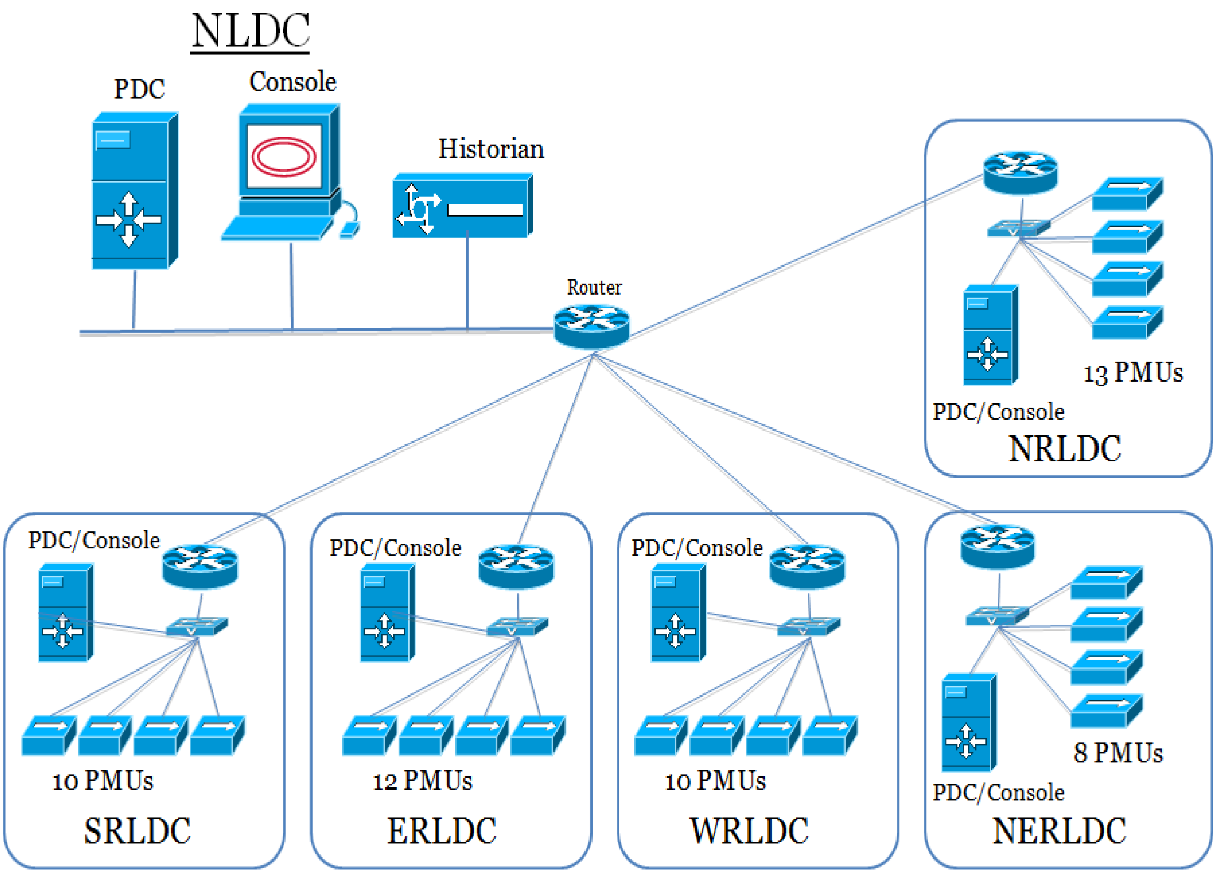


Figure 14: Envisaged architecture after completion of the pilot projects in all the Regions

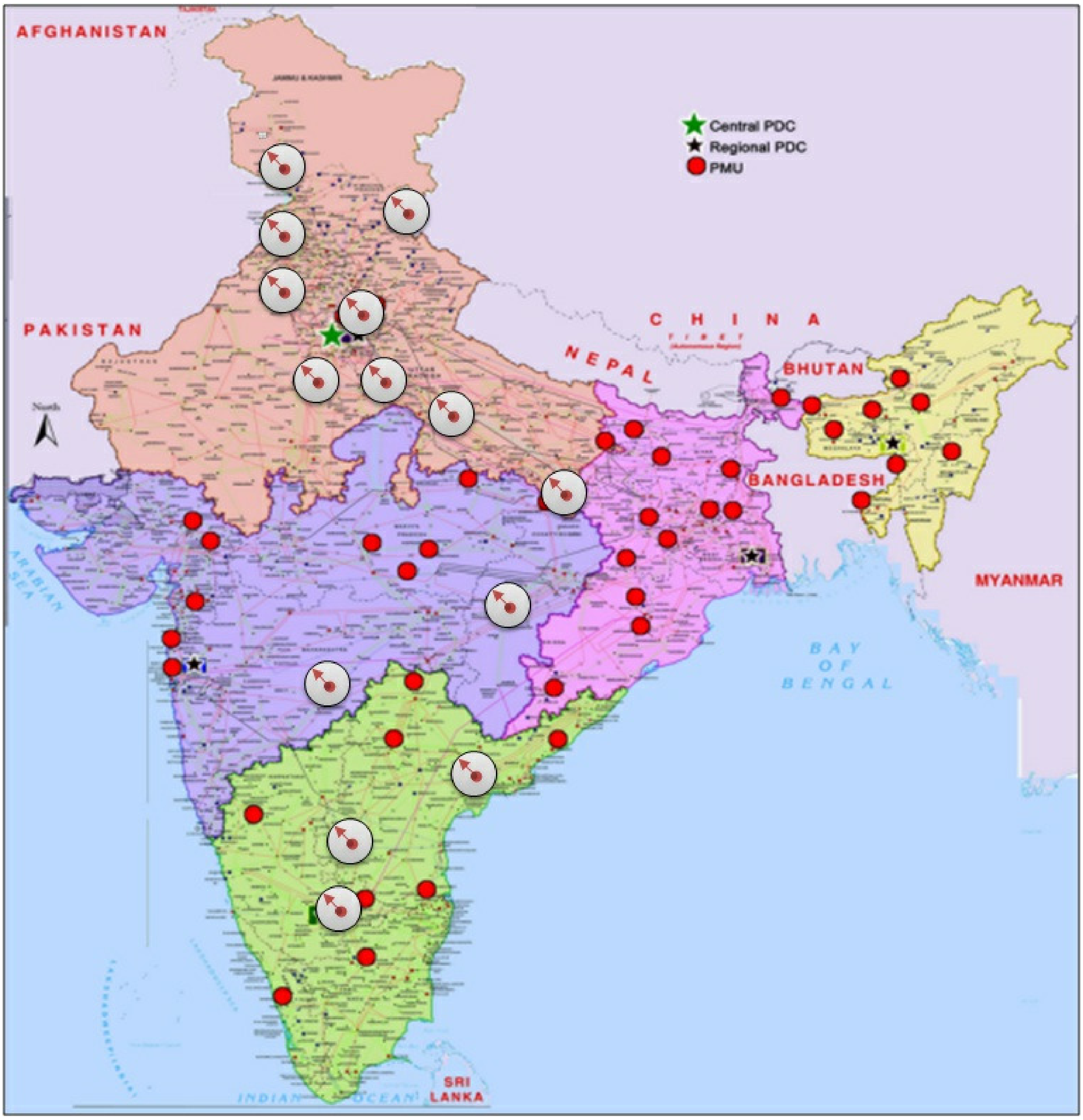


Figure 15: Geographical location of present and prospective PMUs in the pilot projects

CHAPTER 3: ARCHITECTURE OF SYNCHROPHASOR PROJECT

3.1 Architecture in Northern Region

Nine PMUs and one PDC are presently functional in the Northern Region. 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 equipment's installed at NRLDC align the data sent by PMUs and display it on the operator console. The inputs that have been given to the PMU at the chosen substations are three phase voltage of the 400kV buses and three phase currents of the feeders at the chosen substations. Voltage inputs (Vr, Vy, Vb, Vn) have been provided from CVT/PT of 400kV bus of the substation while the line currents (Ir, Iy, Ib,) have been given from the line CT. The synchrophasors installed in 1st phase have one set of voltage and current inputs whereas synchrophasors installed in 2nd phase have two sets of voltage & current inputs. The data available at the control centre are as under:

i. GPS time

ii. Time synchronized voltage phasors i.e. magnitude and angle of each of the three phases from eight locations (400 kV Vindhaychal (north bus), 400 kV Kanpur, 400 kV Dadri, 400 kV Moga, 400kV Agra, 400kV Bassi, 400kV Hissar, 400kV Kishenpur)

iii. Time synchronized frequency from eight locations.

iv. Time synchronized rate of change of frequency from eight locations

v. Time synchronized current phasors i.e. magnitude and angle of line current of lines- 400 kV Vindhyachal-Singrauli-I, 400 kV Kanpur-Ballabgarh-I, 400 kV Moga-Bhiwadi-I and Interconnector between 400 kV Dadri_NTPC-HVDC Dadri (at 400kV Dadri), 400kV Agra-Gwalior ckt-1&2, 400kV Agra-Bassi ckt-2&3, 400kV Kishenpur-Moga ckt-1&2 & 400kV Hisar-Bawana line,

vi. Time synchronized power flow (MW and MVAr) of the four lines

3.1.1 Specifications

The system architecture of synchrophasor pilot project installed in Northern region is shown in Figure-16. Schweitzer Engineering Laboratories, Inc make PMU's (SEL-451) and GPS clock (SEL-2404) with PMU panel which has been installed at the eight location selected for the pilot project (refer figure-16). Synchrophasor data from these eight locations are sent to phase data concentrator (PDC) installed at NRLDC. Synchrophasor visualization software and historian software is installed at NRLDC for visualization and data storage. POWERGRID has provided communication through Multiplexer with 64 Kbps G.703 communication links for linking these PMU's (SEL-451) with SEL make PDC (SEL-3378) and for storage Dell server Poweredge410 installed at NRLDC.

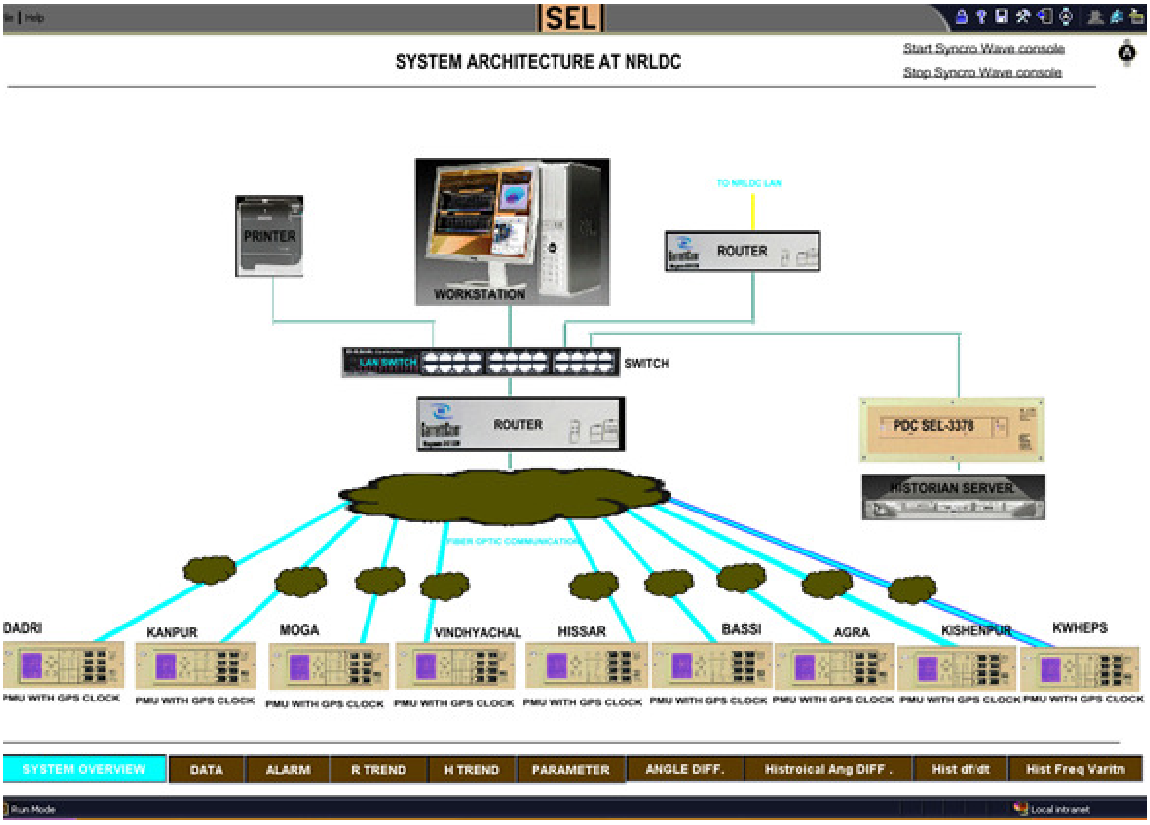


Figure 16: Architecture of pilot project in Northern Region

The synchronized phasor measurement processing system operates as a programmable data concentrator with network access to provide a combination of functions including, but not limited to, simultaneous collection of data from serial- and Ethernet connected phasor measurement units, correlation and concentration of collected data based on UTC time stamp, and simultaneous transmission of time-aligned IEEE C37.118-2005 synchrophasor messages for as many as seven clients.

The Human Machine Interface (HMI) workstation application has been developed using proficy real time information portal SCADA software development environment. The development environment supports creation of graphic objects that represent the status and conditions, display of analogue values, input field for analogue values. The HMI updates the screen once 2 second. It keeps a detailed alarm history of all the alarms, errors and fail-overs.

3.1.2 Displays in Operator Console

Two sets of displays are available; one set of displays with data from Historian and second set of displays with real time data from PDC. Few customized displays have been prepared for the operators. Displays are presently of two types- dial display and trend display.

Synchrowave console SEL-5078 is the application-level software package used for viewing data from server.

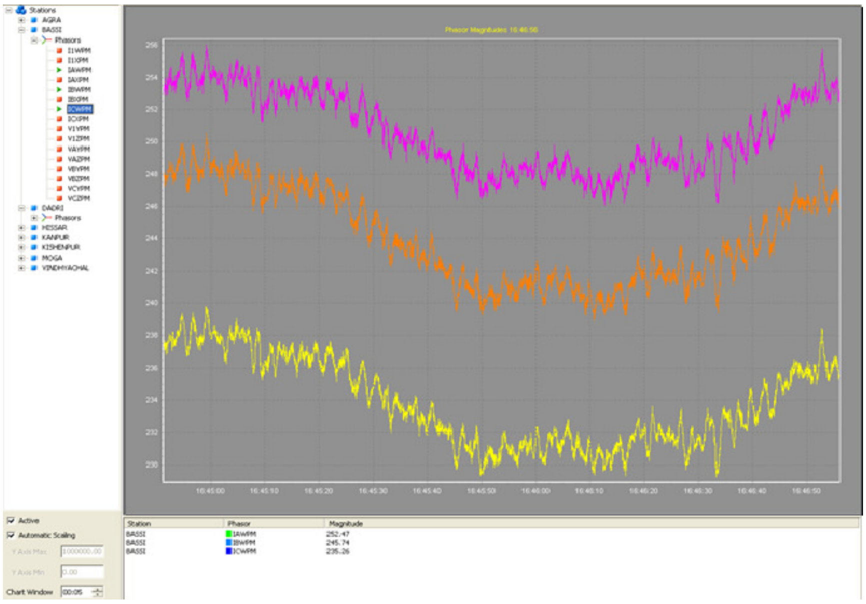


Figure 17: Trend display of current phasor magnitude

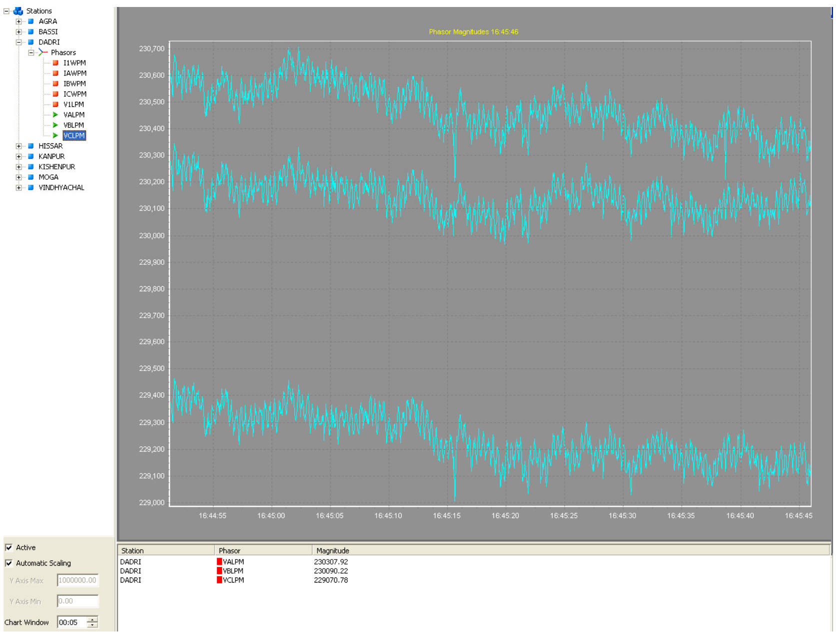


Figure 18: Trend display of voltage phasor magnitude

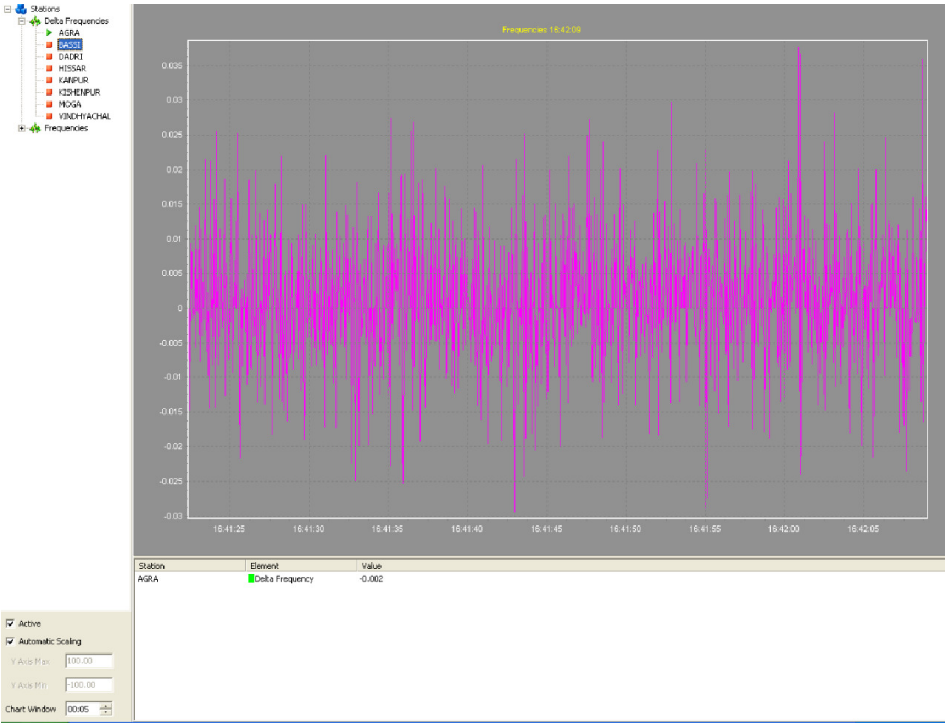


Figure 19: Trend display of the rate of change of frequency

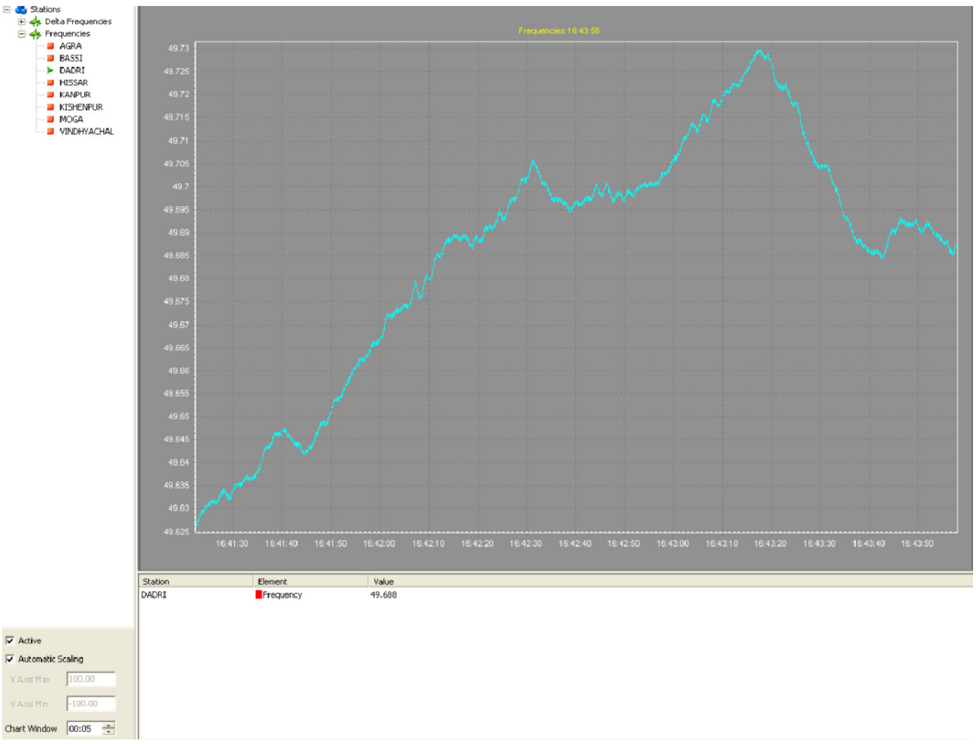


Figure 20: Trend display of frequency

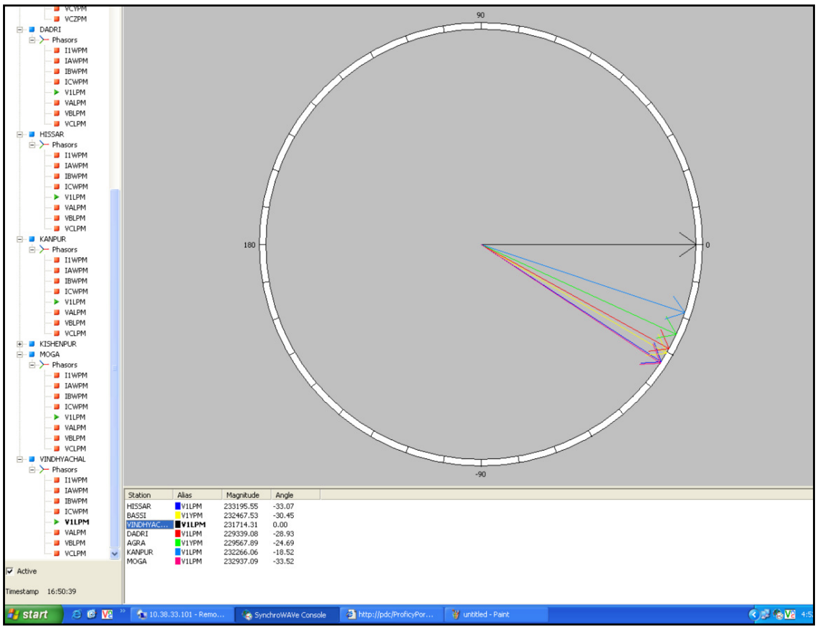


Figure 21: Dial type display of phasor angles

Figure 21 shows the dial type display of phasors of Vindhyachal, Dadri, Kanpur, Moga, Agra, Bassi & Hisar substations. Vindhyachal phasor has been taken as reference.

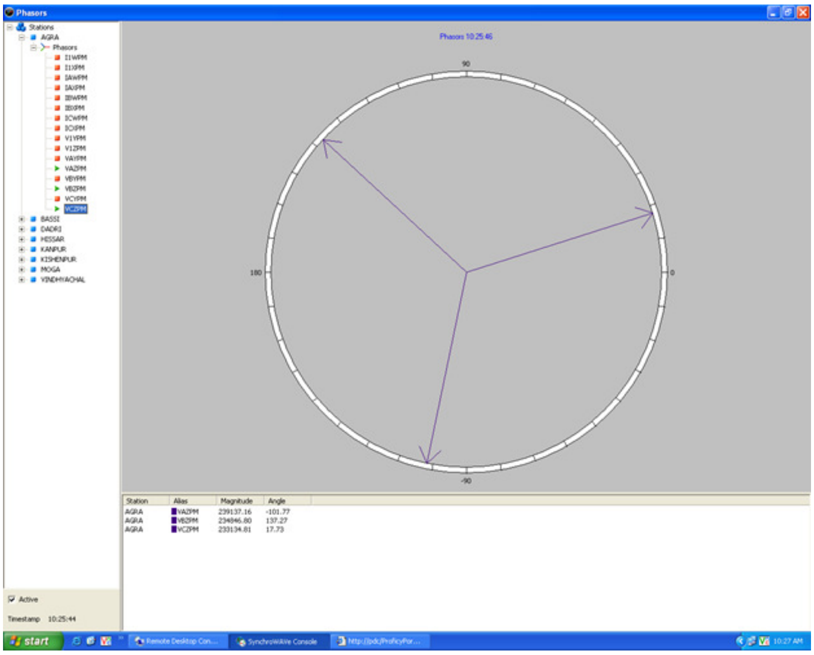


Figure 22: Dial type display of voltage phasors

Figure 22 shows the trend type display of voltage phasors (R, Y & B phase).

It has been observed that the phasors rotate in the anticlockwise (or clockwise) direction depending on whether the grid frequency is below (or above) nominal frequency of 50 Hz.

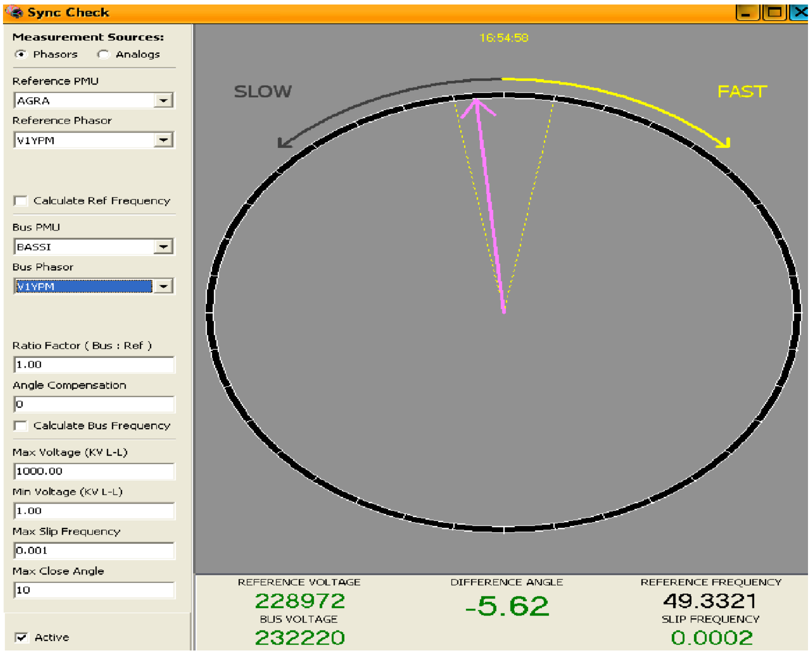


Figure 23: Dial display of opposite voltyage phasors used for synchronising check

Figure 23 shows the dial display for synchronizing check. 400kV Agra & Bassi substations have been taken in this case. The difference in angle between the two stations, incoming and reference voltage & slip frequency are available.

3.1.3 Displays in Historian

Proficy portal is the application-level software used for viewing the data from historian. Few typical displays are as under:

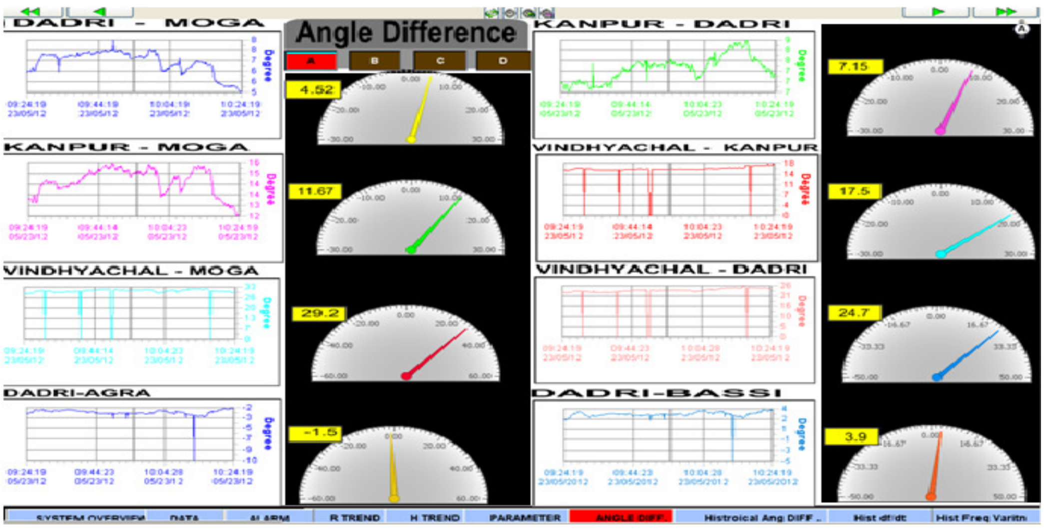


Figure 24: Trend and dial type display for angle difference between different 400kV buses

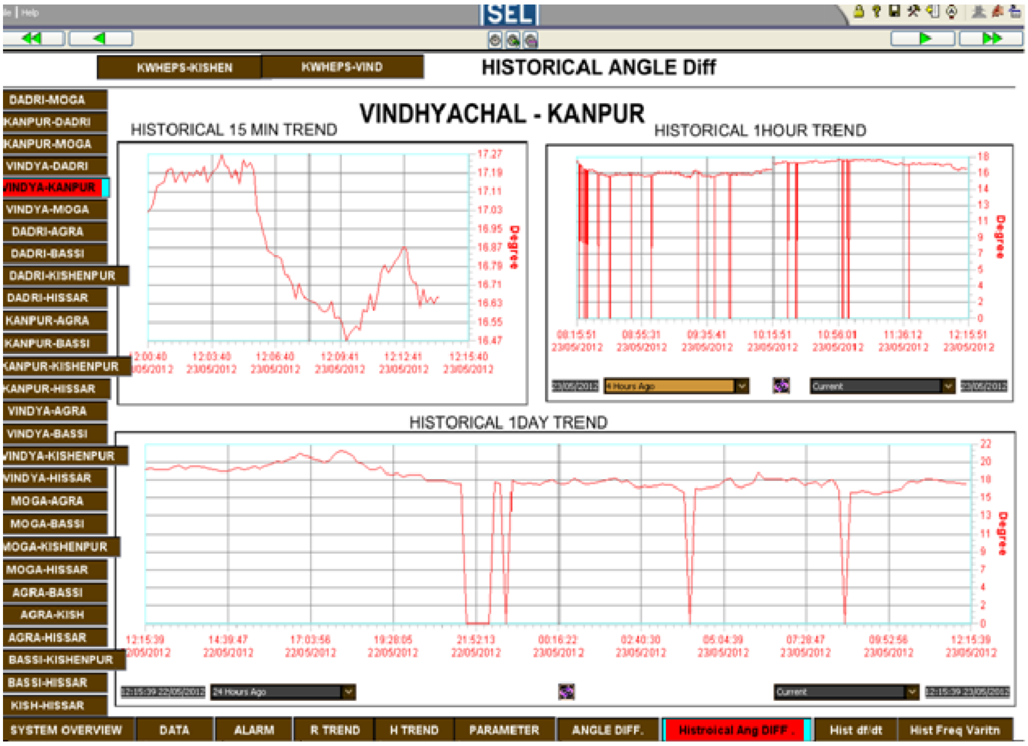


Figure 25: Trends display of angle difference between 400kV buses

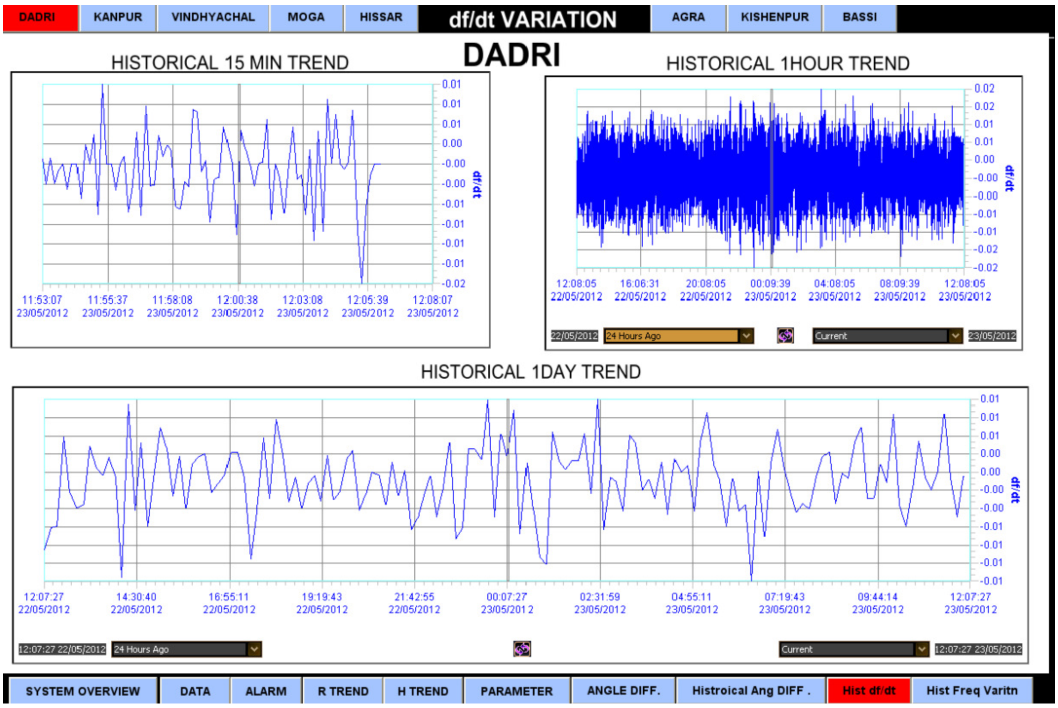


Figure 26: Trends display of rate of change of frequency recorded at 400kV Dadri bus

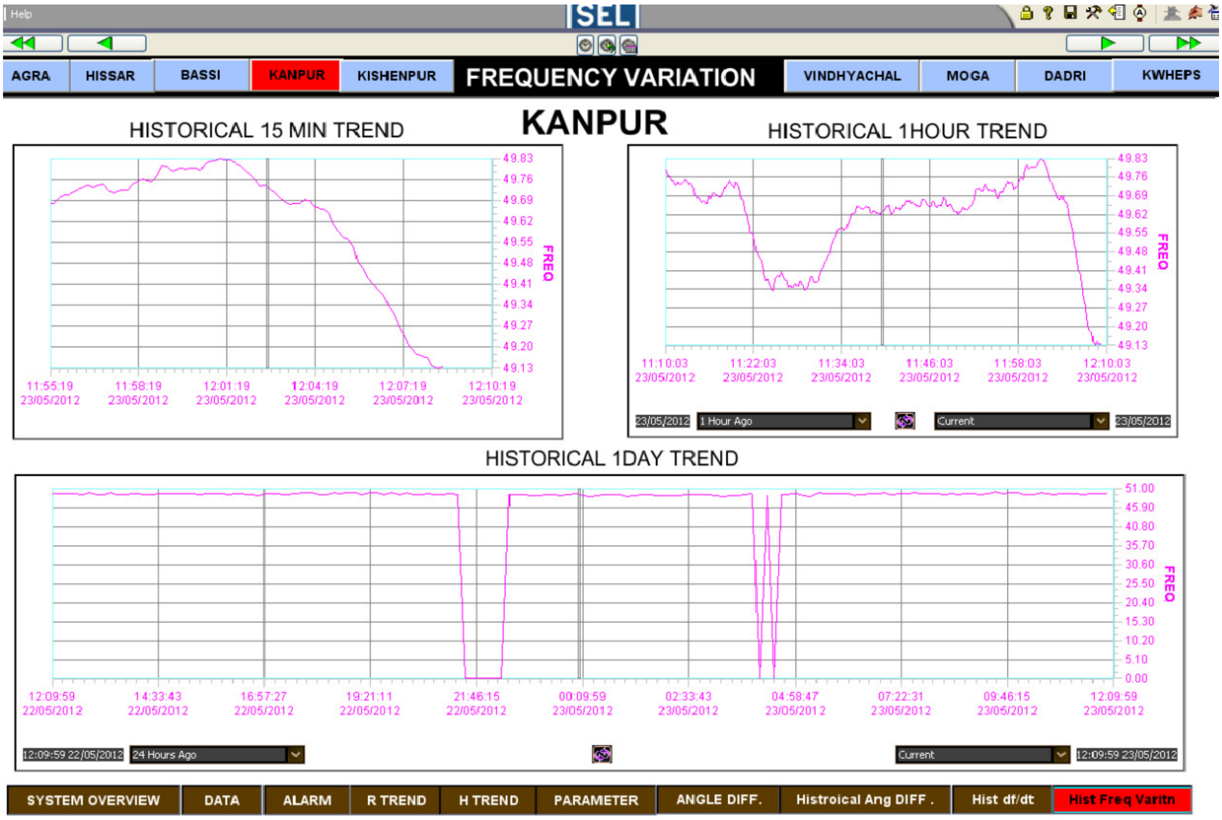


Figure 27:Trend display of frequency profile recorded at 400kV Kanpur bus

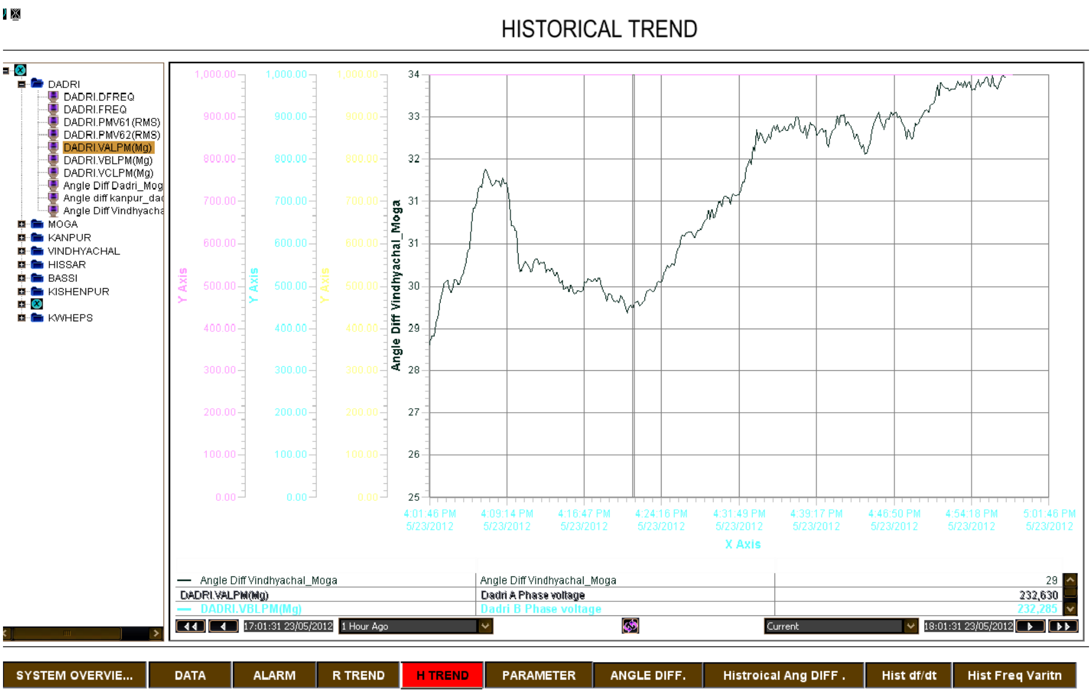
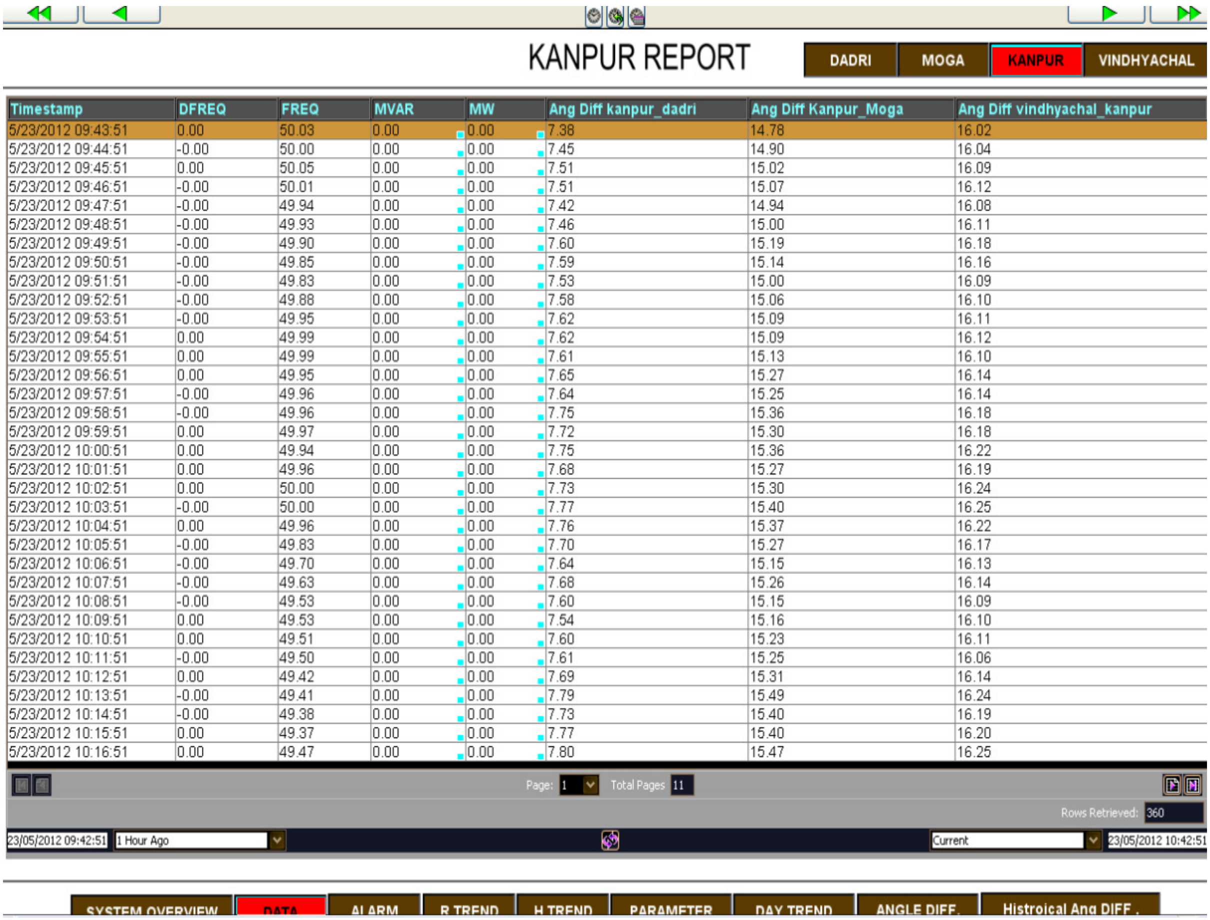


Figure 28: Historical trend display of voltage of 400kV bus at Dadri station



Timestamp	DFREQ	FREQ	MVAR	MW	Ang Diff kanpur_dadri	Ang Diff Kanpur_Moga	Ang Diff vindhyachal_kanpur
5/23/2012 09:43:51	0.00	50.03	0.00	0.00	7.38	14.78	16.02
5/23/2012 09:44:51	-0.00	50.00	0.00	0.00	7.45	14.90	16.04
5/23/2012 09:45:51	0.00	50.05	0.00	0.00	7.51	15.02	16.09
5/23/2012 09:46:51	-0.00	50.01	0.00	0.00	7.51	15.07	16.12
5/23/2012 09:47:51	-0.00	49.94	0.00	0.00	7.42	14.94	16.08
5/23/2012 09:48:51	-0.00	49.93	0.00	0.00	7.46	15.00	16.11
5/23/2012 09:49:51	-0.00	49.90	0.00	0.00	7.60	15.19	16.18
5/23/2012 09:50:51	-0.00	49.85	0.00	0.00	7.59	15.14	16.16
5/23/2012 09:51:51	-0.00	49.83	0.00	0.00	7.53	15.00	16.09
5/23/2012 09:52:51	-0.00	49.88	0.00	0.00	7.58	15.06	16.10
5/23/2012 09:53:51	-0.00	49.95	0.00	0.00	7.62	15.09	16.11
5/23/2012 09:54:51	0.00	49.99	0.00	0.00	7.62	15.09	16.12
5/23/2012 09:55:51	0.00	49.99	0.00	0.00	7.61	15.13	16.10
5/23/2012 09:56:51	0.00	49.95	0.00	0.00	7.65	15.27	16.14
5/23/2012 09:57:51	-0.00	49.96	0.00	0.00	7.64	15.25	16.14
5/23/2012 09:58:51	-0.00	49.96	0.00	0.00	7.75	15.36	16.18
5/23/2012 09:59:51	0.00	49.97	0.00	0.00	7.72	15.30	16.18
5/23/2012 10:00:51	0.00	49.94	0.00	0.00	7.75	15.36	16.22
5/23/2012 10:01:51	0.00	49.96	0.00	0.00	7.68	15.27	16.19
5/23/2012 10:02:51	0.00	50.00	0.00	0.00	7.73	15.30	16.24
5/23/2012 10:03:51	-0.00	50.00	0.00	0.00	7.77	15.40	16.25
5/23/2012 10:04:51	0.00	49.96	0.00	0.00	7.76	15.37	16.22
5/23/2012 10:05:51	-0.00	49.83	0.00	0.00	7.70	15.27	16.17
5/23/2012 10:06:51	-0.00	49.70	0.00	0.00	7.64	15.15	16.13
5/23/2012 10:07:51	-0.00	49.63	0.00	0.00	7.68	15.26	16.14
5/23/2012 10:08:51	-0.00	49.53	0.00	0.00	7.60	15.15	16.09
5/23/2012 10:09:51	0.00	49.53	0.00	0.00	7.54	15.16	16.10
5/23/2012 10:10:51	0.00	49.51	0.00	0.00	7.60	15.23	16.11
5/23/2012 10:11:51	-0.00	49.50	0.00	0.00	7.61	15.25	16.06
5/23/2012 10:12:51	0.00	49.42	0.00	0.00	7.69	15.31	16.14
5/23/2012 10:13:51	-0.00	49.41	0.00	0.00	7.79	15.49	16.24
5/23/2012 10:14:51	-0.00	49.38	0.00	0.00	7.73	15.40	16.19
5/23/2012 10:15:51	0.00	49.37	0.00	0.00	7.77	15.40	16.20
5/23/2012 10:16:51	0.00	49.47	0.00	0.00	7.80	15.47	16.25

Figure 29: Tabular display of analog values

3.2 Architecture in Western Region

Six PMUs are proposed to be installed under the Interim PMU Project in WR having around 90 400kV buses. Concurrent to WR Interim Project, WRLDC had discussion with some vendors for commissioning of PMUs on test basis for gaining firsthand experience of synchrophasor technology. As an outcome of this initiative, M/s Infosys Limited proposed and subsequently commissioned two PMUs at Bhadrawati and Raipur ends of 400 kV Bhadrawati – Raipur Ckt-I by 16th March 2012. Two additional PMUS are likely to be commissioned at 400 kV Itarsi and 400 kV Jabalpur by M/s GE in near future. Considering the coordination and logistics support at site all proposed locations for the test PMU project were POWERGRID substations. Subsequent sections will be limited to experience gathered from WR test PMU project, viz., Infosys Project.

3.2.1 Specifications

During the initial discussions it was clarified by M/s Infosys that the PMUs to be installed under the test project will be from National Instrument (NI) and are based on open PMU concept. The technical specifications of PMUs are mentioned below:

- Sample Rate (50Hz): 1000 Samples/Cycle
- Communication Protocols: Ethernet (TCP and UDP)
- Voltage Module Specification : 3-Channel, 300 V_{rms}, 24-Bit, Simultaneous, Channel-to-Channel Isolated Analog Input Module
- Current Module Specification: 4 current input modules were designed to measure 5 A_{rms} nominal on each channel with channel-to-channel isolation.
- Built-in anti-alias filters

Phasor Data Concentrator – open PDC in Western Region

The PDC installed at WRLDC by Infosys is software PDC (openPDC) which is developed as an open source technology by Grid Protection Alliance (GPA). The openPDC is a complete Phasor Data Concentrator software system designed to process streaming time-series data in real-time. Measured data gathered with GPS-time stamp from numerous input sources (here PMU) is time-sorted and displayed on a common display window. The acquired data is also archived for offline studies and historian trending. It Supports IEEE C37.118 with added advantage that other protocols for phasor like IEEE 1344, BPA PDC stream, FNET, SEL Fast Message, and Macrodyne are also supported. Data flow in openPDC consists of adapters which can be split into three layers:

i. The input adapter layer is typically responsible for receiving data from an outside source (PMU). That data is used to create measurements which are sent to other adapters to be processed or archived.
ii. The action adapter layer is typically responsible for concentration and processing of the input measurements.
iii. The output adapter layer is typically responsible for archival of measurements received from the input adapter layer and the action adapter layer.

These adapters can be configured using any one of three supported database systems: Microsoft SQL Server, MySQL, and Microsoft Access.

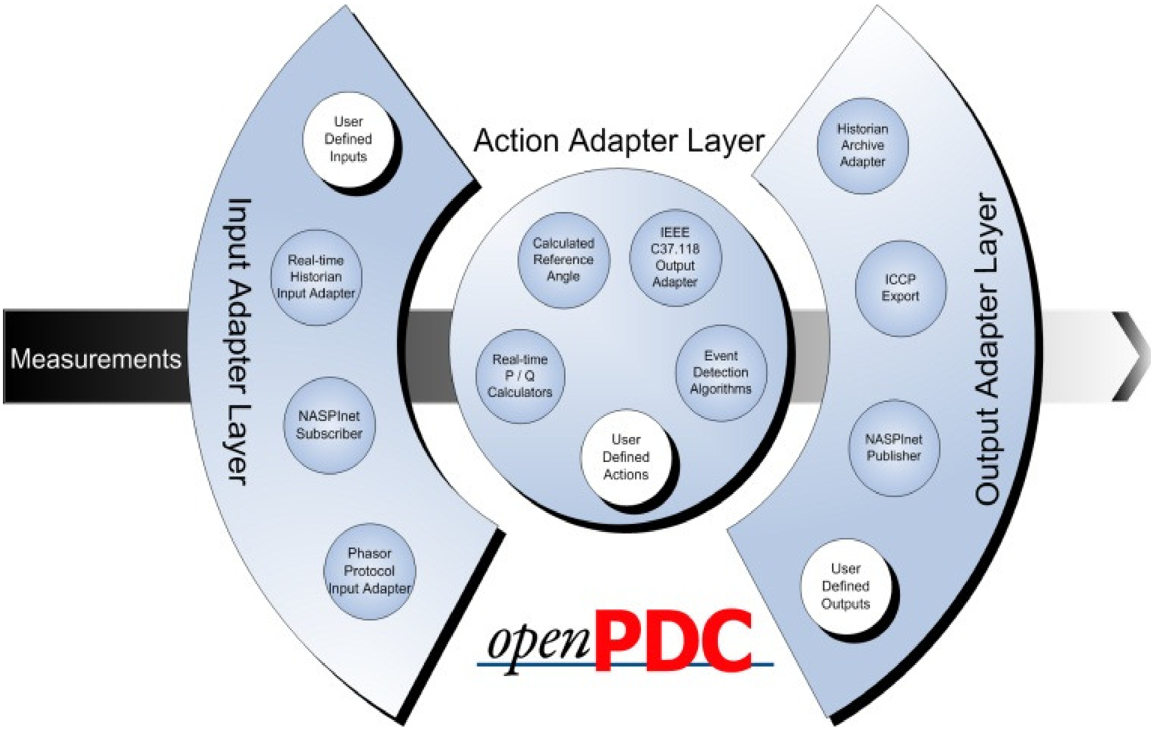


Figure 30: Open PDC data flow

PMU Installation

As a prerequisite for PMU logistics, substations were requested to make necessary arrangements for power supply (220 VAC or 24 VDC) and to extend connections from metering core of PT and CT.

Installation of PMU at Bhadrawati

At Bhadrawati the PMU was installed in 400 kV Raipur Feeder-I which is housed in the 400 kV AC Control Room along with dedicated GPS module. However, existing MUX for routing data to WRLDC was housed in 400 kV HVDC Control Room which is around 1.5 kms away from the AC Control Room. Ethernet cable normally used for data communication will not be able to carry data over the distance in this case. The situation was resolved using media converters and an existing spare FO cable already laid between the AC and HVDC Control Rooms. Installation and integration of Bhadrawati PMU was completed on 14th March 2012.

Installation of PMU at Raipur

At Raipur, the situation was relatively simpler with all relevant panels housed within the same control room. Here, data communication from PMU to PDC at WRLDC was established using existing MUX and standard ethernet cable. Installation and integration of Raipur PMU was completed on 16th March 2012.

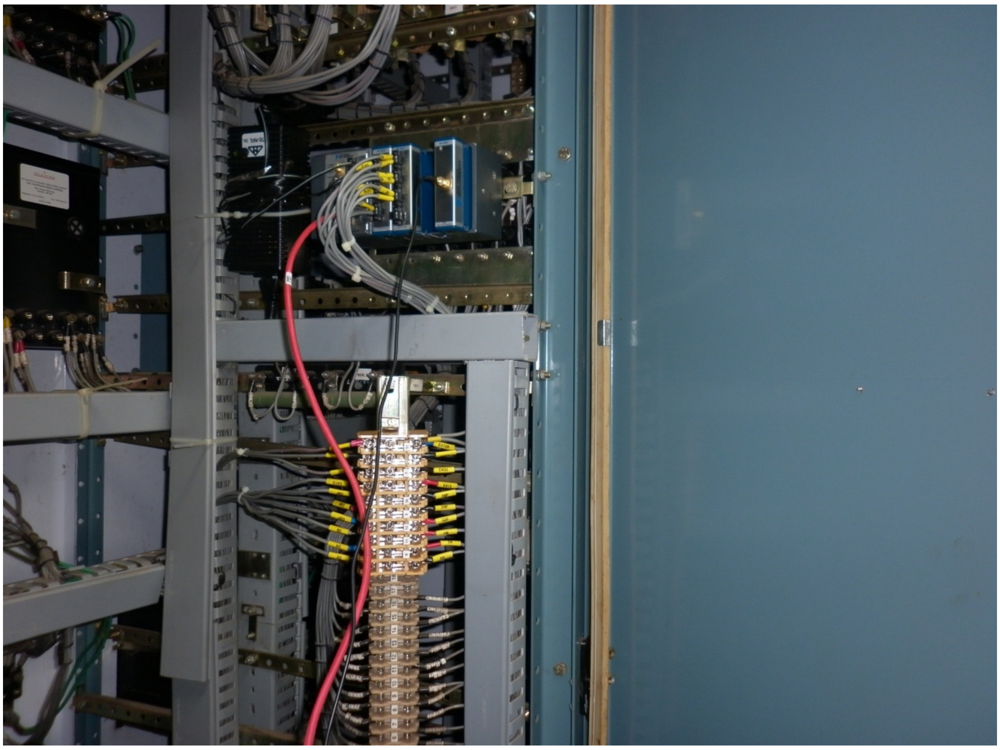


Figure 31: Installed PMU at Raipur

Installation of PDC at WRLDC

After successful installation of PMUs at Bhadrwati and Raipur, Infosys had installed a software version of Phasor Data Concentrator (PDC) – *openPDC* in WRLDC, Mumbai. The PDC was successfully configured to integrate data from both PMUs. Data archiving has been implemented for forensic analysis of various grid incidents. Some of the openPDC screenshots are reproduced below.

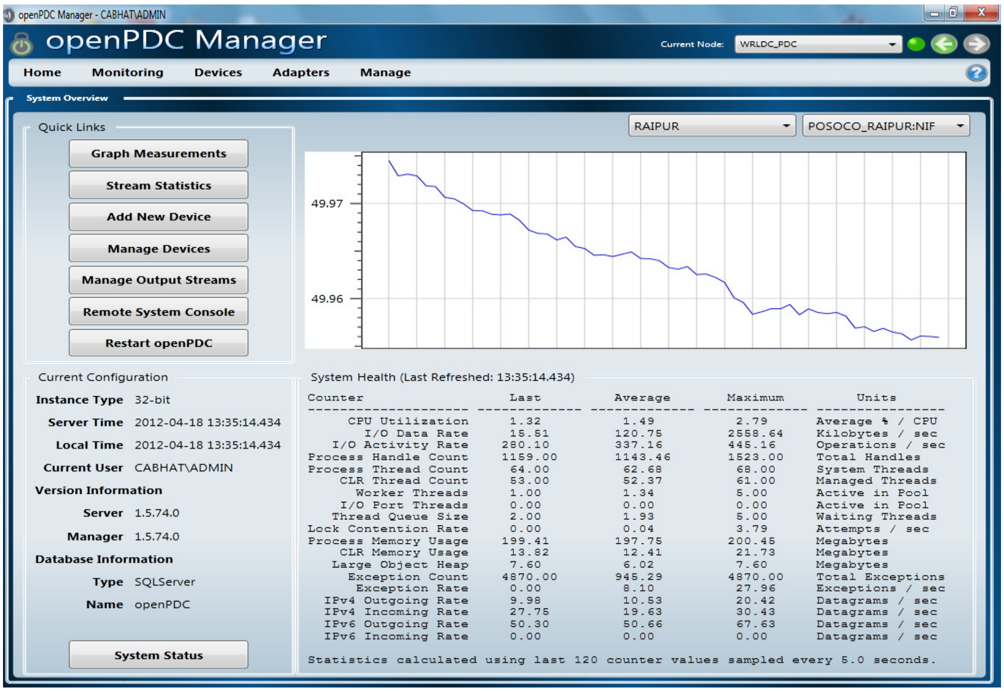


Figure 32: openPDC home page showing system health information

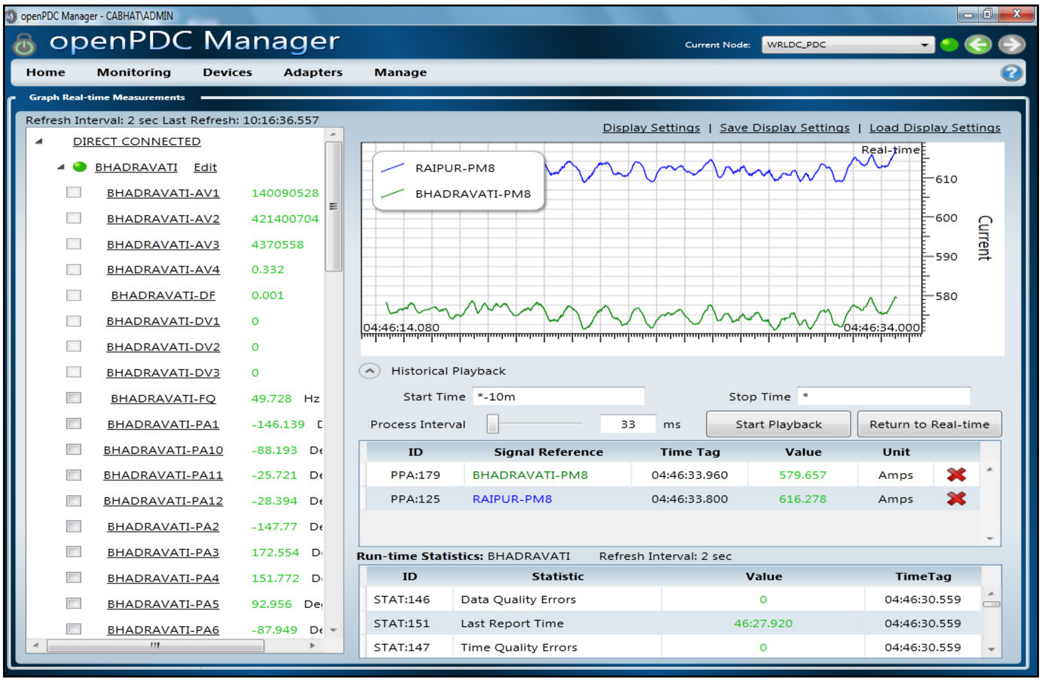


Figure 33: Real time PMU data visualisation window in openPDC

PMU Data from both PMU is available from 14th April 2012 and onwards.

3.3 Architecture in Southern Region

The pilot project implemented in Southern Region has three PMUs installed at 400 kV Hyderabad, 400 kV Salem and 400 kV Bengaluru. The three locations were selected based on availability of communication as well as their importance in giving a view of power system dynamics in SR. The PMUs report to Phasor Data Concentrator via the existing wideband communication links available. The phasor monitoring application consists of historian, web based user interface and play back function for off line application. It also consists of a proprietary oscillation monitoring system for event analysis. A limited SCADA interface has been also successfully implemented integrating PDC with scada. This is albeit with limitations of SCADA but helps real time operators to view the angular separation and df/dt. Considering the constraints of wideband speed and availability PMUs have been configured in the following manner.

Table 7: Features in PMUs in Southern Region

S No.	Attribute	Property
1	PMU data update	25 samples/second
2	Phasors	Vr, Vy, Vb magnitude & angle Ir, Iy, Ib magnitude & angle Frequency and df/dt
3	Sequence components of phasors	V+, V-, V0
4	Analog	MW, MVAr, pf
5	Communication profile	UDP
6	Communication protocol	C37.118
7	Bandwidth	64 kbps

3.3.1 Specifications

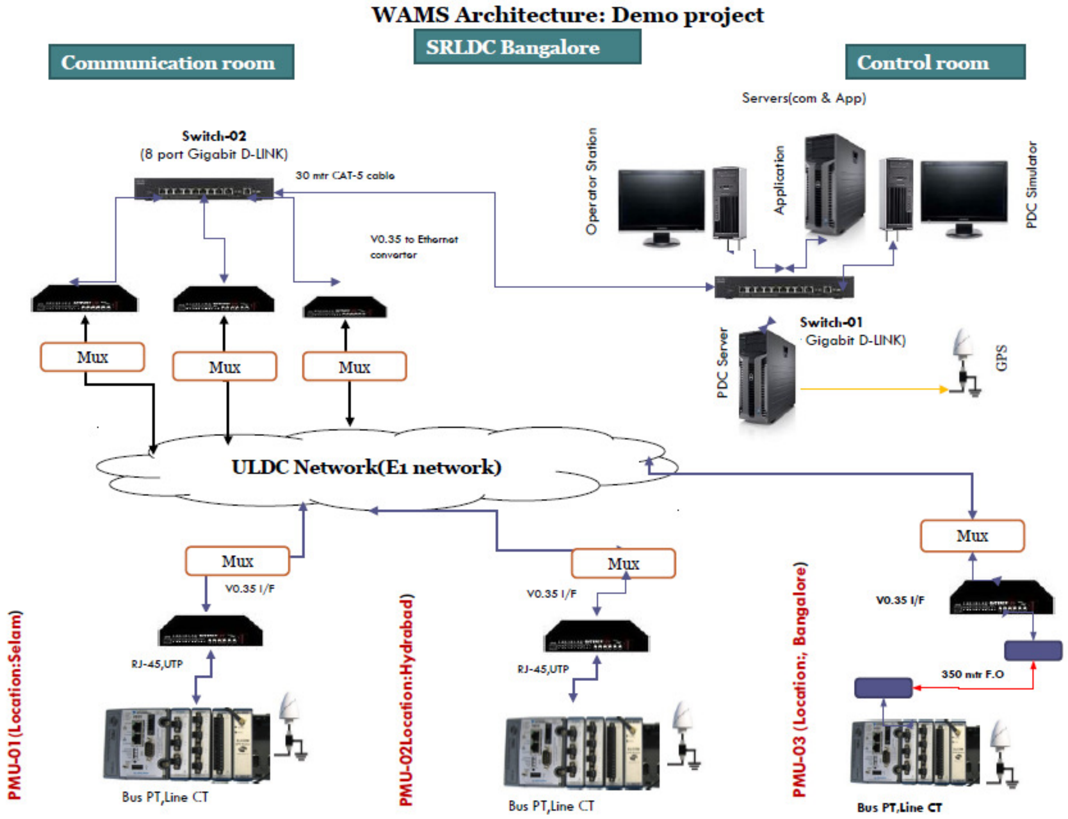


Figure 34: Architecture in Southern Region

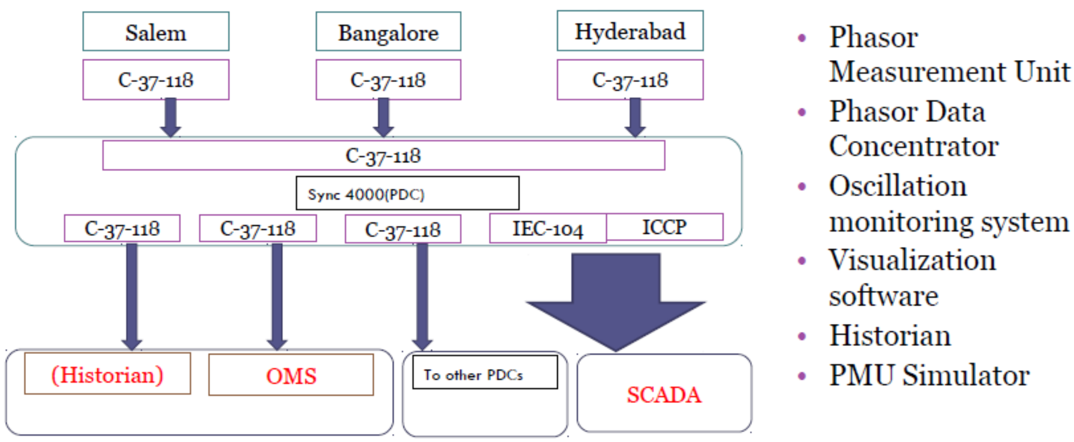


Figure 35: Data flow and protocols in Southern Region

3.3.2 Displays in Operator Console

This console provides the following information in real time

i. Frequency at the three locations

ii. Angle difference

iii. Voltage magnitude

iv. Power flow

These can be configured to give visual alarm as per the threshold limits set for each parameter. It has user selectable views geographical and bus view as per operator preference.Typical displays available in operator console at SRLDC, Bengaluru are given below:

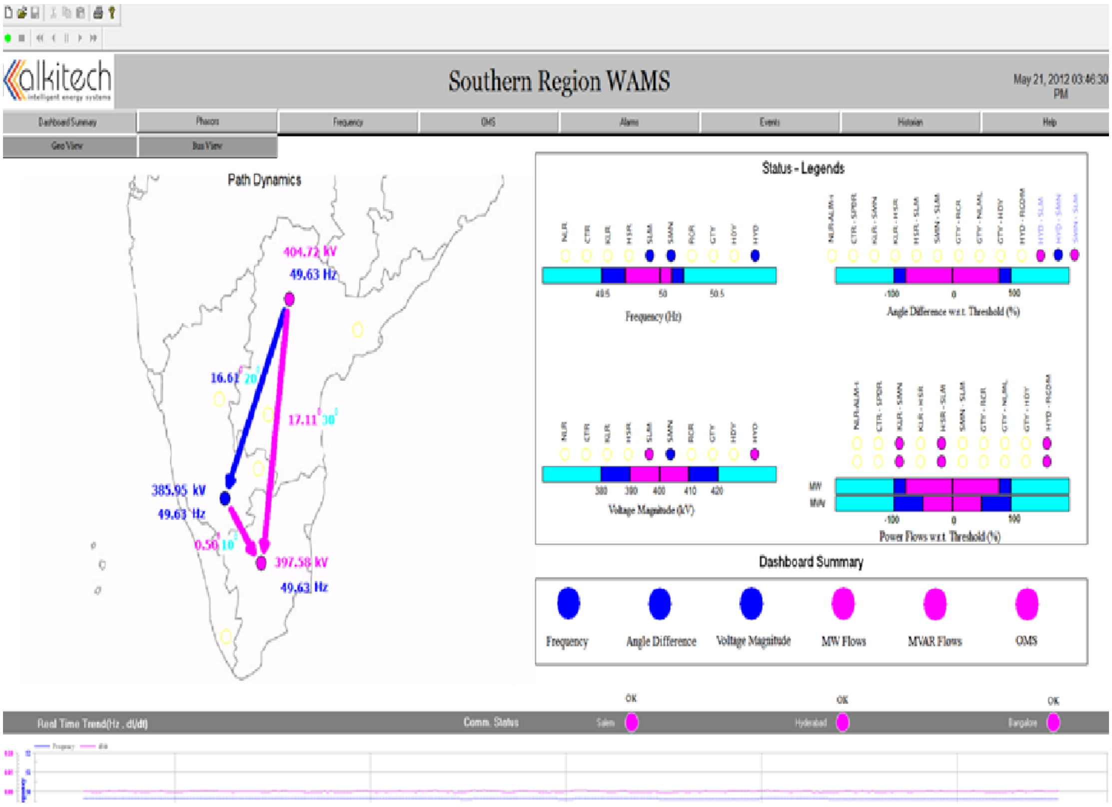


Figure 36: Geographical display of PMUs and operator alarm display

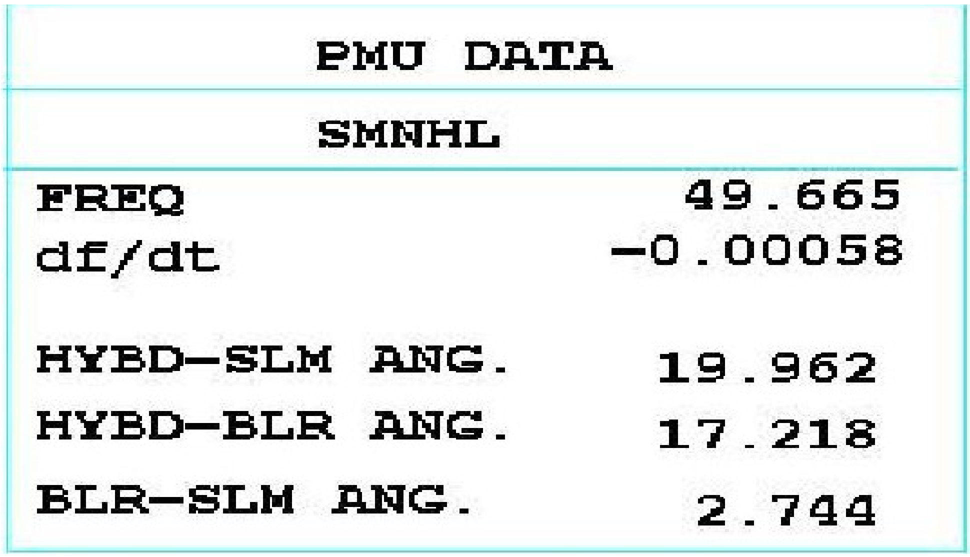


Figure 37: Synchrophasor display integrated in SCADA display

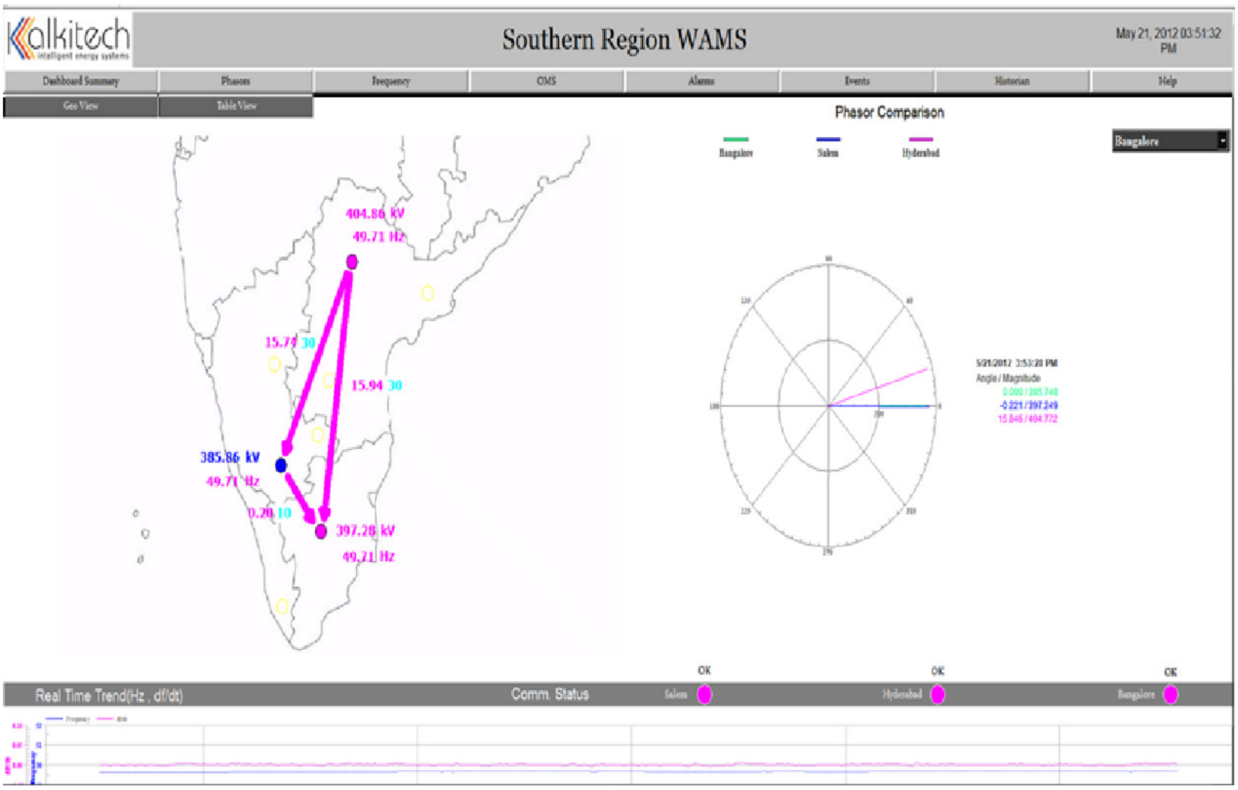


Figure 38: Dial display of angular separation

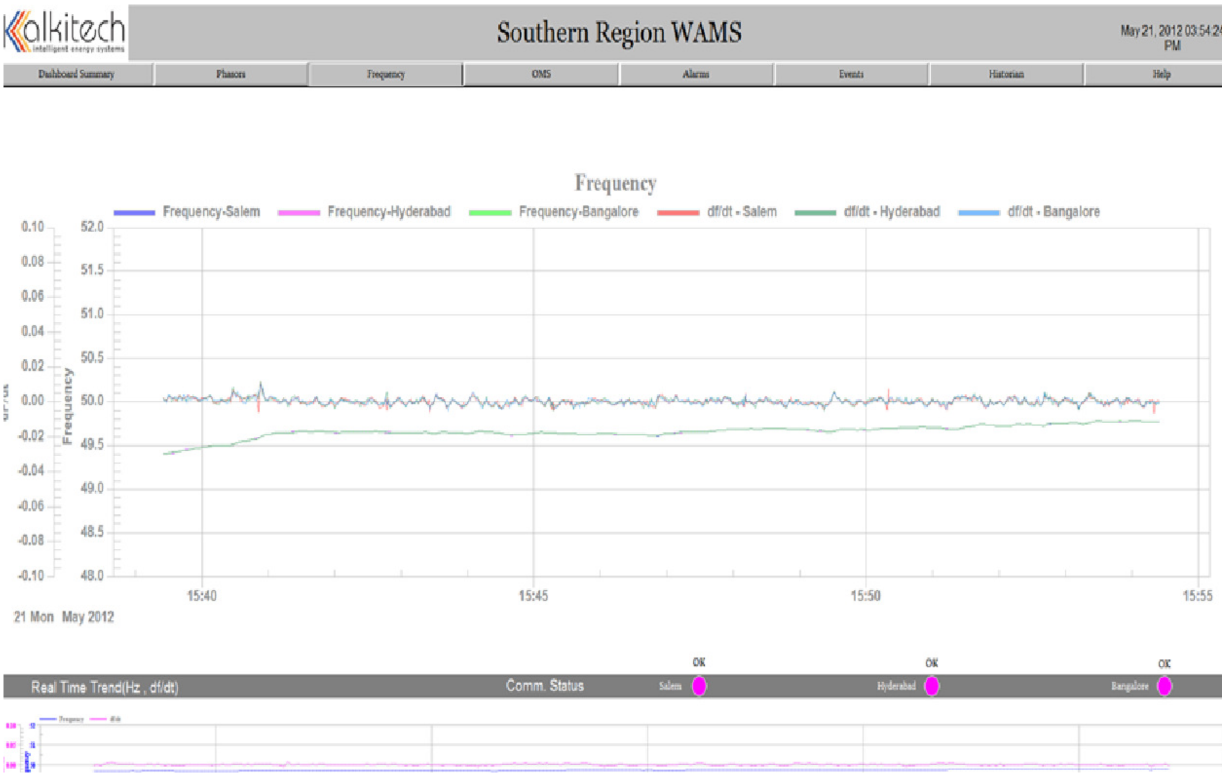


Figure 39: Frequency trend display

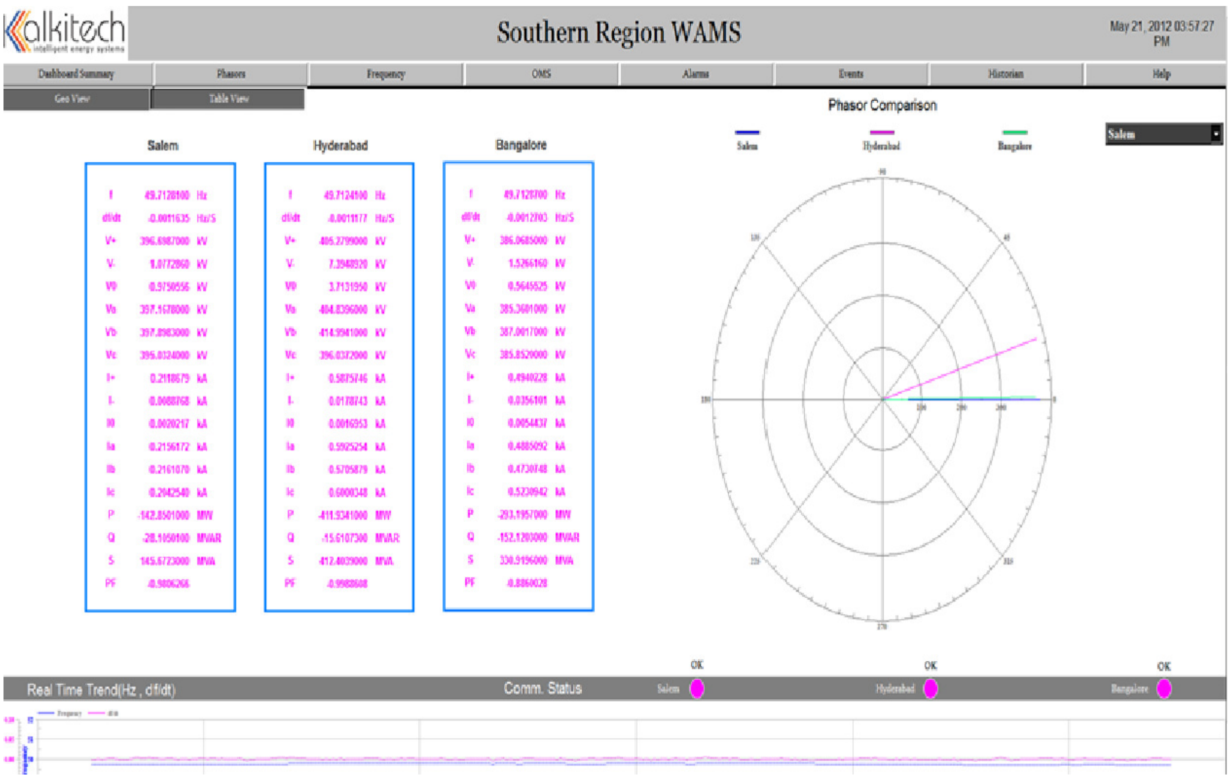


Figure 40: Tabular and dial display

3.3.3 Displays in Historian

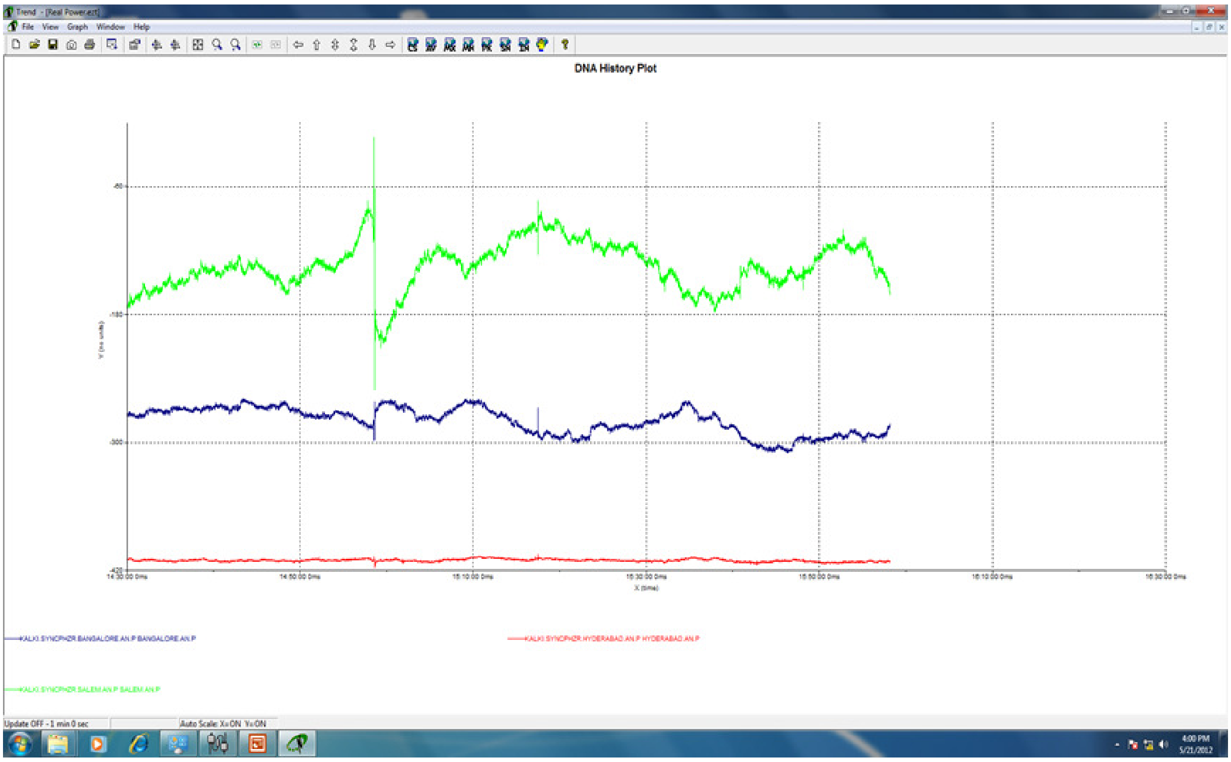


Figure 41: Typical display in Historian

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CHAPTER 4: UTILIZATION OF SYNCHROPHASORS IN REAL TIME

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. SCADA data has 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. The synchrophasors technology overcomes the above limitations to a large extent and it has been found to supplement the real time data available from SCADA/EMS. Two sets of displays are available; one set of displays with data from Historian and second set of displays with real time data from PDC. Few customized displays have been prepared for the operators. Displays are presently of three types- tabular display, dial display and trend display.

In control room the synchrophasor data has helped in improving/enhancing situational awareness through real time monitoring of frequency, df/dt, angular separation and voltage. It is possible to recognize the occurrence of transmission line tripping/ revival within a flow gate by observing the step change in angular separation, step change in voltage magnitude, step change in line current (MW & MVAR). It is also possible to recognize the occurrence of generator tripping by observing the frequency decline, increase in df/dt, change in angular separation, decrease in voltage magnitude. Occurrence of load crash/ load throw off can be observing sustained High frequency, sustained abnormal phase angle separation, Sustained High voltage. It also helps in subsystem synchronization during restoration by using standing phase angle separation and phase sequence.

4.1 Visualization of grid frequency

A synchronous system is generally characterized by a same frequency at all nodes in steady state as observed in SCADA/EMS.

4.1.1 Case Study-1: Difference in frequency at different locations in Northern Region

Figure 42 and 43 show the frequency profile recorded by PMU's on 23rd May 2010 and 3rd January 2011. The difference in the frequency at Vindhyachal, Kanpur, Dadri and Moga can be clearly seen from the synchrophasors data. All these four nodes are located far from each other within the synchronous grid.

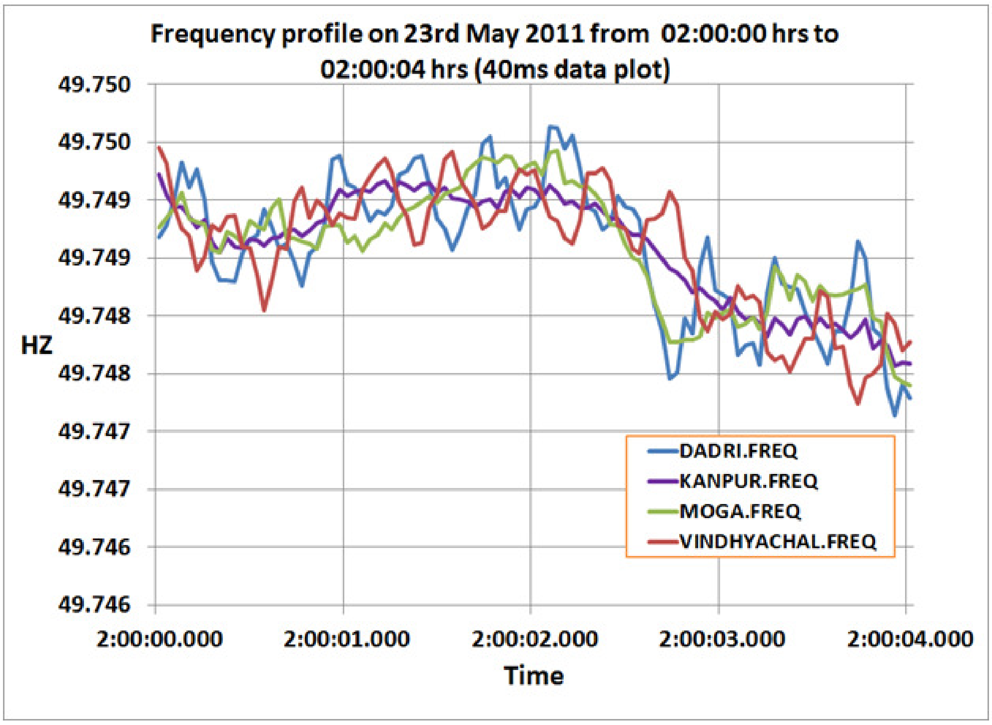


Figure 42: Difference in frequency profile at Dadri, Kanpur, Moga, Vindhyachal-1

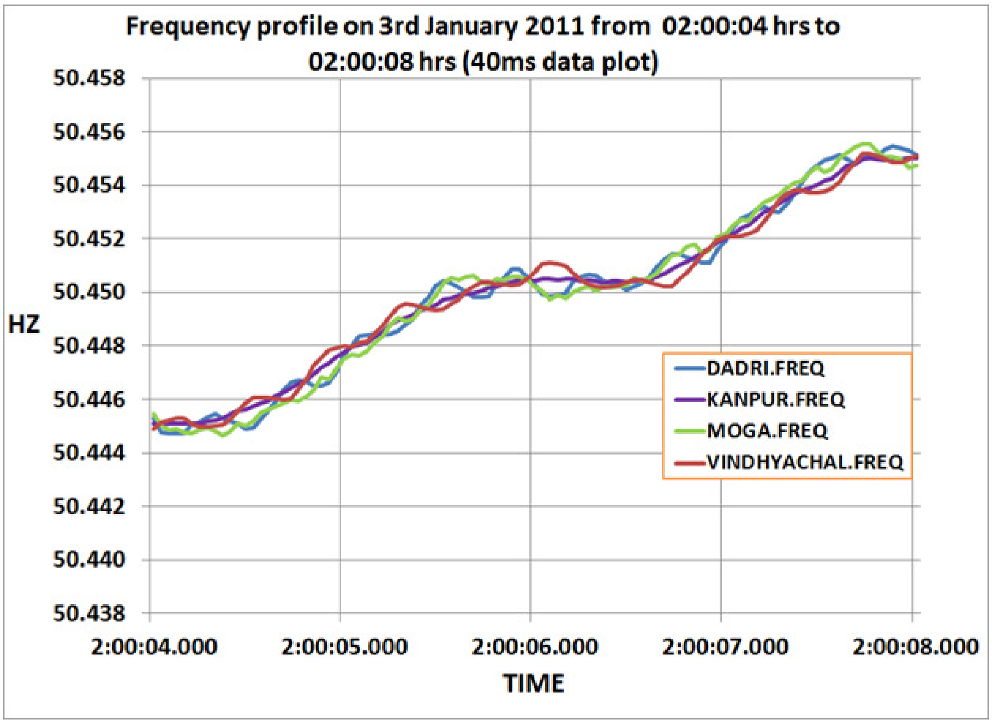


Figure 43: Difference in frequency profile at Dadri, Kanpur, Moga, Vindhyachal-2

4.2 Visualization of angular separation between two nodes in the grid

$$\delta = \sin^{-1}\left[\frac{P.X}{V1.V2}\right]$$

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. This has been illustrated with the help of plot showing variation in angular separation between Vindhyachal/Kanpur/Dadri/Agra/Hisar/Bassi/Moga during the following four grid incidents:

- Complete 400/220 kV Allahabad substation handling 1900 MW;
- Tripping of $\pm$ 500 kV Rihand-Dadri HVDC bipole carrying 1400 MW
- Tripping of 400/220 kV ICTs at Greater Noida carrying 430 MW
- Tripping of complete power station at Rihand STPS generating 2000 MW

4.2.1 Case Study-2: Complete outage of 400/220kV Allahabad

On 14th January 2012, a bus fault on 400 kV bus at Allahabad resulted into loss of all the incoming and outgoing lines at the 400/220 kV Allahabad substation handling 1900 MW. This power was diverted through other parallel circuits. The consequent change in the impedance and the voltage caused a change of 34 degrees in the angular separation between Vindhyachal and Kanpur which are located on either side of the 400/220 kV Allahabad.

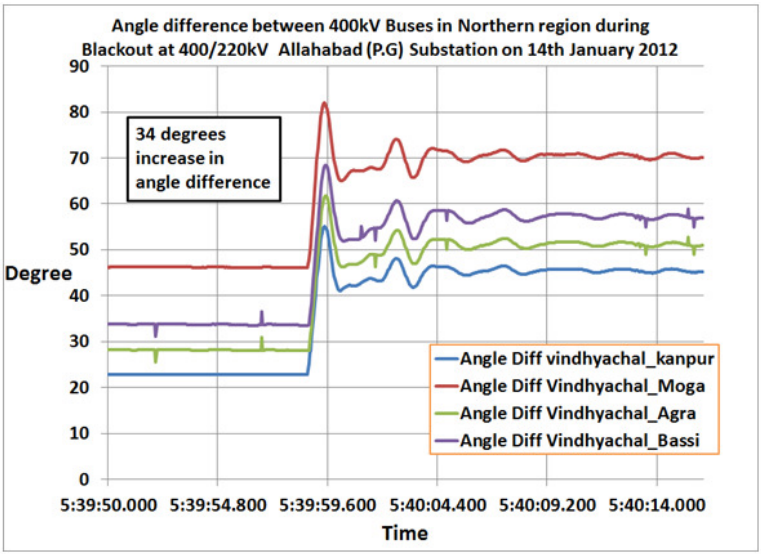


Figure 44: Angular difference between buses in NR during blackout at 400 kV Allahabad

4.2.2 Case Study-3: Tripping of HVDC Rihand-Dadri Bipole

± 500 kV Rihand-Dadri HVDC bipole is a high capacity transmission flowgate between the large generation complex in the South eastern part of Northern Grid and large load centre in the Western part of the Northern Grid. There are several other 400 kV lines running in parallel to this HVDC link. A System Protection Scheme is in place to run back generation in the generation complex and shed load at the load centre subsequent to the contingency of the bipole tripping.

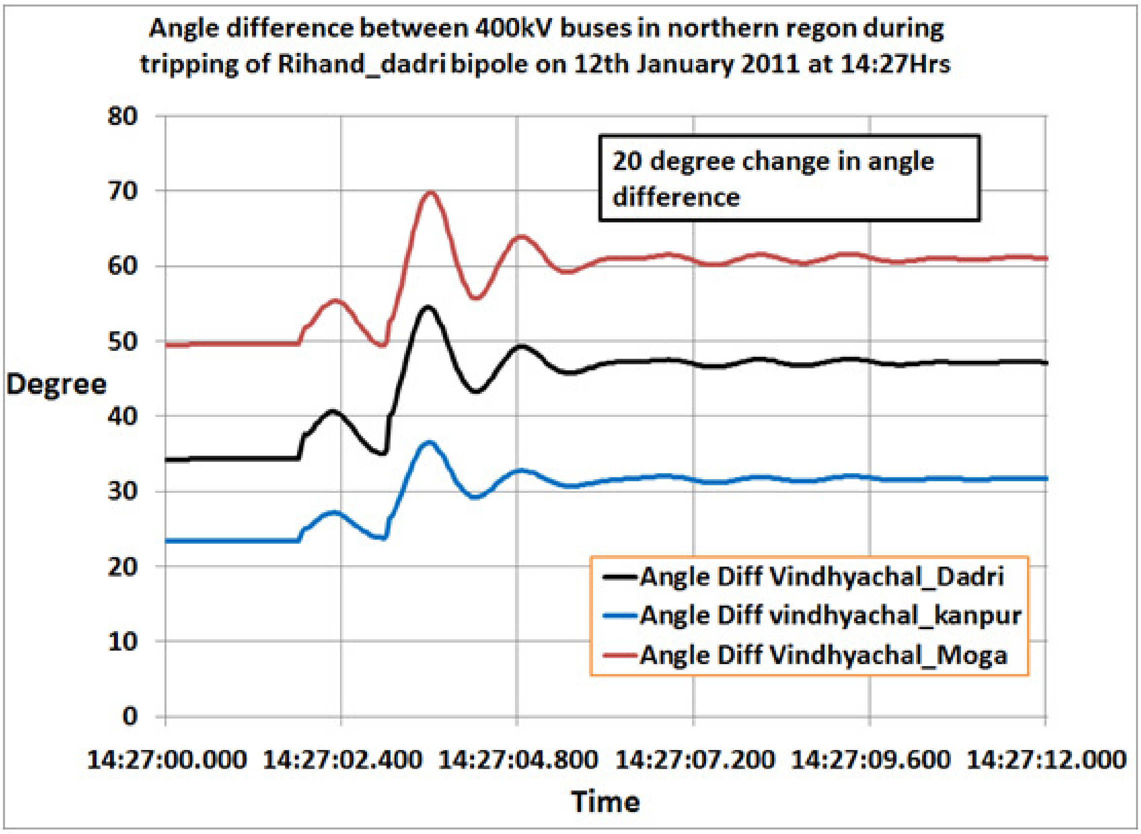


Figure 45: Angular difference during tripping of Rihand Dadri bipole

On 14th Jan 2012, the HVDC Rihand-Dadri pole-I and II tripped within a difference of 2 seconds. The increase in the angular separation can be clearly seen with the tripping of each pole. The total increase in the angular separation between Vindhyachal and Dadri was 20 degrees which reduced to 10 degrees due to the automatic corrective action due to successful operation of the System Protection Scheme.

4.2.3 Case Study-4: Tripping of ICT's and 400kV lines at Greater Noida

During this event three 400/220kV, 315 MVA ICT's carrying 430 MW power tripped resulting in load loss in the system. Also 400kV lines connected to the station tripped. It can be observed from figure that the initial swing in angle is 6 to 7 degrees and the angle settles down to at the same value as the antecedent angle. In this case there is decrease in power due to load loss due to which angle should decrease but due to counter action the angle settles down near to the antecedent value.

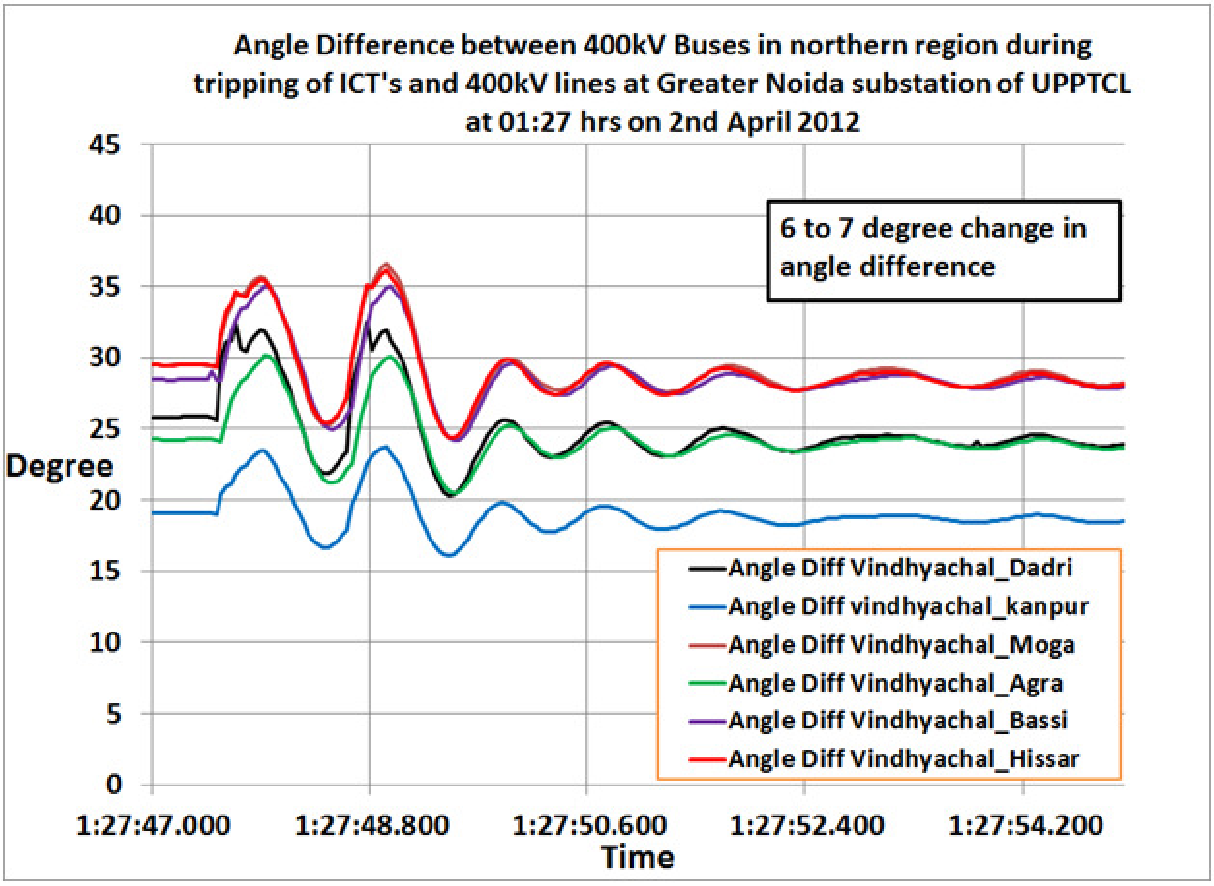


Figure 46: Swing observed in angles during multiple trippings at 400 kV Greater Noida

4.2.4 Case Study-5: Loss of generation at Rihand STPS

Rihand STPS has an installed capacity of 2000 MW (4 x 500 MW). During the loss the complete power station a decrease of 10 degrees in the angular separation between Vindhyachal and Moga can be seen in Figure 47.

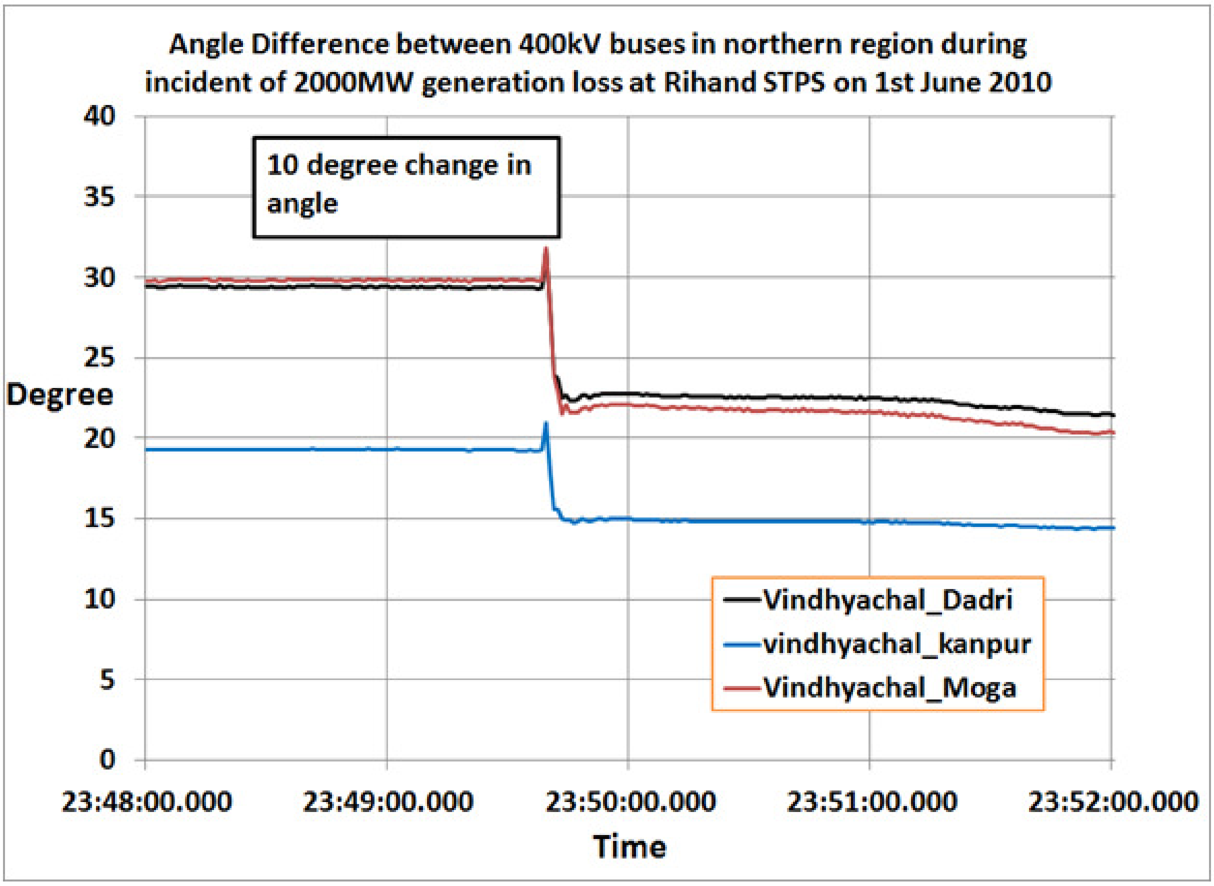


Figure 47: Angular separation during generation loss at Rihand

CHAPTER 5: UTILIZATION OF SYNCHROPHASOR IN OFF LINE

The synchrophasors data from the PMUs archived in the historian has been utilized extensively in analysis of grid events and validation of protection system. These applications have been illustrated with the help of case studies in the sections ahead.

5.1 Identifications of the type, nature and duration of fault

A fault in A.C system gets reflected in the entire synchronized grid. Hence it is possible to analyze the fault at a particular location by analyzing PMU data of any other substation connected in the grid. Using voltage and current 40 ms data plots, it is possible to find out the type of fault, fault duration, successful/ un-successful auto-reclosure and operation/ mis-operation of protection system.

Faults in transmission line could be balanced (Three phase line to line or line to ground) or unbalanced (Line to line or line to ground). During the fault, the voltage in the faulted phase dips sharply while the current rises sharply. The voltage/current normalize after the fault is cleared by operation of the protective switchgear. Thus, the examination of the 3-phase voltage/current trends available from synchrophasors would reveal the time of the fault, the type/nature of fault that has occurred and the duration in which it was cleared.

5.1.1 Case Study-6: Three phase fault at 400kV Dadri on 13-Mar-2012

The figure below shows the 400kV Agra bus voltage profile (Phase to Earth) during the three phase fault at 400 kV Dadri at 17:37:920 hrs on 13th March 2012. It can be observed that there is a sharp dip in voltage in all the three phases.

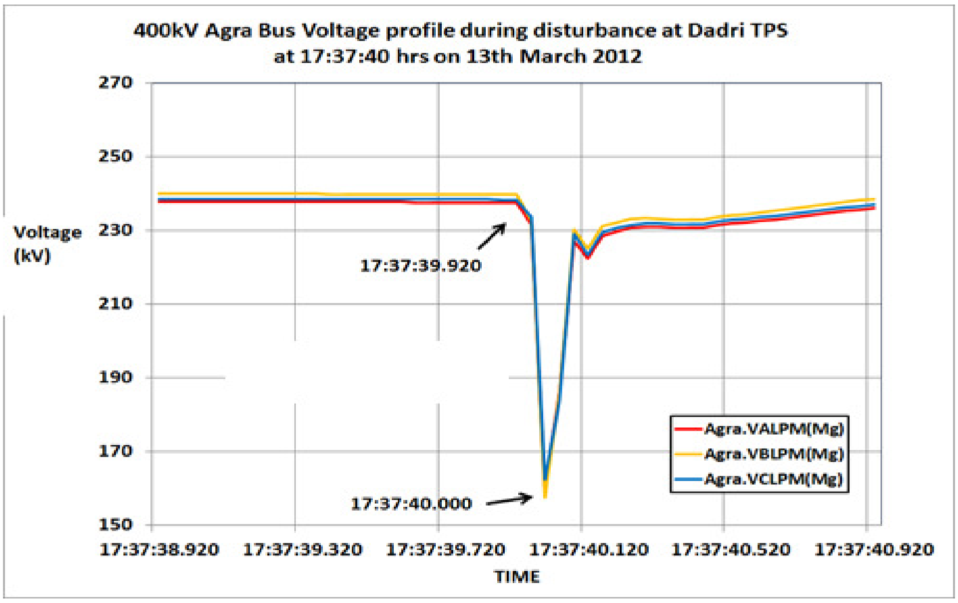


Figure 48: Dip in phase voltage at 400 kV Agra during 3 phase fault at 400 kV Dadri

Figure 49 shows the 400kV Agra-Gwalior ckt-2 line current during the occurrence. It is evident that there is an increase in current in all the phases. Hence the occurrence of 3 phase fault is confirmed. This was also confirmed from the information available from substation.

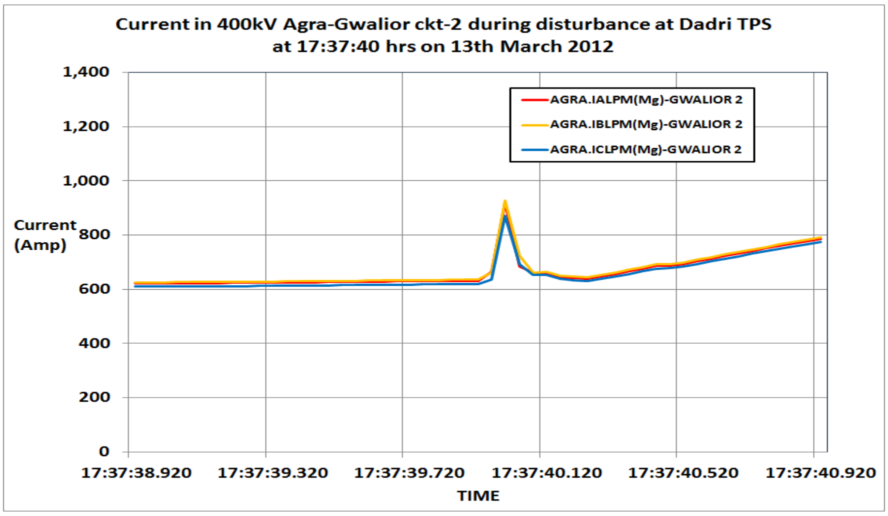


Figure 49: Increase in phase current in 400 kV Agra-Gwalior ckt 2

5.1.2 Case Study-7: 1 phase fault on 400 kV Bassi-Heerapura-I on 2-Jan-2012

Figure 50 shows voltage profile of 400kV Bassi substation during the transient fault in R phase of the 400 kV Bassi-Heerapura –I. The voltage dip in R phase can be seen while the remaining Y & B phase voltage is healthy. The voltage starts recovering after 80 ms which indicates that the single phase fault transient is in R phase of the circuit. The fault got cleared within the auto reclosure time.

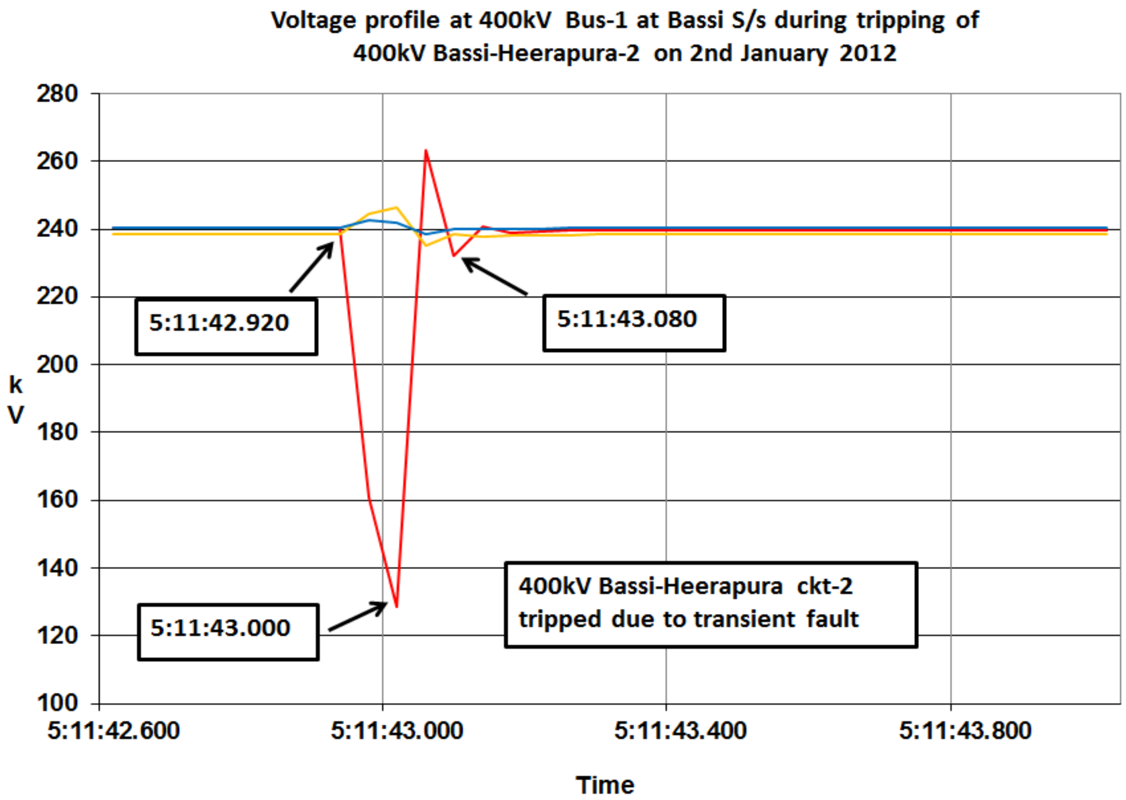


Figure 50: Dip in R phase voltage at Bassi during tripping of 400 kV Bassi-Heerapura II

5.1.3 Case Study-8: Multiphase fault at Khedar TPS on 5-Apr-2012

Figure 51 shows 400kV Hisar bus voltage profile during the occurrence of a multiphase fault at Khedar TPS in Northern region. It can be observed that the 1st fault in B-phase got cleared in around 200ms. A second fault involving R & Y phase occurs 680milli second after occurrence of 1st fault. The second fault gets cleared in 120 milli seconds.

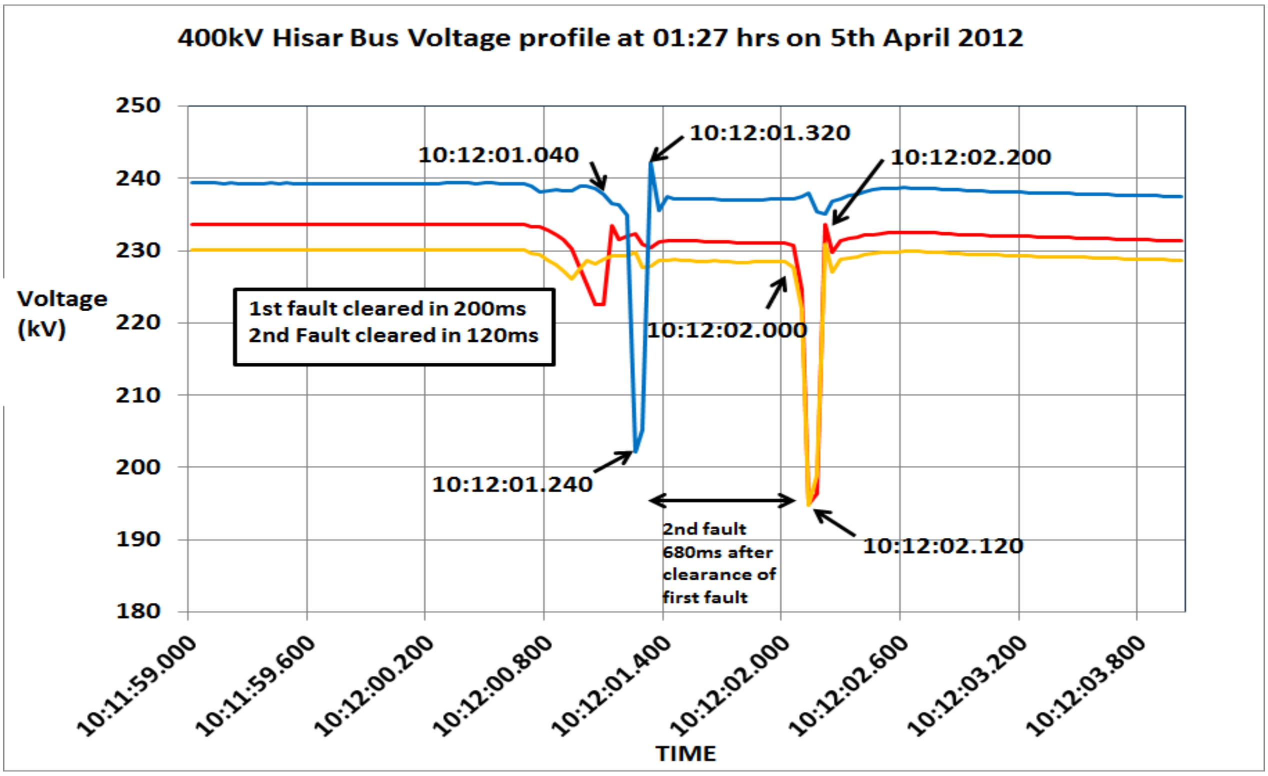


Figure 51: Voltage profile corroborating the fault clearance time at Hissar

5.1.4 Case Study-9: Tripping at 400kV Muradnagar & Moradabad on 29-May-2011

Voltage profile at 400kV Kanpur Bus during incident of multiple tripping at 400kV Muradnagar and Moradabad Substations is shown in the figure 52. It can be observed that there is delayed fault clearance i.e., in 520 milli seconds which is much beyond the fault clearing time as mandated in the Indian Electricity Grid Code (IEGC). This indicates the clearing of fault in Zone-2 time of distance protection. The same was validated based on field information.

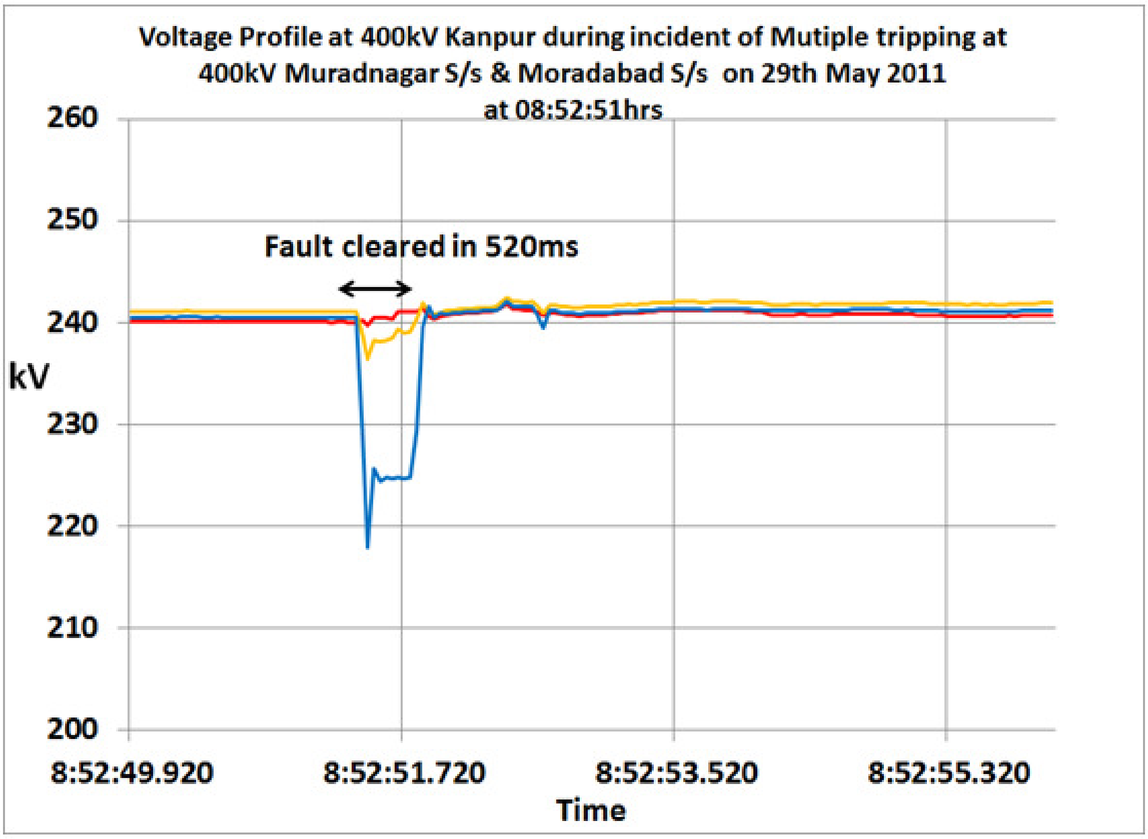


Figure 52: Detection of delayed fault clearance

5.1.5 Case Study-10: Generation loss at Rihand STPS on 1-June-2010

Voltage profile at 400kV Vindhyachal bus during incident of generation loss at Rihand STPS in Northern region is shown at figure 53. It can be seen that the fault got cleared in around 320milli seconds which indicated the possible operation of Local breaker Backup protection. The same was confirmed by the information received from substation.

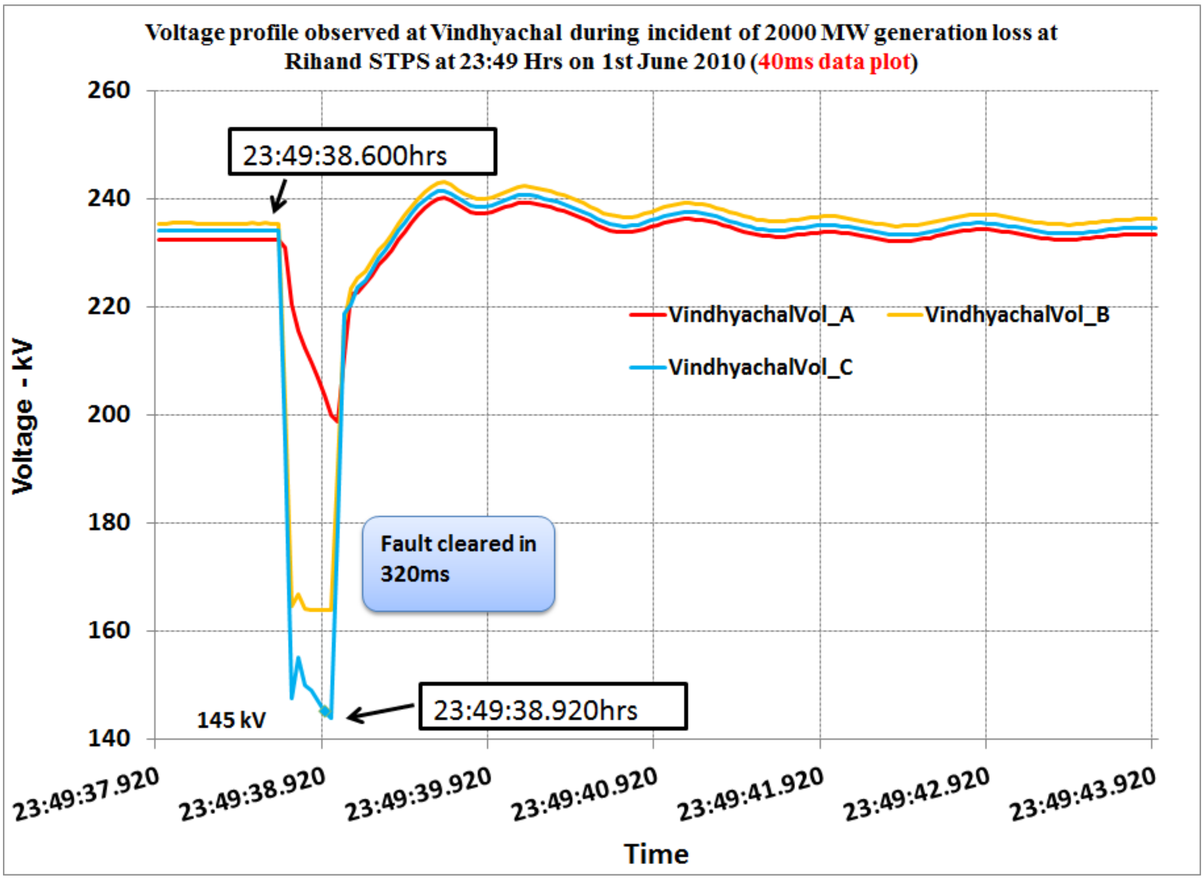


Figure 53: Voltage profile at Vindhyachal indicating the probable operation of LBB protection

5.1.6 Case Study-11: Multi-phase fault at Bamnauli on 20-Jan-2012

The figure below shows the voltage profile of 400kV Dadri bus during occurrence of multiphase fault at Bamnauli substation in Northern region. It can be made out from the graph that the fault got cleared in 920 milliseconds. The same was later confirmed from the information received from substation.

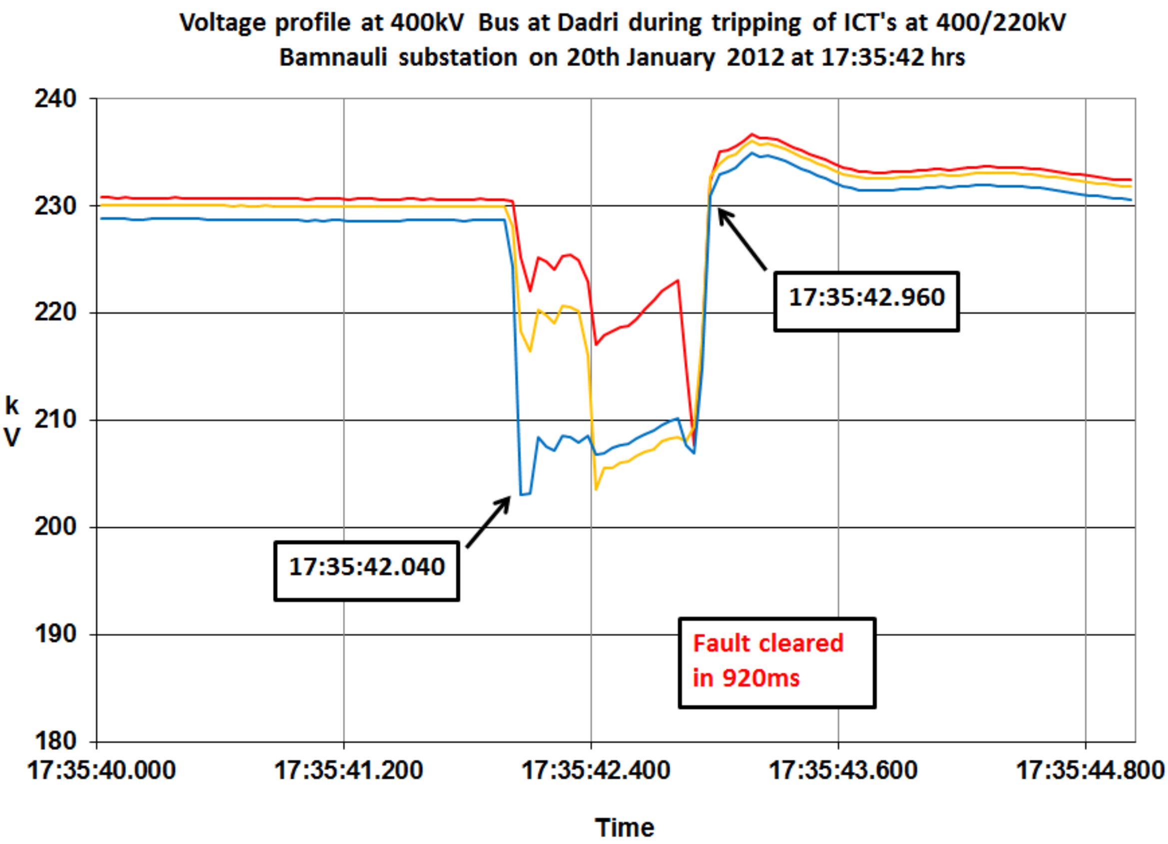


Figure 54: Voltage profile at Dadri indicating possible operation of back up protection

5.1.7 Case Study-12: Fault at 400kV Bareilly on 2-Jan-2011

Voltage profile of 400kV Kanpur bus during occurrence of fault at 400kV Bareilly (UPPTCL) substation in Northern region is shown in figure 55. It can be interpreted that there is an initial fault in R-phase, the dip in voltage does not recover fully and remains for around 20 seconds which is much beyond the fault clearing time mandated IEGC. Then there is a 2nd fault in B-Phase and fault gets cleared. The less dip in voltage for 20 seconds after occurrence of 1st fault indicates a high resistance fault.

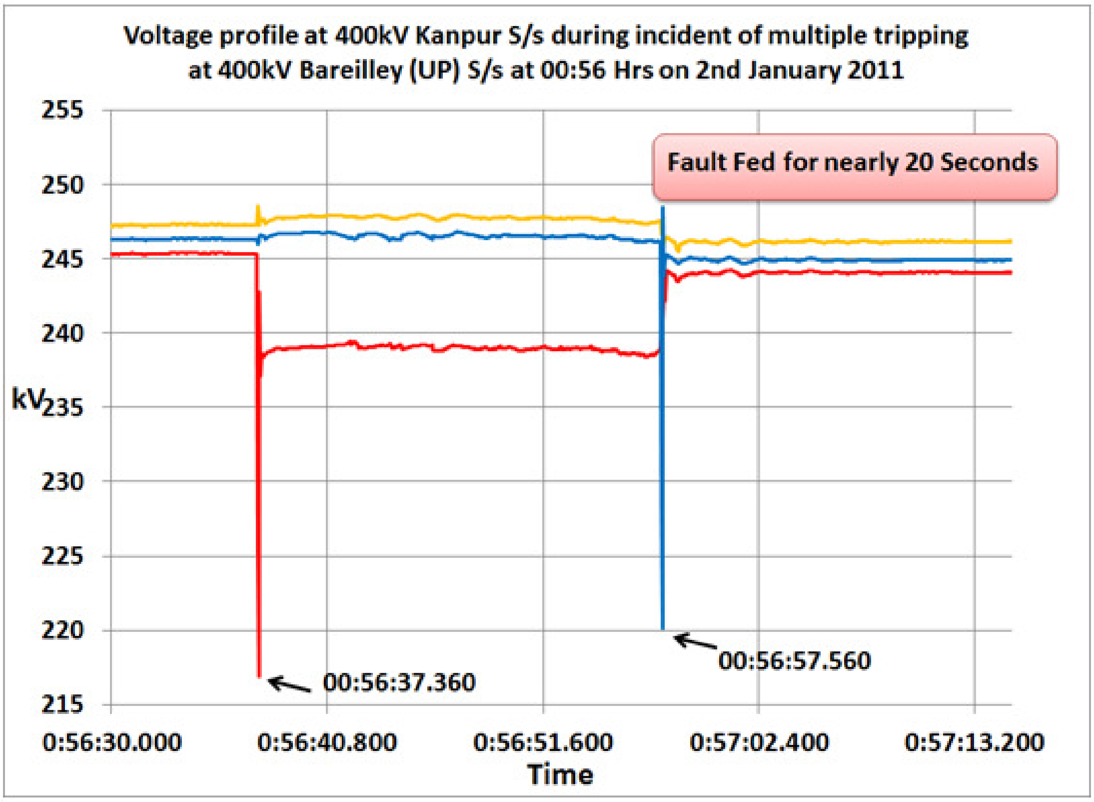


Figure 55: Voltage profile at Kanpur showing delayed clearance of fault

5.1.8 Case Study-13: Tripping of HVDC Rihand-Dadri Bipole on 12-Jan-2011

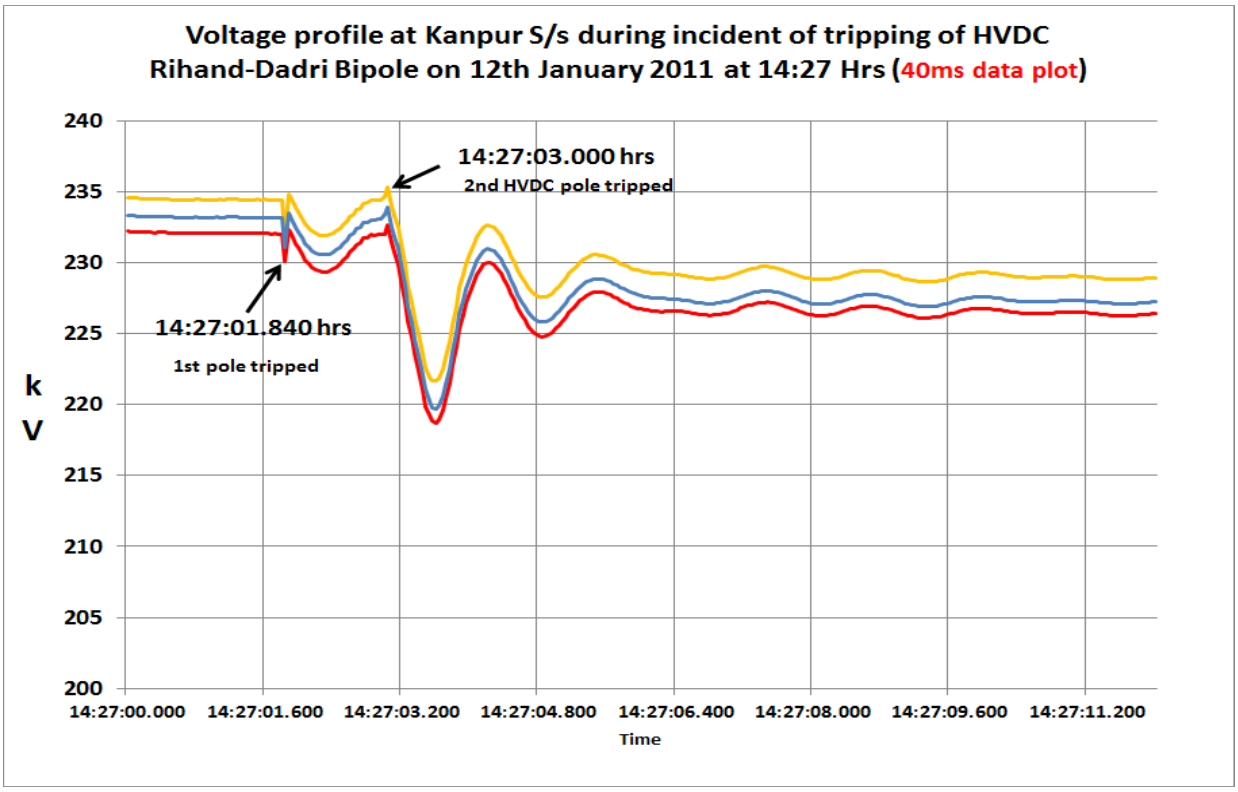


Figure 56: Dip and rise in voltage profile at Kanpur

The graph above shows voltage profile at 400kV Kanpur Bus during tripping of HVDC Rihand-Dadri Bipole. Some rise and dip in voltages were observed during tripping of HVDC pole-1 & pole-2.

5.1.9 Summary of fault analysis using synchrophasors data

The synchrophasor data has been extremely useful in forensic or post event analysis even in the absence of disturbance recorder/Event logger prints in most cases.

Since the commissioning of 1st phase of synchrophasors in May 2010, the synchrophasor data has been utilized to analyze a total of 106 grid events. In several cases the vital information from Disturbance Recorder/Event logger installed at the substation was not available. In most cases the event analysis report was also not available. In all these cases the synchrophasors data proved to be extremely useful. Few of the grid events that occurred in 2012 wherein the synchrophasor data was the mainstay for post fault analysis has been tabulated below:

Table 8: Grid events in 2012 wherein synchrophasors were used for post fault analysis

Sl. No.	Date	Time	Event Details	Availability of		Events analyzed with PMU data
				Disturbance Record /Event log	Analysis report	
1	2-Jan-12	4:00 to 6:00	Multiple autoreclosure of 400kV Bassi-Heeerapura lines	Yes	No	Yes
2	12-Feb-12	10:20	Multiple tripping at 400/220kV Muradnagar Substation (UPPTCL)	No	No	Yes
3	14-Jan-12	5:39	Multiple tripping at 400kV Allahabad substation (PG)	Yes	No	Yes
4	20-Jan-12	17:35	Multiple tripping at 400kV Bamnauli substation (DTL)	No	Yes	Yes
5	13-Mar-12	17:37	Generation loss at Dadri TPS (NTPC)	No	No	Yes
6	2-Apr-12	1:26	Tripping of ICT's at Greater Noida substation (UPPTCL)	Yes	Yes	Yes
7	4-Apr-12	12:43	Multiple tripping at 400kVAzamgarh Substation (UPPTCL)	No	No	Yes
8	5-Apr-12	10:22	Multiple tripping and generation loss at Khedar TPS (HVPNL)	Yes	Yes	Yes
9	8-Apr-12	15:19	Multiple tripping at 765/400kV Unnao Substation(UPPTCL)	No	No	Yes
10	19-Apr-12	3:29	Generation loss at Anpara TPS (UPPTCL) & Rihand Stage-1(NTPC)	No	No	Yes
11	26-May-12	8:32	Generation loss and miltiple tripping in 220kV system of delhi and Haryana	No	No	Yes

5.2 Detection of fault in neighboring grids

The synchrophasors data provides a signature of the dynamic power system. In an interconnected synchronous system the effect of the perturbation in one part can be sensed at other parts with the help of data from synchrophasors.

5.2.1 Case Study-14: Three phase fault at 400 kV Bina on 22-Feb-2012

From figure 57 the voltage profile at 400 kV Dadri (in Northern Region) shows dip in voltage of all the three phases for a fault a 3 phase fault at 400/220kV Bina substation of MPPTCL (Western region). It can be seen that the fault got cleared in 520 milli second i.e. in Zone-2 time.

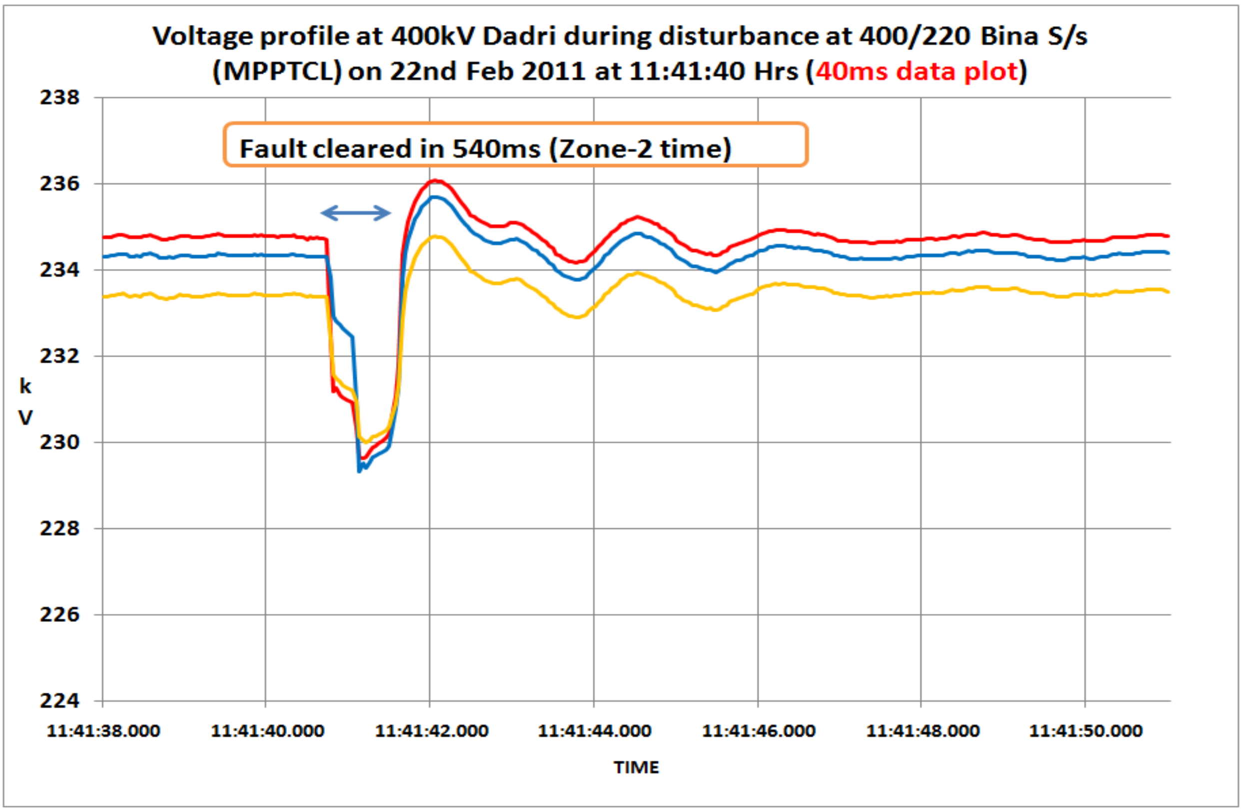


Figure 57: Dip in 3-phase voltage seen in Dadri (NR) during fault at 400 kV Bina (WR)

5.2.2 Case Study-15: Three phase fault at 400 kV Farakka on 16-Mar-2012

Similarly figure 58 shows the dip in voltage of all the three phases at 400kV Vindhyachal (Northern Region) can be seen during a 3 phase fault at Farakka STPS (in Eastern region). It can be seen that there was delayed fault clearance i.e. in 1280 milli seconds.

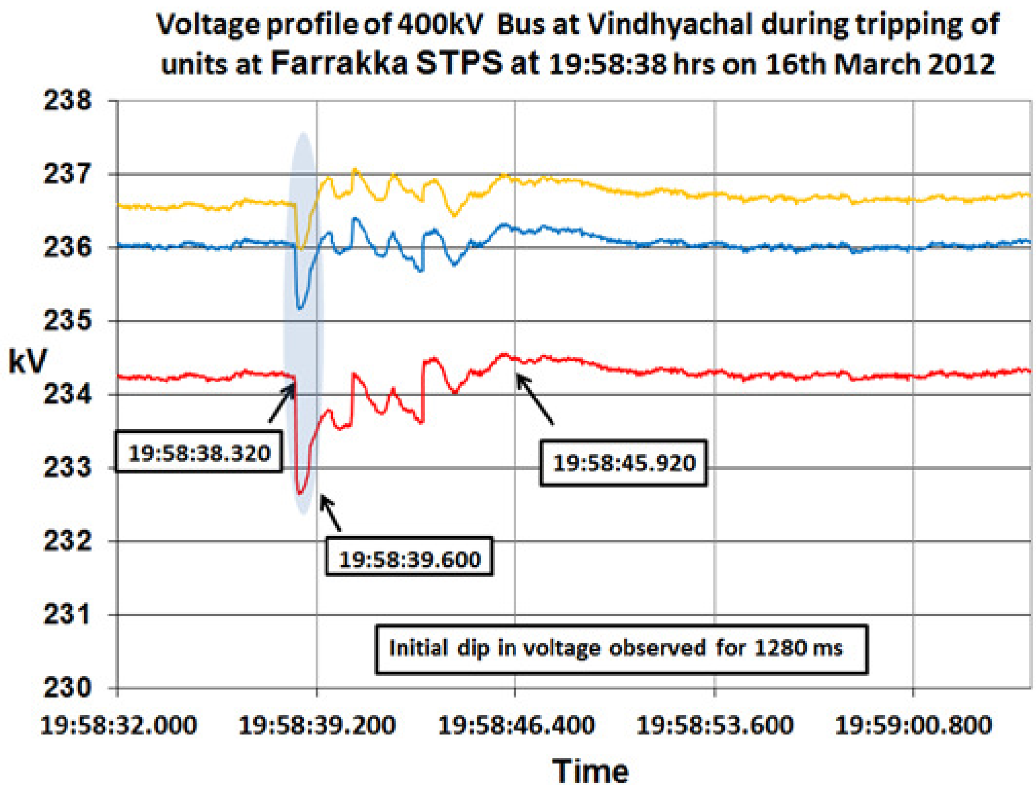


Figure 58: Voltage profile at Vindhyachal (NR) during tripping of units at Farakka STPS (ER)

5.3 Detection of exceptional grid events

Synchrophasor data has also been utilized to detect load throw off or generation loss in the grid as described ahead.

5.3.1 Case Study-16: Partial disturbance due to voltage collapse

A partial disturbance caused by voltage collapse occurred in 220 kV Punjab system on 20th July 2011. The voltage at 220 kV Bhatinda and 220 kV Lehra Mohabbat was reported to have gone as low as 78 kV and 92kV respectively. The voltage profile of 400 kV Moga bus during the event is shown in the below figure 59. It can be observed that there is around 4kV to 6kV dip in voltages in all the three phases of 400kV system for around 9 seconds. The bus voltage recovers after the cascade tripping.

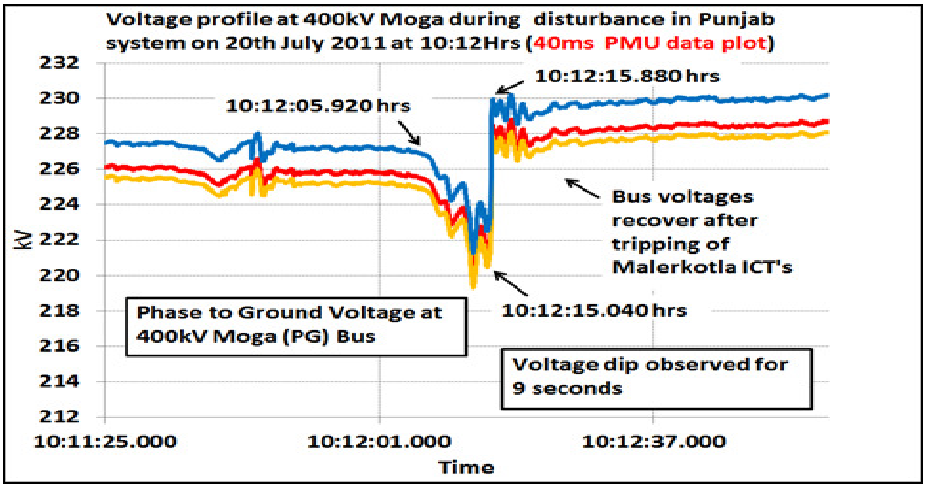


Figure 59: Dip in voltage at Moga during disturbance in Punjab system

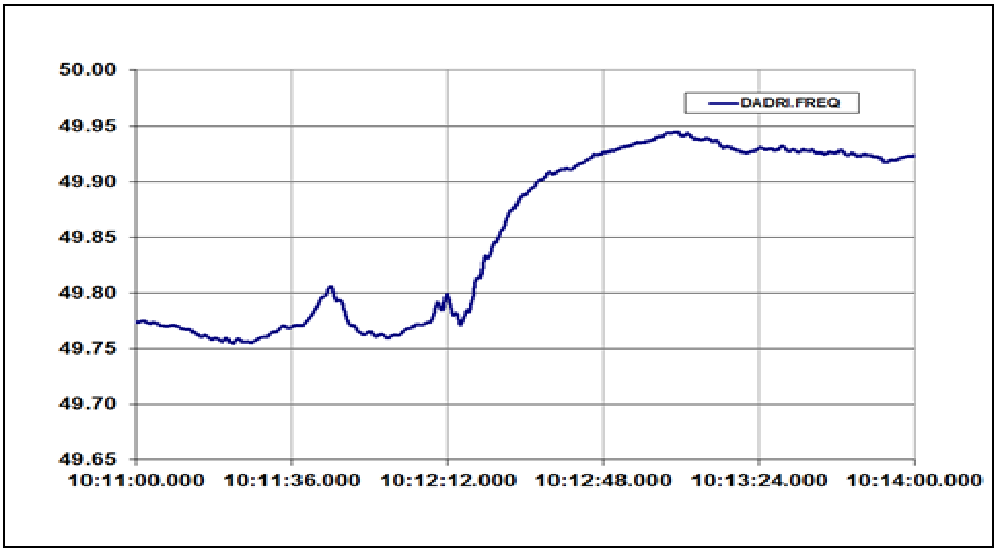


Figure 60: Increase in frequency during the incident in Punjab due to loss of load

5.3.2 Case Study-17: Cascade tripping at Roza on 02-Feb-2012

An incident of generation loss had occurred at Roza TPS on 2nd February 2011 at 15:14hrs. It was inferred from voltage plot of Dadri PMU (refer figure 62) that there was a transient fault in B-phase at 15:14:21.600hrs. After nearly 13 seconds a dip in three phase voltage of around 2 kV is observed. One of the evacuating feeders i.e., 220kV Roza-Shahjahanpur had tripped due to transient fault and the remaining lines evacuating power from Roza TPS had tripped due to cascading after 13 seconds which is indicated by the dip in voltage in all the phases.

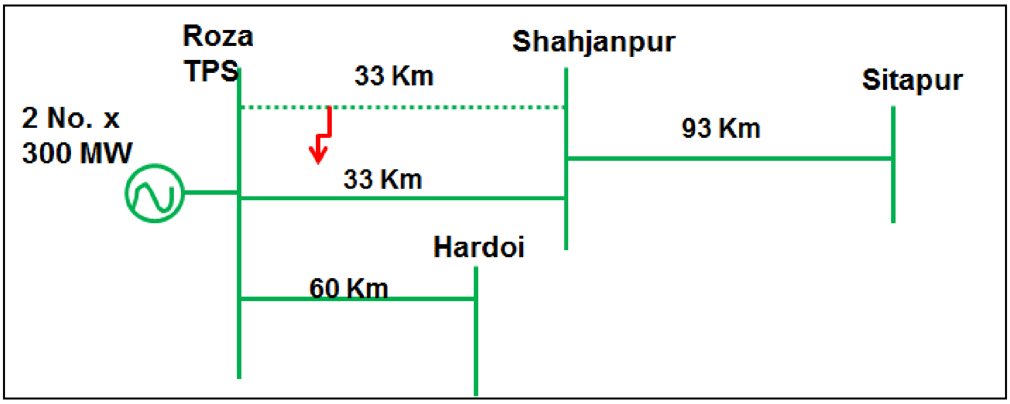


Figure 61: Connectivity diagram of Roza TPS in Northern region

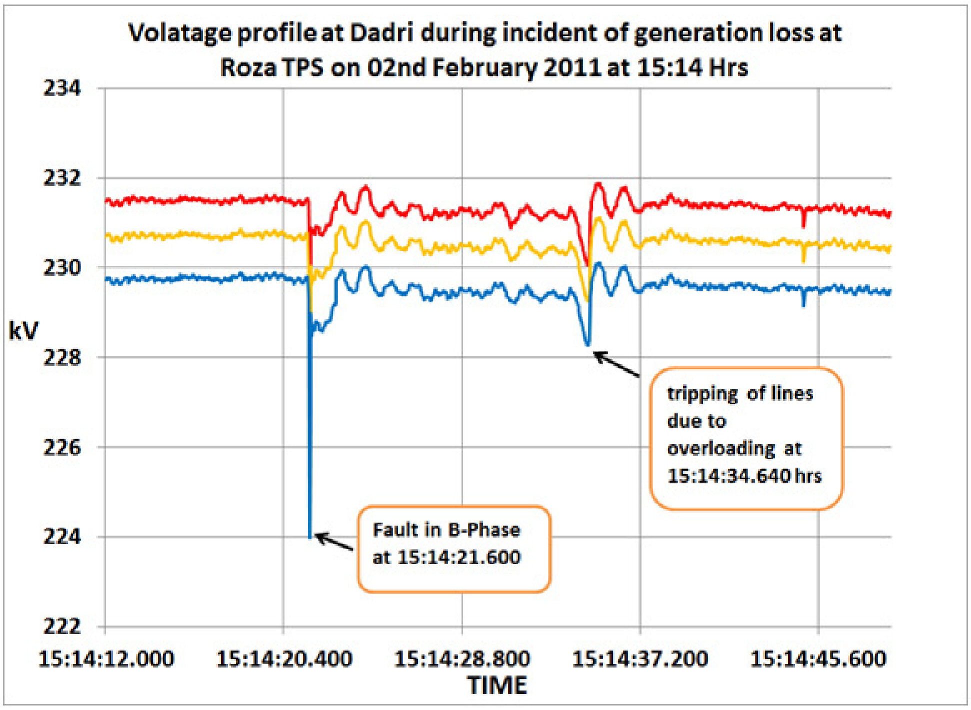


Figure 62: Dip in voltage at Dadri during generation loss at Roza TPS

From the frequency plot shown at figure 63 it can be observed that there is a fall in frequency which indicates a generation loss. Also the frequency starts to fall after 15:14:34.800 hrs which indicates the tripping of units on over-speeding due to tripping of associated evacuating lines.

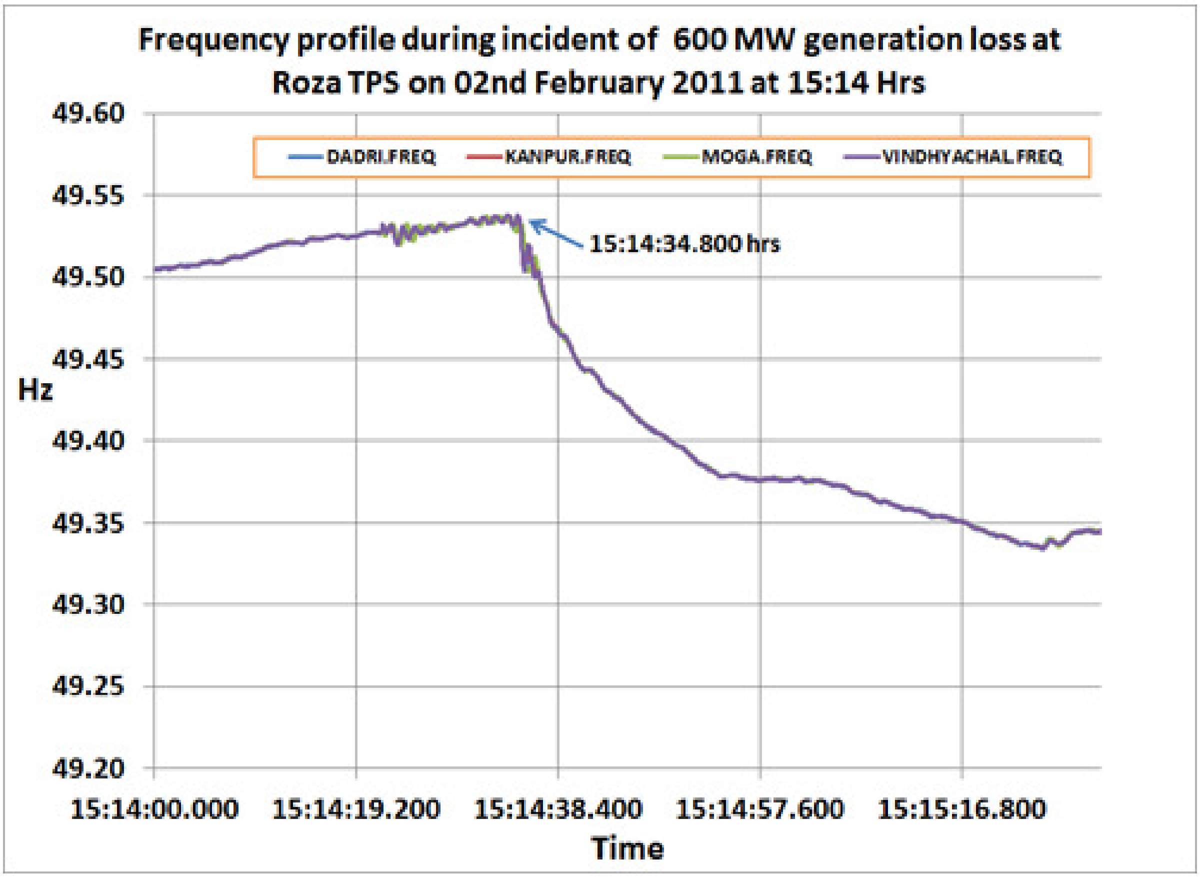


Figure 63: Fall in frequency during 600 MW generation loss at Rosa TPS

5.3.3 Case Study-18: Load crash in NR on 20, 21, 22-May 2011

Thunderstorm and rains swept across large parts of Northern Region during the night and early morning hours of 20th ,21st and 22nd May 2011. The drop in temperature resulted in drastic reduction in the weather beating and agricultural loads. Consequently load crash was experienced on three consecutive days during morning hours of 20th, 21st and 22nd May 2011.

In the Northern Region the major pit head super thermal power stations are located in the South eastern part while the major snow-fed hydro stations are located in the North-western part of the grid. The load centre is located in and around the National Capital Region (NCR). In the month of May the hydro generation is at its peak level. Consequently the direction of power flow is generally from South-east towards NCR and from Northwest towards NCR. The angular separation between the nodes close to the generation and load centre on the day of load crash vis-vis on a typical day in the month of May is shown in the figures 64, 65.

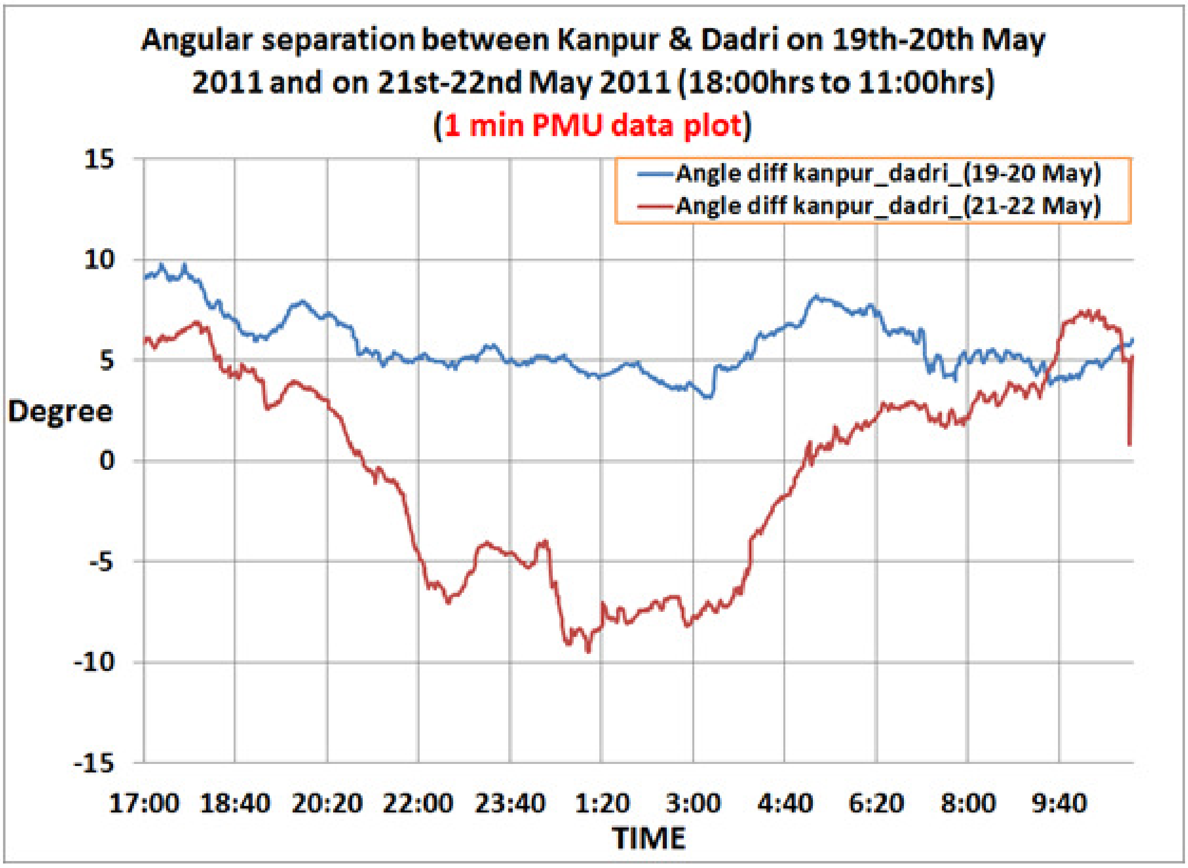


Figure 64: Angular separation between Kanpur and Dadri

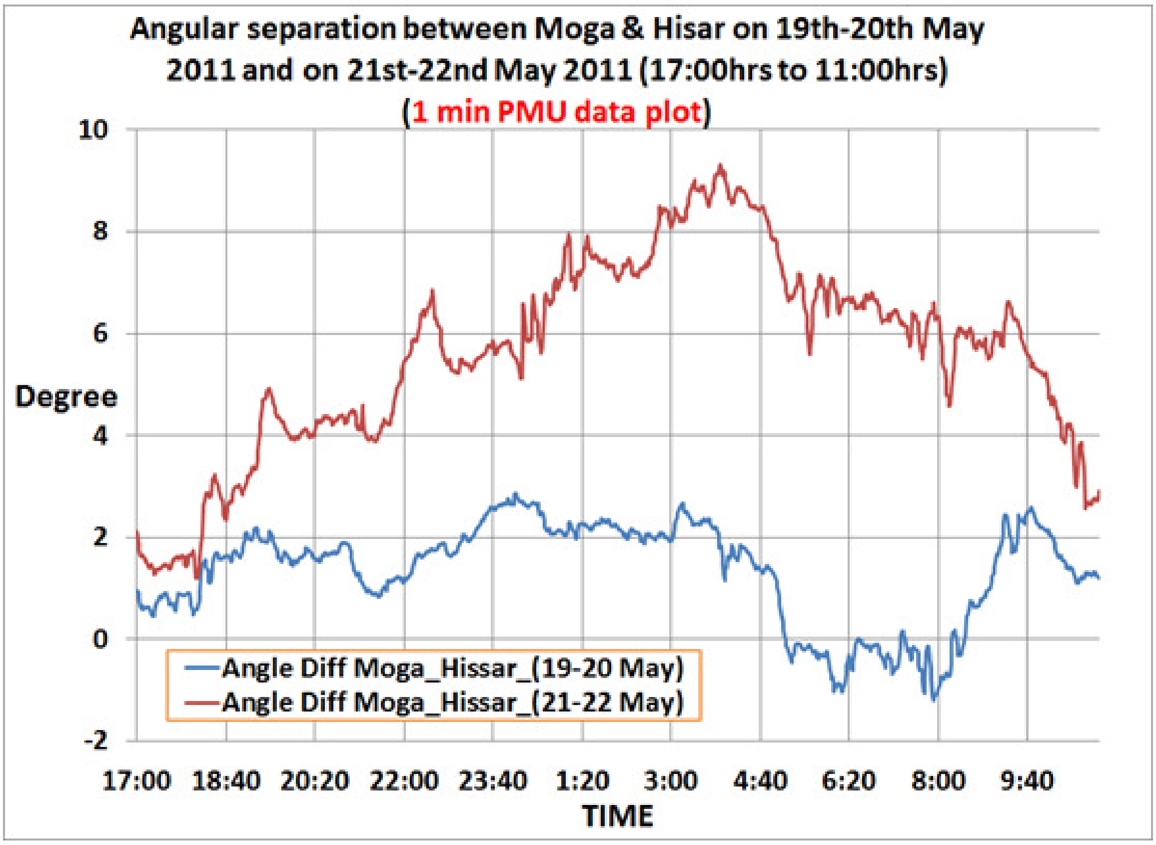


Figure 65: Angular separation between Moga and Hissar

It would be seen that on a typical day the voltage Phasor at 400 kV Kanpur (close to major thermal generation) leads the voltage Phasor at 400 kV Dadri (close to load centre). Likewise the voltage Phasor at 400 kV Moga (close to hydro generation) leads the voltage Phasor at 400 kV Hisar (near load centre). On the day of load crash the angular separation has been steadily increasing between the generation and the load centre. In fact the voltage Phasor of Dadri reverses its position and starts leading the voltage Phasor at Kanpur.

5.3.4 Case Study-19: Visualization of the charging of 765kV line on 11-Apr-2012

765kV Fatehpur-Gaya line was charged on 11th April 2012 at 19:06hrs. The line reportedly tripped after few minutes of charging. The synchrophasor data was analyzed for this event. Figure 66 below shows the 400kV bus voltage profile at 400kV Kanpur substation. It can be observed that immediately upon charging the 765kV line there is an increase in voltage in 400kV system. This rise in voltage was observed for around 1 min & 45 seconds after which the voltage drops down to the level before charging of 765kV line. This also indicates the tripping of 765kV line at 19:08:05.800hrs.

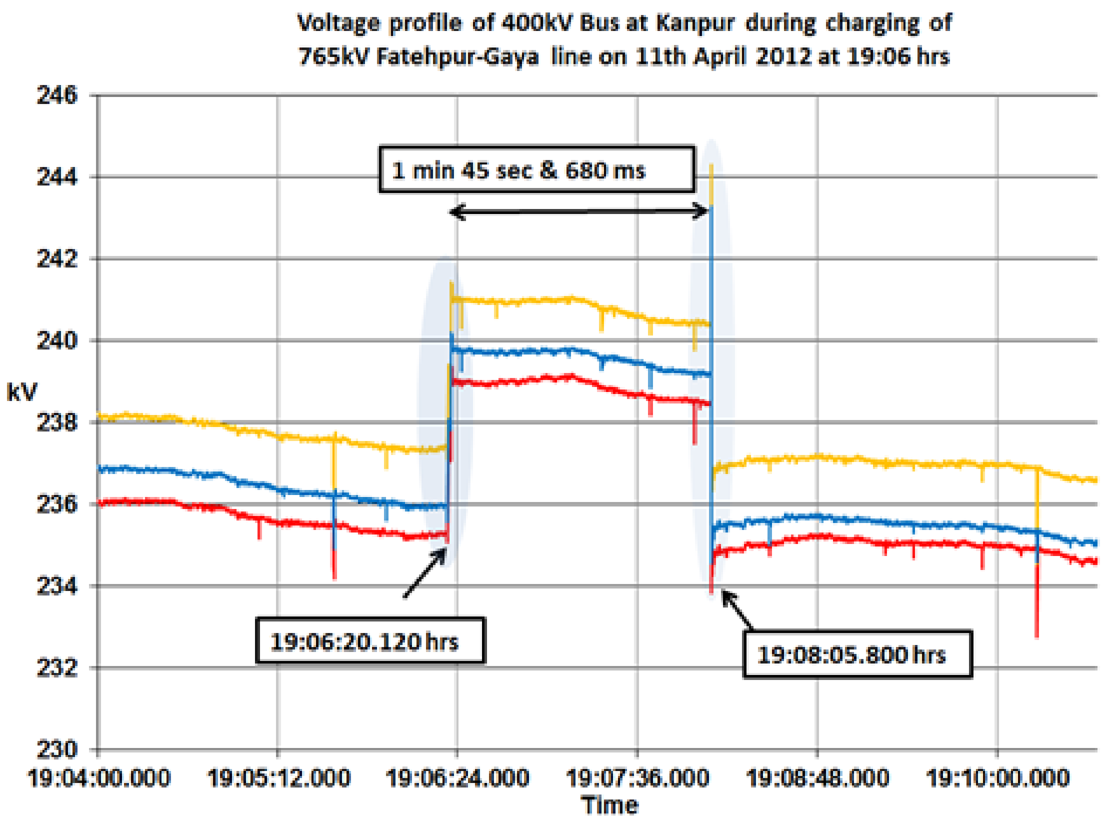


Figure 66: Voltage at 400 kV Kanpur during charging of 765 kV Fatehpur-Gaya

Figure 67 shows the zoom of voltage plot shown at figure 66. It can be observed that upon charging the 765kV line, there was around 4kV increase in voltage in all the phases in 400kV system. Figure 68 shows the zoom of the tail of voltage plot shown at figure 66. It can be observed that there was further 4kV increase in all the phases in 400kV system before tripping of 765kV line.

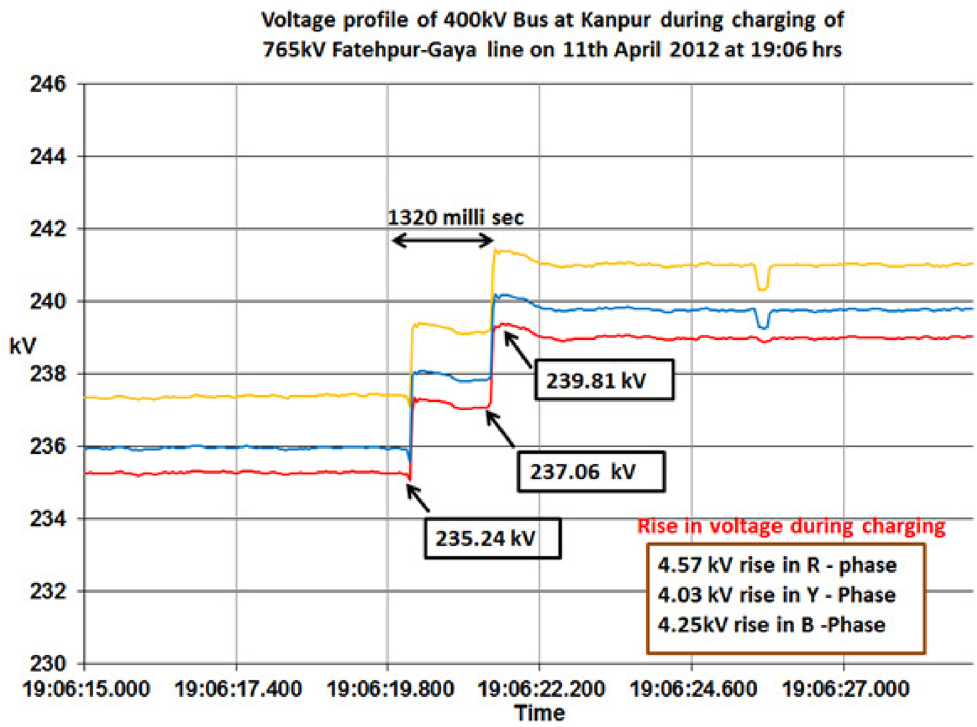


Figure 67: Zoom in voltage at 400 kV Kanpur during charging of 765 kV Fatehpur-Gaya

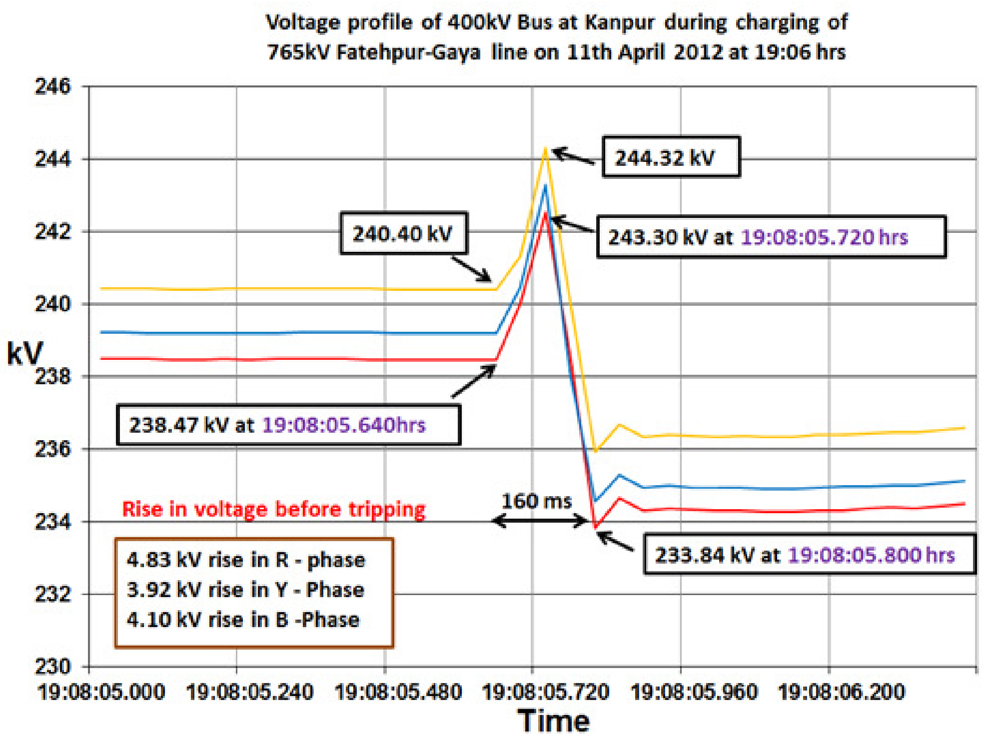


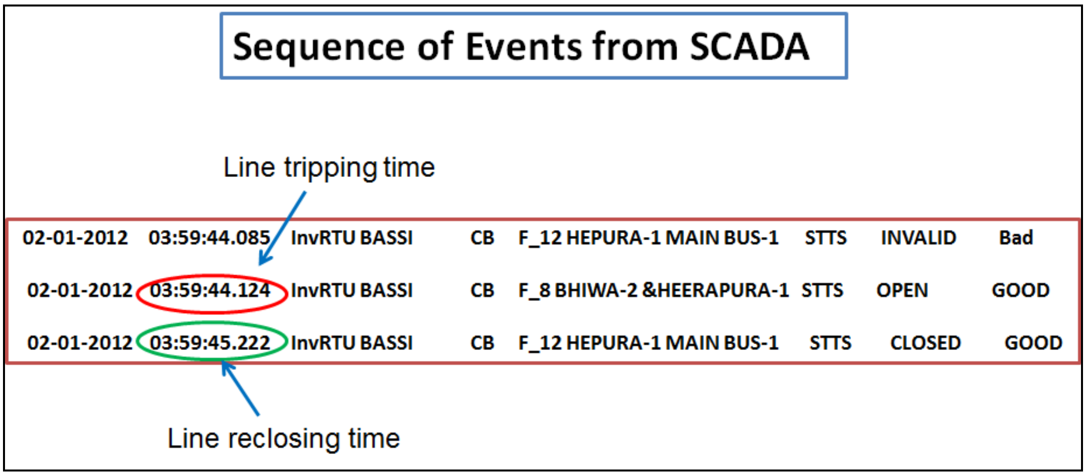
Figure 68: Zoom in of voltage at 400 kV Kanpur during charging of 765 kV Fatehpur-Gaya

5.4 Validation of protection system with synchrophasor data

Analysis of the operation of the protection system has been illustrated in the earlier sections. The section ahead illustrates few case studies of audit of the df/dt relays, Disturbance Recorder and System Protection Schemes.

5.4.1 Case Study-20: Validation of Auto-reclose of EHV line

Single phase auto reclosure has been provided in 400 kV lines for transient faults. The I operation of single phase autoreclosure gets recorded in the Disturbance Recoder 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 validation of the auto reclosure operation in the Load Despatch Centre. In Northern Region PMU has been installed at 400 kV Bassi substation also. The voltage input to this PMU is from 400 kV bus CVT and the current input is from 400 kV Agra-Bassi I and 400 kV Agra-Bassi II lines. The event of auto-reclosure of 400 kV Bassi-Heerapura I on 2nd January 2012 could be inferred with the help of data received from Bassi PMU and confirmed with the help of SCADA Sequence of Events (SOE) records at NRLDC.



Sequence of events in SCADA shows the opening and closing time of 400kV Heerapura-Bassi ckt-1 breaker is shown. It is observed that the breaker closes after 1 second which indicates its closure after dead time. The event as visulaized with the help of the voltage phasor data available from the PMU installed at 400kV Bassi substation is displayed as figure 69.

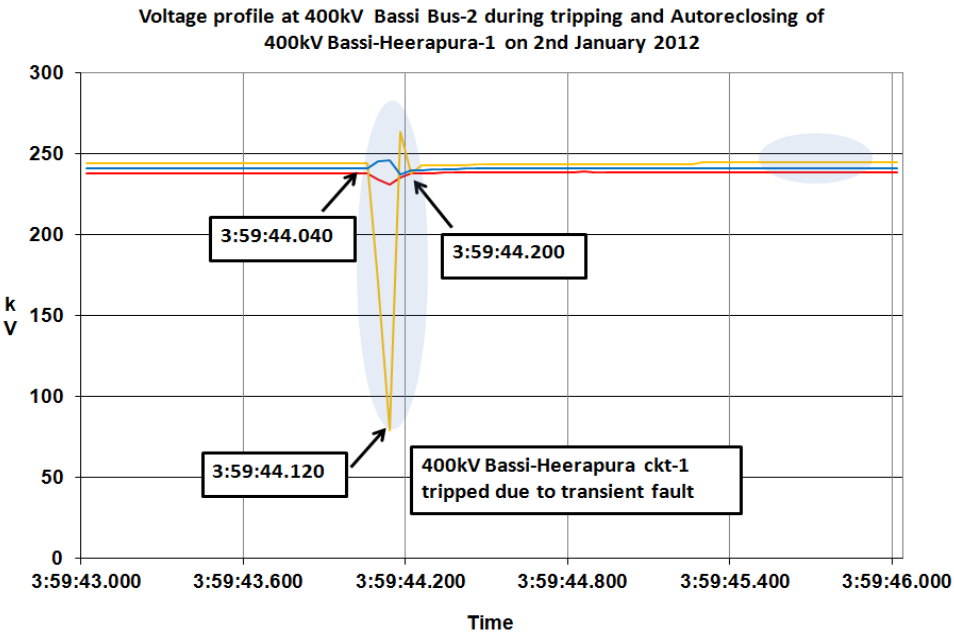


Figure 69: Tripping and auto-reclosing of 400 kV Bassi-Heerapura

It can be observed from figure that there is a transient fault occurring in Y-phase at 03:59:44.040hrs which matches with the SCADA SOE time. Thus the auto-reclosure of Bassi-Heerapura I could be inferred even though the current input to Bassi PMU is from 400 kV Agra-Bassi line.

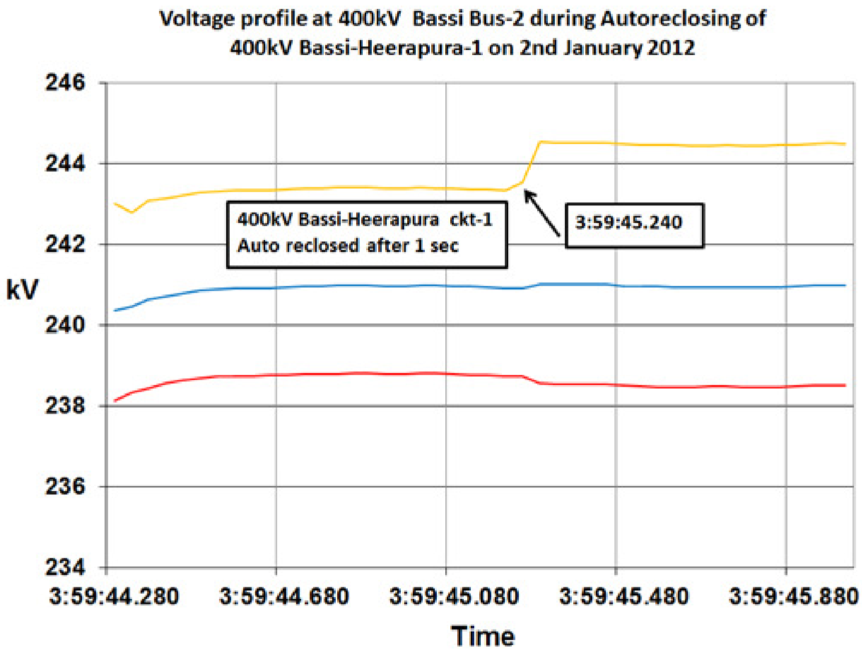


Figure 70: Rise in Bassi Y-ph voltage during auto-reclose of 400 kV Bassi-Heerapura

Figure 70 shows that 1 second after occurrence of fault in Y-phase i.e., at 03:59:45.240 hrs, there is a rise in Y-Phase voltage whereas no rise in voltage in R & B phases. This rise in Y-phase voltage indicates closing of Y-pole which in-turn confirms auto-reclose of line. The time observed from PMU matches with the SCADA SOE time.

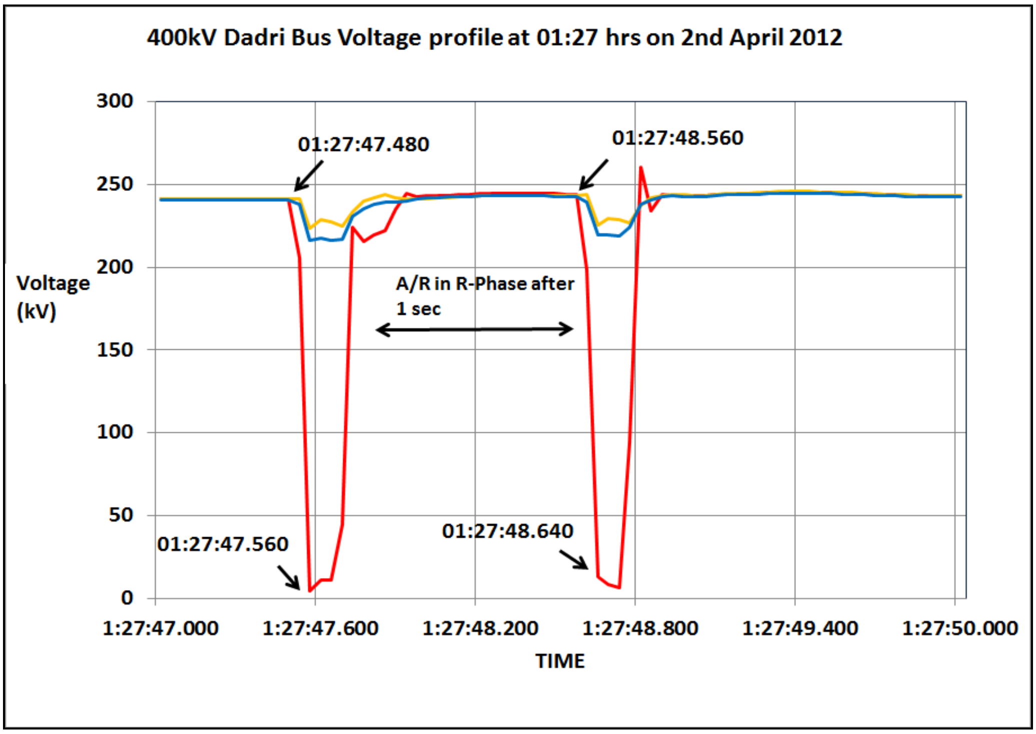


Figure 71: Voltage profile at Dadri showing unsuccessful auto-reclosure

Figure 71 shows the case of an unsuccessful auto-reclosure. Plot shows the 400kV Bus voltage of Dadri bus during fault in 400kV Dadri-Greater Noida line (current and voltage of this line is not wired to Dadri PMU). It can be observed that the 1st fault occurred in R-phase which got cleared in 80milli seconds (approx) and 1 second after occurrence of fault there is 2nd dip in R-phase voltage which indicates that the R-pole of breaker tried to reclose but still fault was persisting.

5.4.2 Case Study-21: Validation of measurement cycle of df/dt relay

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. Operations of df/dt relay are reported by the State Transmission Utilities/State Load Despatch Centre in the regional protection sub-committee. On several occasions it was 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.

Thereafter the df/dt recorded during the event of 2000 MW generation loss on 1st June 2010 at Rihand STPS was analyzed with different measurement cycles.

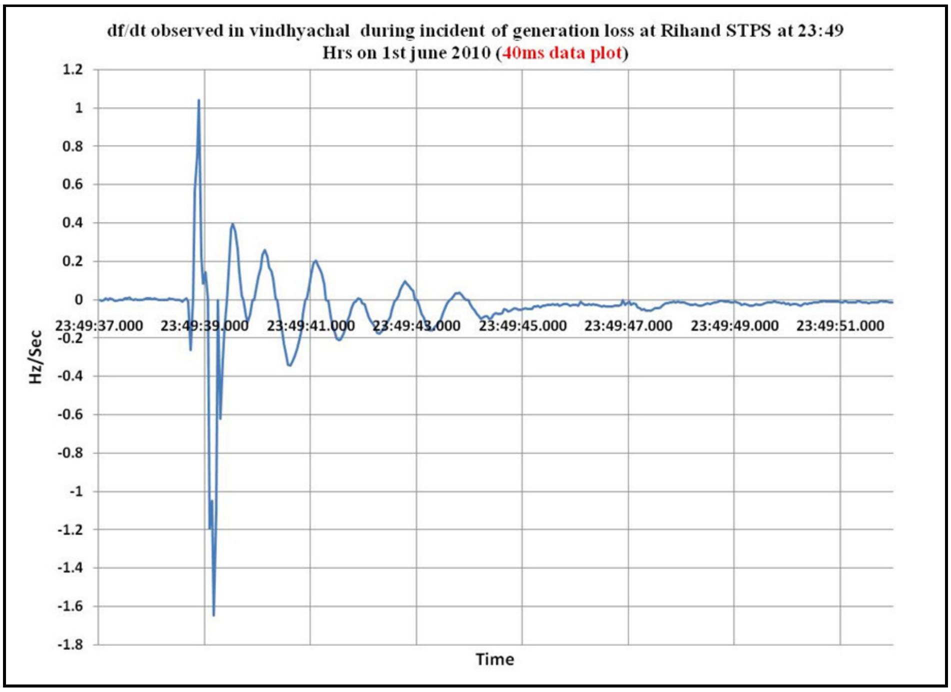


Figure 72: df/dt observed at Vindhyachal with 40 ms plot

Figure 72 above shows that the df/dt measured with 40milli seconds measurement cycle would be between 1 to 1.6 Hz per second. Figure 73 shows the df/dt measured with 160 milli seconds measurement cycle would be between 0.6 to -1.2 Hz per second. Figure 58 shows that the df/dt measured with 200 milli seconds measurement cycle would be between 0.4 to -1.0 Hz per second. Thus it could be inferred that the rate of change of frequency recorded by the df/dt installed at the various substation would depend on the measurement cycle.

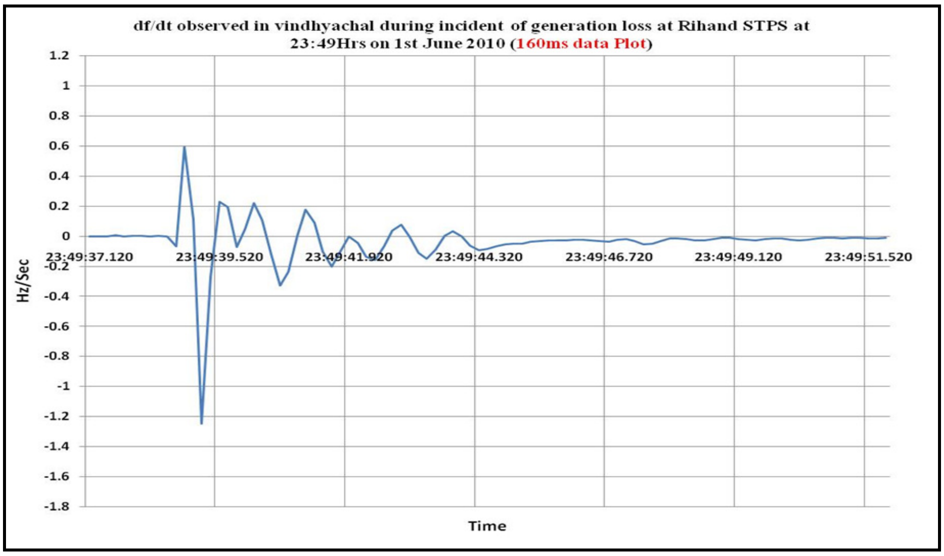


Figure 73: df/dt observed at Vindhyachal with 160 ms plot

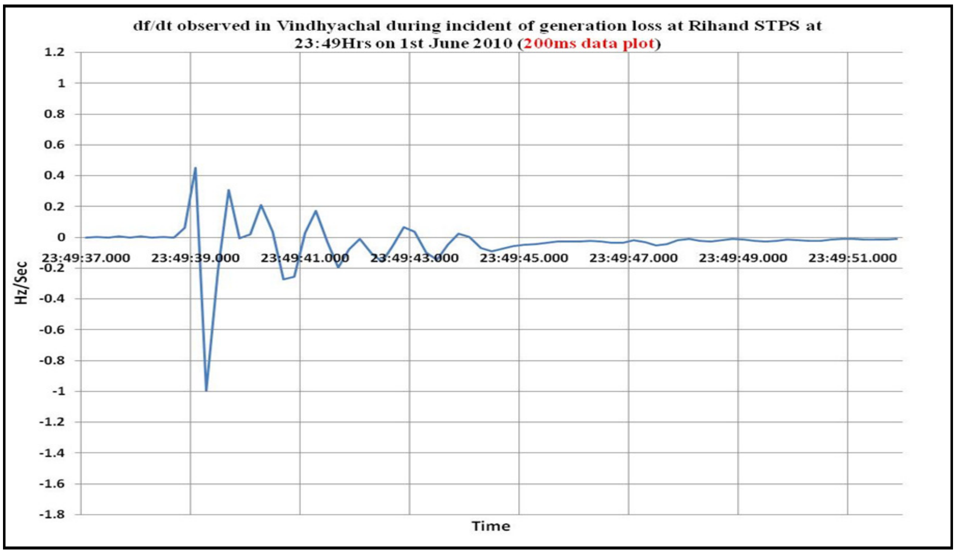


Figure 74: df/dt observed at Vindhyachal with 200 ms plot

Hence based on the study the 12th protection subcommittee meeting of Northern Region recommended increase the measuring cycle of df/dt relay to 8 to 10 cycles (i.e., 160 – 200 millisecond) in-order to counter the initial transients in frequency during a fault. After implementation of these recommendations the mis-operation of df/dt relays was significantly reduced. The extract from minutes of 13th Protection Subcommittee (PSC) meeting of Northern Regional Power Committee (NRPC) held on 28thJanuary 2011 is as under:

''SE (O) stated that it was decided in 12th PSC that the measurement time of df/dt relay shall be 08 to 10 cycles. The members informed that the spurious tripping due to df/dt relay had not occurred after change of setting.''

5.4.3 Case Study- 22: Validation of the DR / EL at Dulhasti HEP

Disturbance Recorder (DR) and Event Loggers (EL) installed at the substations are triggered during operation of the protective system at the substation. The DR are supposed to be time synchronized with the GPS to so as to infer the correct sequence of events during events involving multiple elements/substations. An incident of generation loss had occurred in Dulhasti Hydro station in Northern region during to tripping of evacuating line. From 400kV Vindhyachal voltage plot (refer figure 75) it can be observed that a transient fault had occurred in B-phase at 15:17:07.840 hrs.

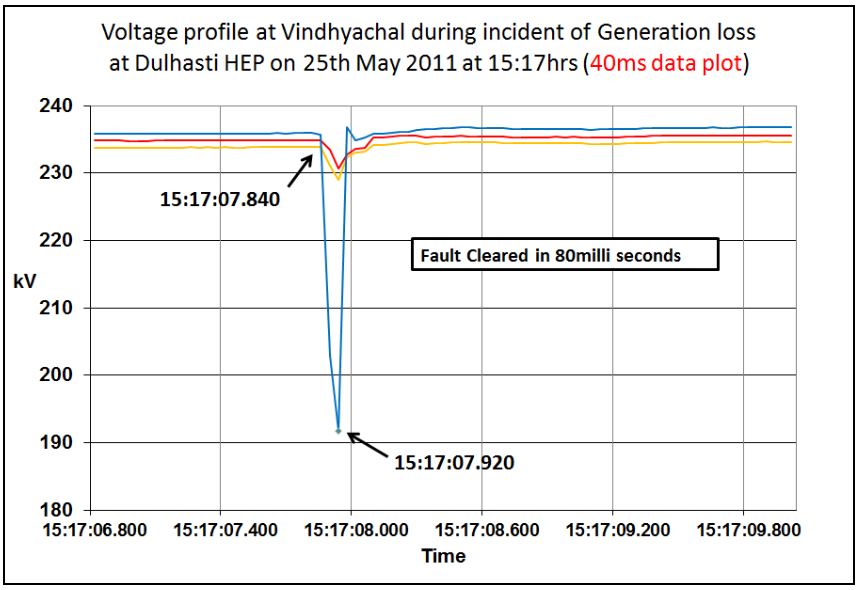


Figure 75: 400kV Vindhyachal voltage profile confirming transient fault in B phase

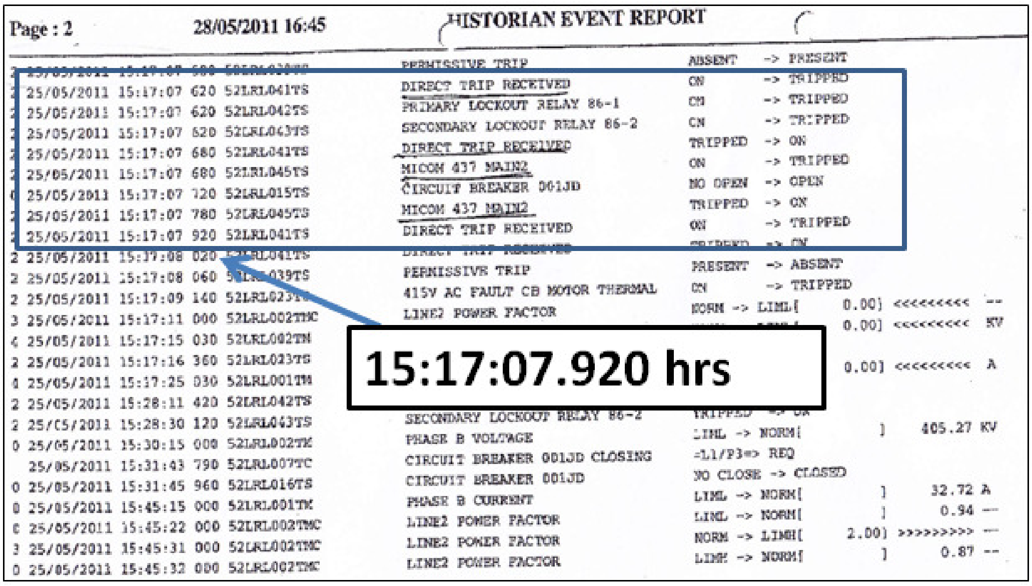


Figure 76: Snapshot of Dulhasti station Event logger

Snapshot of Dulhasti station Event logger is shown above. It can be observed that the Station Event logger print time matches with PMU time.

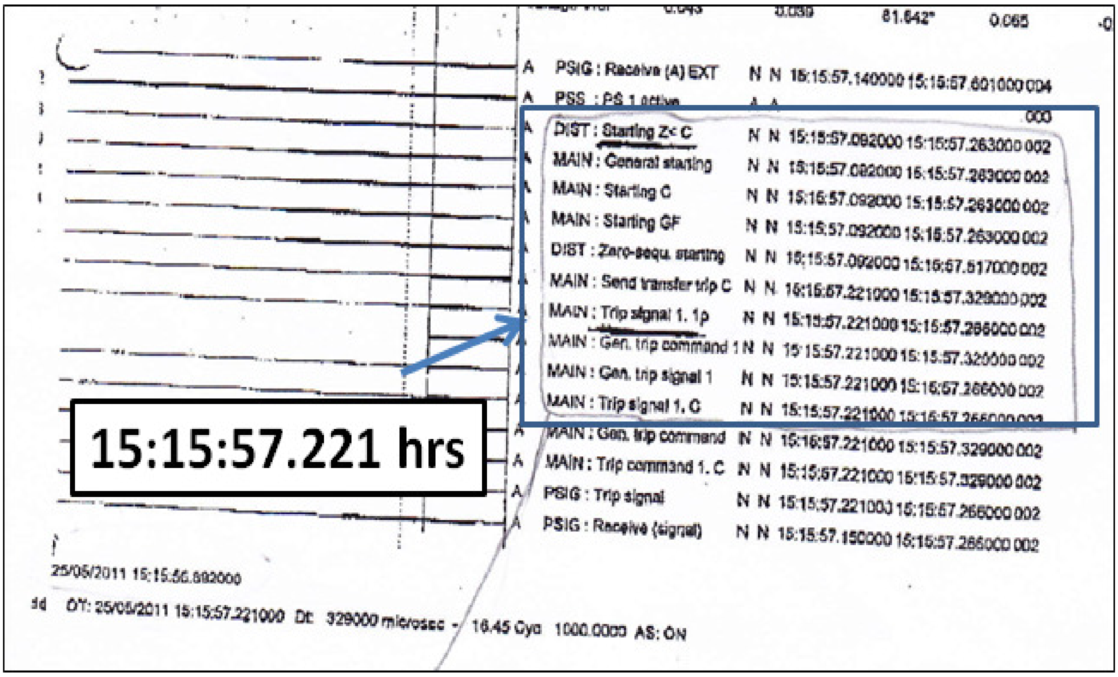


Figure 77: Snapshot of Disturbance Recorder

Figure above shows the Disturbance recorder (digital signal) prints and it can be observed that the PMU time is not matching with Disturbance record. Hence it was concluded that the D.R was not time synchronized & same was later rectified by Dulhasti HEP.

5.4.4 Case Study-23: Validation of the DR at 400 kV Bareilly (PG)

Figure 78 shows the voltage profile of 400kV Kanpur bus during a high resistance fault in R-Phase at 400kV Bareilly (UPPTCL) which persisted for nearly 20 seconds. The synchrophasors data received from 400 kV Kanpur was compared with Disturbance recorder print sent by Bareilly (P.G) substation (refer figure 79). It can be observed that the fault in neutral remained for nearly 20 seconds and got cleared at 00:56:57.699 which closely matches with PMU time.

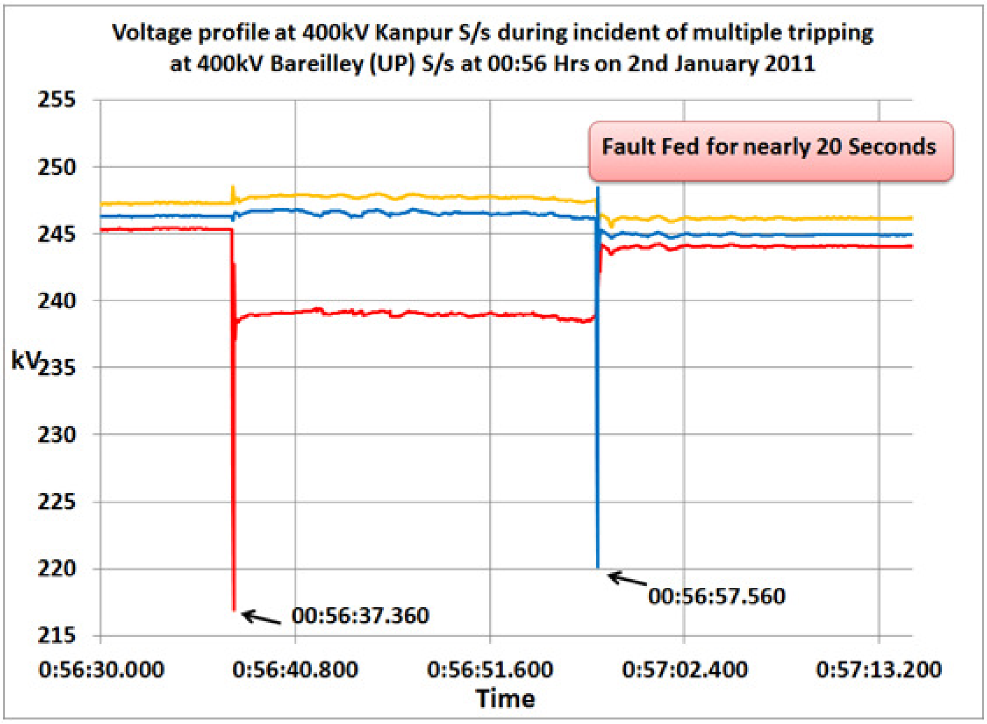


Figure 78: Voltage profile of Kanpur bus showing a high resistance fault at 400kV Bareilly UP

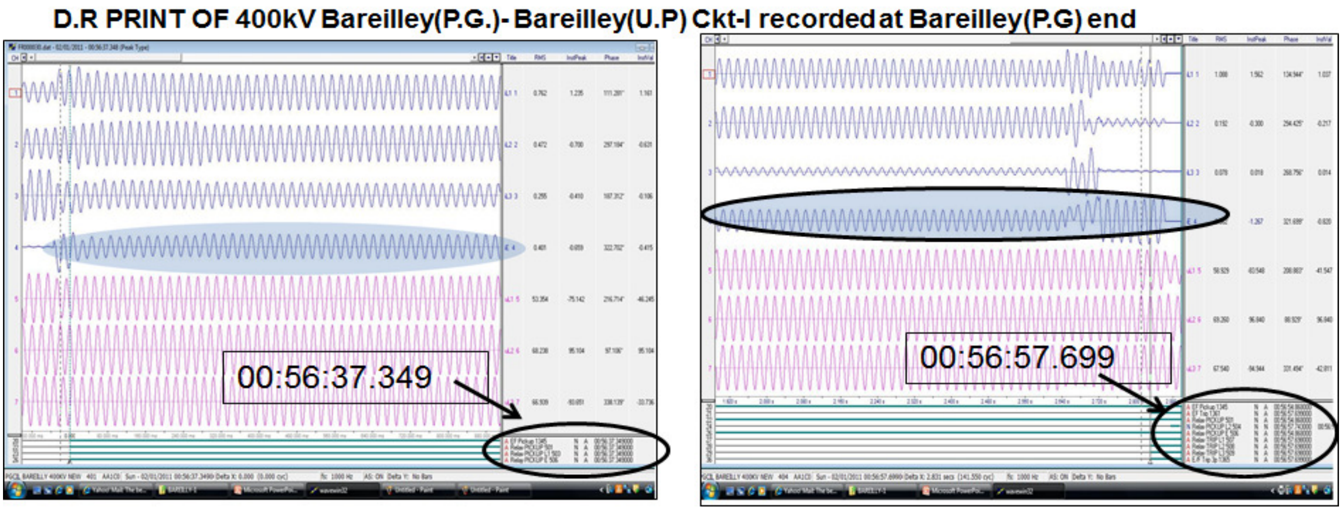


Figure 79: D R print recorded at Bareilly (PG)

5.4.5 Case Study-24: Validation of DR from 400 kV Dadri

The DR received from 400 kV Dadri NTPC substation during the incident of bus-fault due to Y-Ph CT failure on 10th July 2011 was compared with the synchrophasors data received from Dadri HVDC.

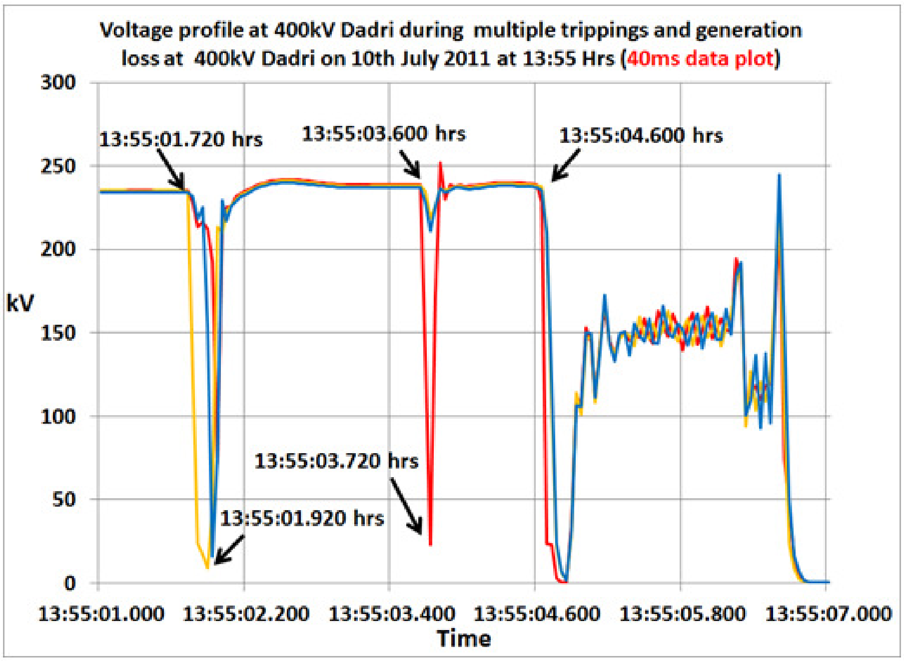


Figure 80: Fluctuations in voltage at Dadri during generation loss at Dadri on 10th July 2011

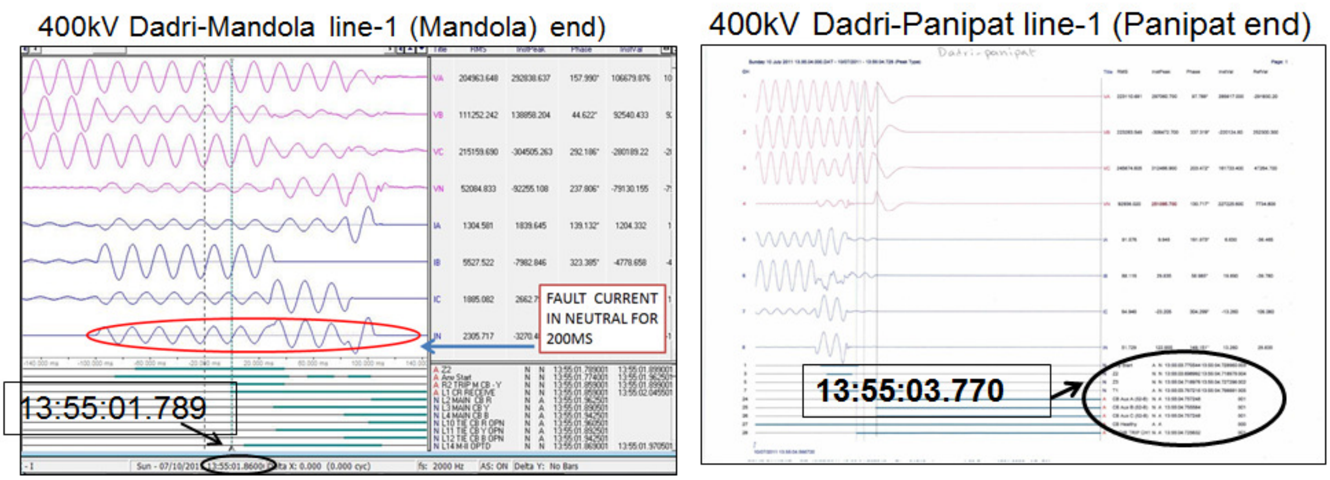


Figure 81: DR print from Mandaula and Panipat

The following inferences can be drawn from the above data:

- There were two events, 1st event at 13:55:01.720 hrs & 2nd event at 13:55:03.720 hrs.
- The fault in neutral remained for nearly 200ms during the 1st event.

5.4.6 Case Study-25: Validation of the operation time of SPS

A System Protection Scheme (SPS) has been installed at NapthaJhakri Hydro station to trip one or more generating units at Karcham Wangtoo in case of tripping of one or more evacuation feeders from the complex. The SPS operated on 16th July 2011 due to tripping of 400kV Jhakri-Abdullapur line-1. The running units at Karcham Wangtoo HEP tripped. The synchrophasors data captured during the event along with SCADA sequence of events and Disturbance record/ Event logger from 400kV Abdullapur (P.G) substation & Karcham Wangtoo HEP were used to compare the actual SPS operation time with the envisaged operation time.

Table 9: Tripping time details of Jhakri-Abdullapur line

Event	**Abdullapur (P.G) Disturbance record**	**SCADA sequence of Events (SOE)**	**As inferred from PMU data at NRLDC**
Time of receipt of Direct trip at Abdullapur	04:28:57.330	04:28:57.302	4:28:57.240
Time of opening of 400kV Abdullapur-Jhakri Main breaker	04:28:57.370	04:28:57.326	
Time of opening of 400kV Abdullapur-Jhakri Tie breaker	04:28:57.371	04:28:57.342	

Table No. 9 shows the 400kV Jhakri-Abdullapur line-2 tripping time obtained from Abdullapur end disturbace recorder, SCADA SOE & PMU data. It can be observed that circuit breakers of 400kV Jhakri-Abdullapur line-2 tripped at 4:28:57.371 hrs which matches with the SCADA SOE and PMU data.

Table 10: Tripping time details of Karcham Wangtoo station

Event	Karcham E.L	NRLDC SOE	NRLDC PMU
Time of receipt of SPS signal at Karcham	04:29:07.217	---	---
Tripping of unit -2 at Karcham	04:29:07.898	---	04:29:07.800
Tripping of unit -1 at Karcham	04:29:07.990	---	04:29:07.800

Table No.10 shows the tripping time of running units at Karcham Wangtoo HEP. It can be observed that the units tripped at 4:29:07.800 hrs which closely matches with PMU data.

It is observed that the time of opening of 400kV Jhakri- Abdullpur breaker (Jhakri end), NRLDC SOE time and NRLDC PMU time is almost similar i.e., 04:28:57.371hrs which can be taken as the time of the initiating event. By 4:29:07.990, both units at Karcham HEP had tripped. This time matches with the event time as inferred from PMU data i.e., 4:29:07.800. Therefore total SPS operating time is 10.764 seconds which is significantly higher that the envisaged operation time of few hundred milliseconds. Based on the above information, the SPS design was modified to obtain faster SPS operation.

5.4.7 Case Study-26: Validation of the utility of SPS for N-2 contingency

A System Protection Scheme for automatic generation reduction at Singrauli/Rihand STPS (South eastern part of NR) and load shedding in the (Western part of NR) in the event of tripping of ±500 kV Rihand-Dadri Bipole is in place in Northern Region. An event of tripping of HVDC Rihand–Dadri bipole carrying 1400 MW power tripped at 14:27 hrs of 12th January 2011. The tripping resulted in operation of the System Protection Scheme (SPS) intended to take care of the contingency and ensuring the security of the grid. The figure 82 shows the frequency plot of Dadri, Kanpur, Vindhyachal & Moga substation in Northern region. It can be observed that upon of tripping of bipole carrying 1500MW power, frequencies had started swinging in different directions and then after few cycles they attain the same direction.

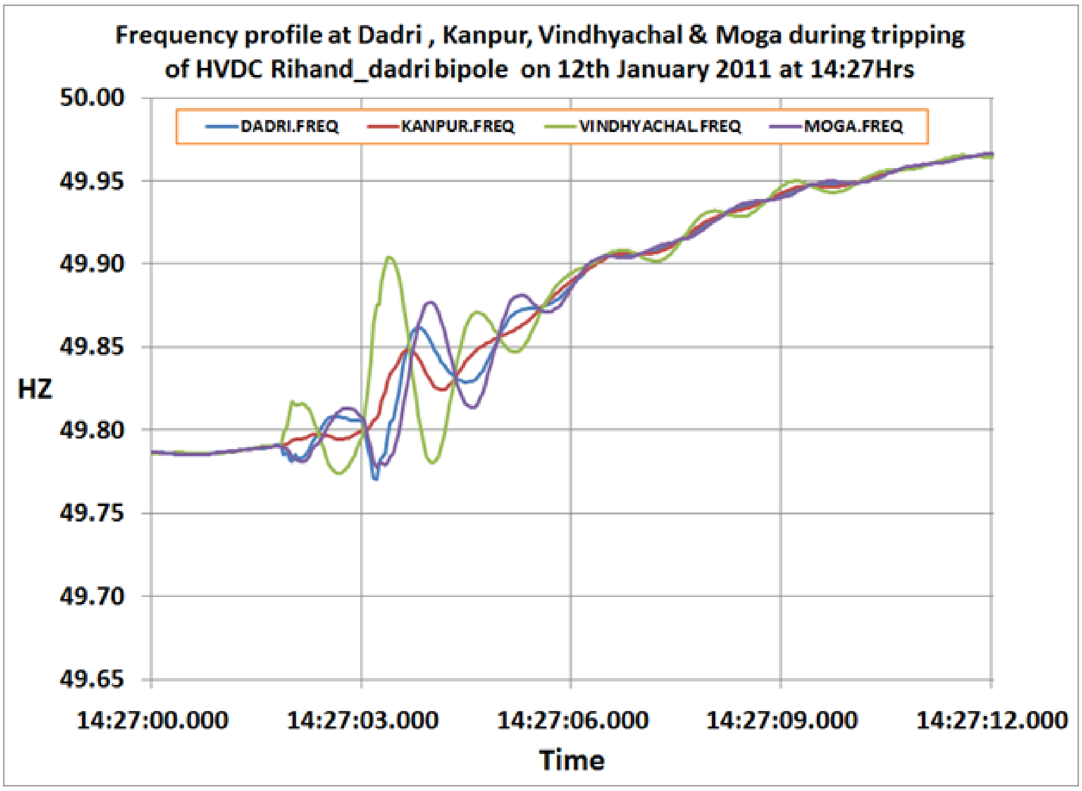


Figure 82: Frequency at Dadri, Kanpur, Vindhyachal and Moga in a grid event

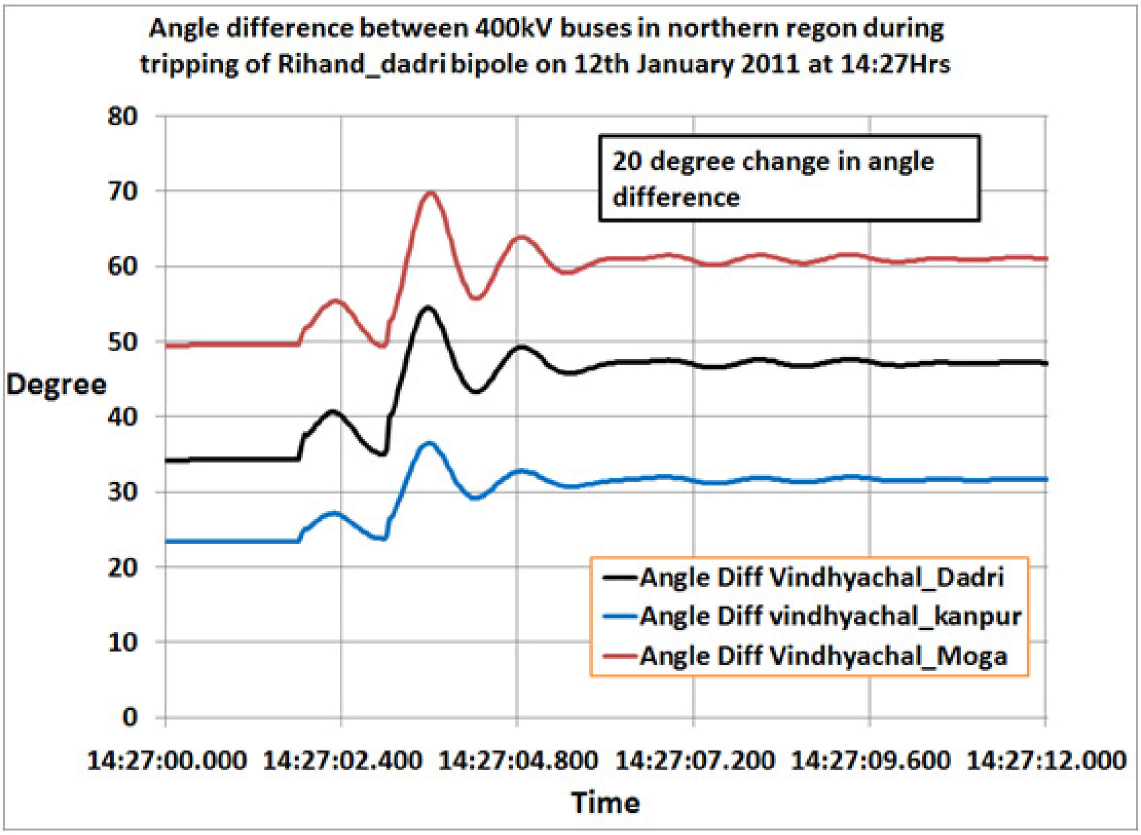


Figure 83: Angular swing observed on tripping of HVDC Rihand Dadri bipole

Figure 83 shows the angle difference plot where Vindhyachal has been taken as a reference. The change in angle is observed to be 20 degree which later settles down to 10 degree. The swing frequencies and angular separation between the buses would have been much higher if counter action in the form of SPS was not available for tripping of HVDC bipole. This established the need of SPS upon tripping of HVDC bipole.

5.5 Validation of steady state SCADA and offline network model

The synchrophasors data has been used for validation of network model in SCADA or offline simulation studies. Case studies in the following section illustrate these applications.

5.5.1 Case Study-27: Validation of the SCADA network model in NR

A study was carried out to validate the SCADA network model with the help of synchro-phasor data. Figure 84 shows the phase angles obtained from SCADA data and synchrophasor data. Rihand and Vindhyachal at located in close vicinity in south eastern part of Uttarpradesh. The angle between Rihand and Dadri (SCADA) and Vindhyachal and Dadri (PMU data) were recorded and compared. It can be observed that both the data are closely matching with each other.

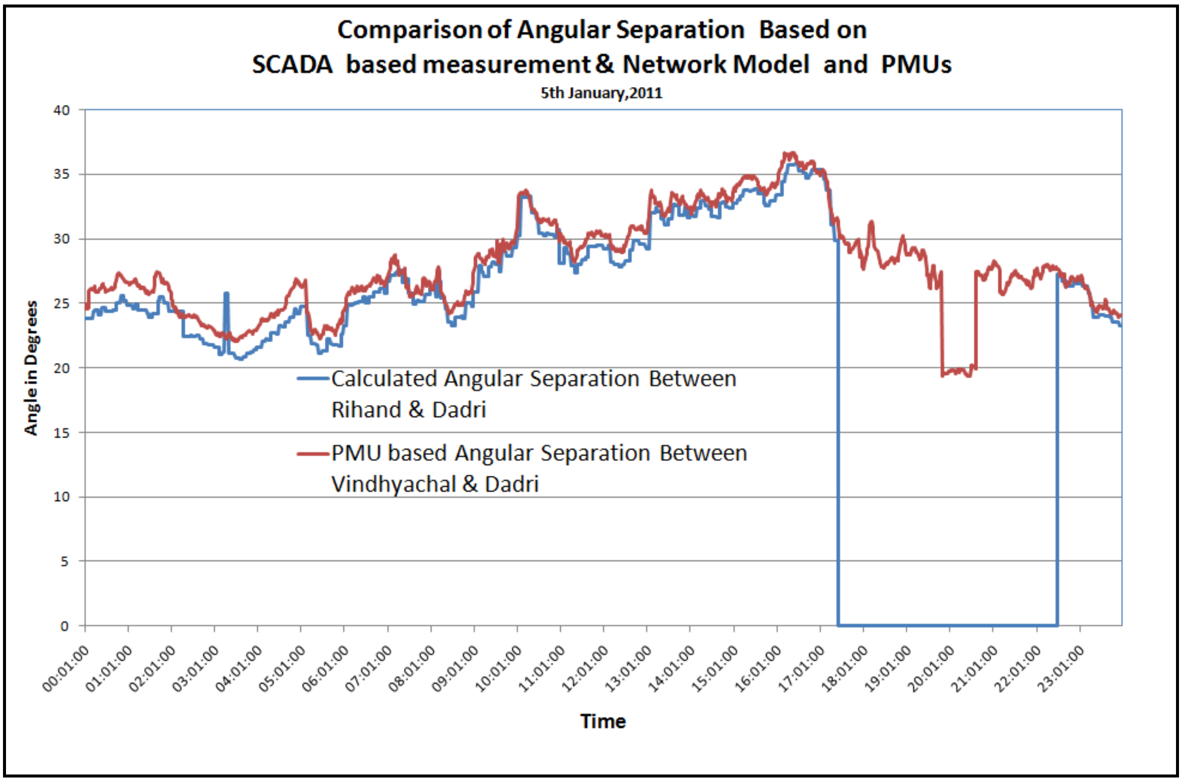


Figure 84: Comparison of Angular Separation based on SCADA measurement and PMUs

5.5.2 Case Study-28: Validation of offline simulation study with PMU data

A 3 phase fault had occurred in 400kV Bus-2 at Dadri TPS on 13th March 2012 at 17:37:39hrs. The event was simulated in the PSS/E software and the fault current, bus voltage and short circuit MVA at the faulted bus was computed and compared with the data obtained from the synchrophasors data during the above event.

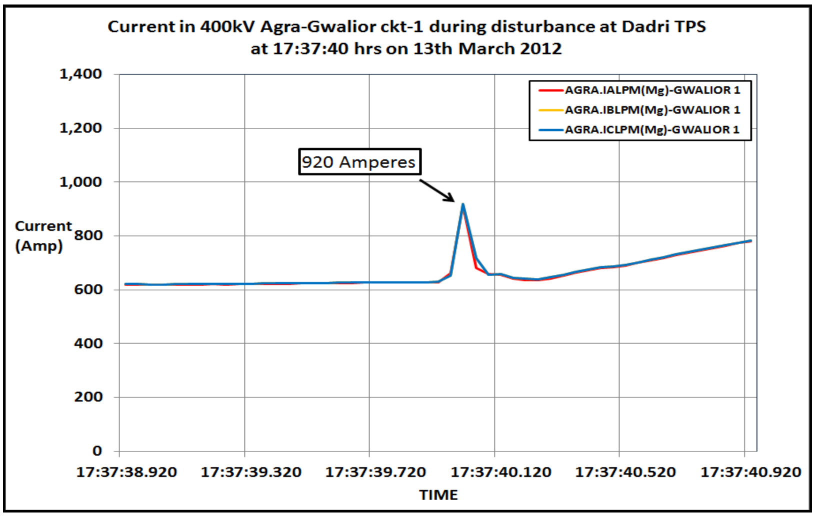


Figure 85: Current flow in 400kV Agra-Gwalior line -1

Figure 85 shows the current flow in 400kV Agra-Gwalior line -1. The current went up to 920 Amperes during the occurrence of fault at Dadri TPS.

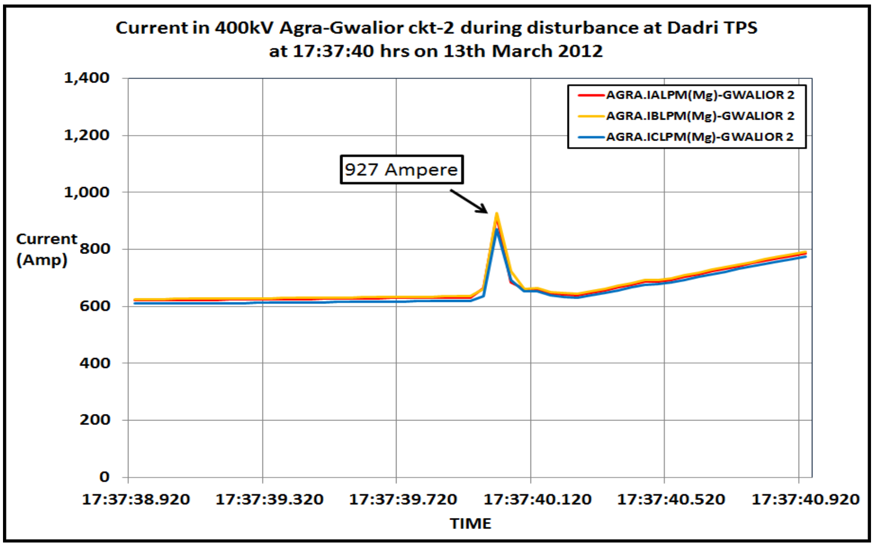


Figure 86: current flow in 400kV Agra-Gwalior line -2

Figure 86 shows the current flow in 400kV Agra-Gwalior line -2. The current went upto 927 Amperes during the occurrence of fault at Dadri TPS.

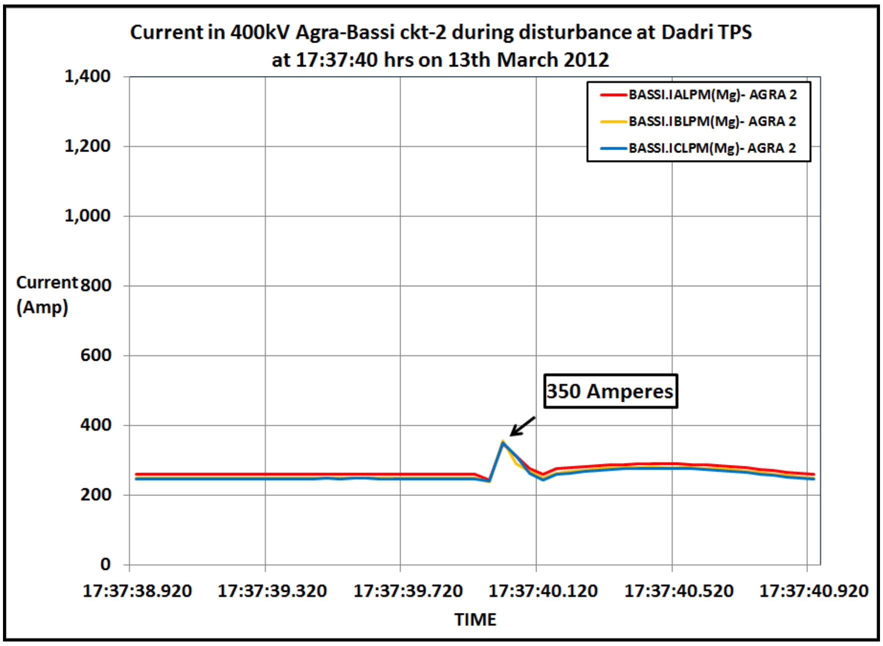


Figure 87: Current flow in 400kV Agra-Bassi line -2

Current flow in 400kV Agra-Bassi line -2 is shown in figure 87. The current went upto 350 Amperes during the occurrence of fault at Dadri TPS.

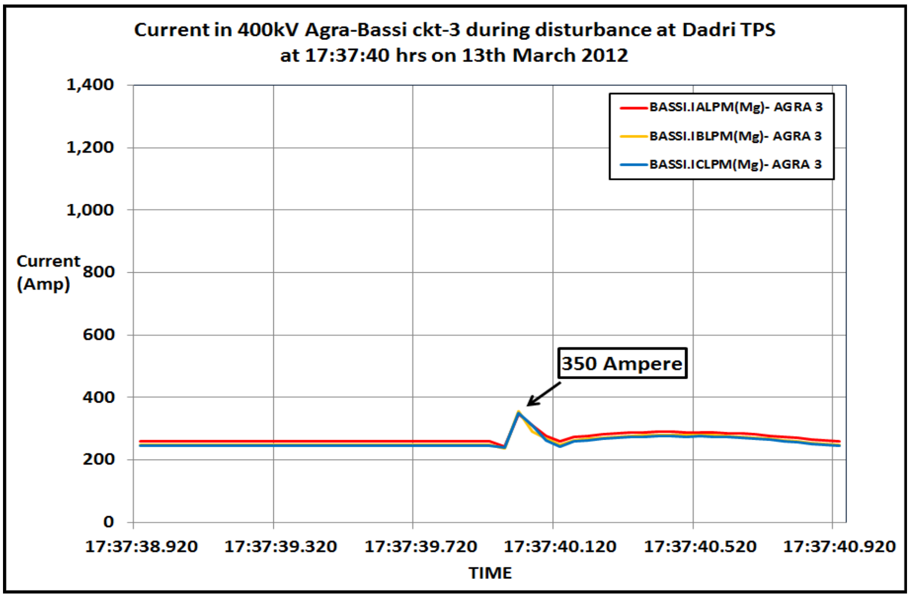


Figure 88: Current flow in 400kV Agra-Bassi line -3

Figure 88 shows the current flow in 400kV Agra-Bassi line -3. The current went upto 350 Amperes during the occurrence of fault at Dadri TPS.

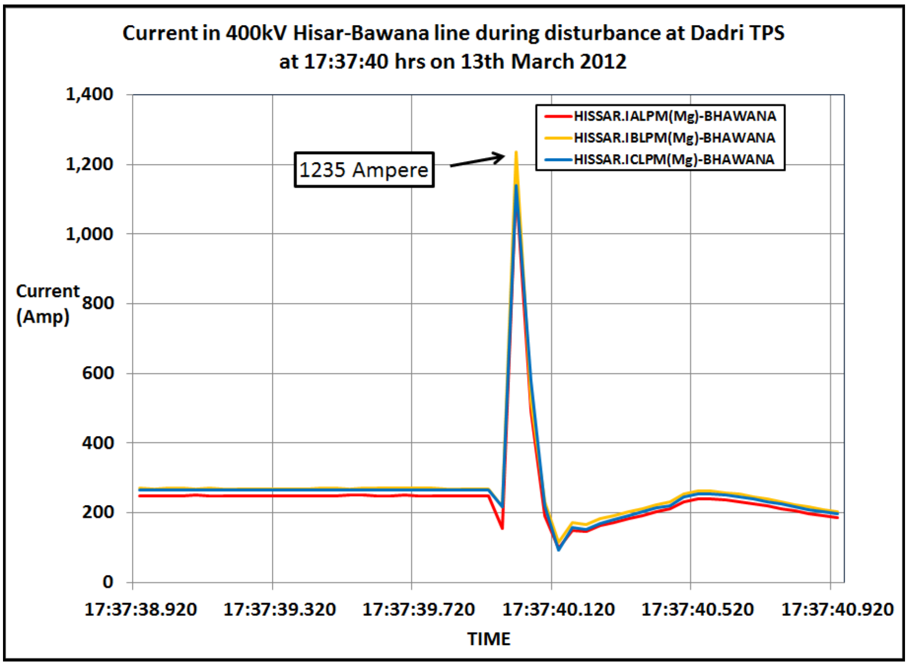


Figure 89: current flow in 400kV Hisar-Bawana line

Figure 89 shows the current flow in 400kV Hisar-Bawana line. The current went upto 1235 Amperes during the occurrence of fault at Dadri TPS.

Table 11: Comparison of fault currents from PMU data and offline simulation studies

Name of Line	Fault current contribution (3-Ø fault at Dadri)	
	As per offline simulation study	As per PMU
	Amp	Amp
400kV Agra-Gwalior-1	897	920
400kV Agra-Gwalior-2	907	927
400kV Agra-Bassi-2	294	350
400kV Agra-Bassi-3	294	350
400kV Bawana-Hisar	1238	1235

Table 11 shows the current values obtained from PMU data and from offline simulation studies. It can be observed that current obtained from PMU an offline study is closely matching. Hence this also validates the correctness of offline network model.

5.6 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.

5.6.1 Case Study-29: Validation of Transfer capability for Karcham Wangtoo HEP

The Nathpa Jhakri and Baspa generation complex in Northern region has an installed generation capacity of 1800 MW. The generation from this complex is evacuated through 400kV Jhakri-Nalagarh ckt-1&2 and 400kV Jhakri-Abdullapur ckt-1&2. A new hydro station i.e., Karcham Wangtoo hydro station was coming in the vicinity and additional power of 600 MW from this power plant had to be evacuated through the existing transmission system due to delay in construction of evacuating lines from this hydro station to Abdullapur(P.G) substation. Now a total of 2400MW of power had to be evacuated during peak hydro period through Jhakri-Nalagarh & Jhakri-Abdullapur lines.

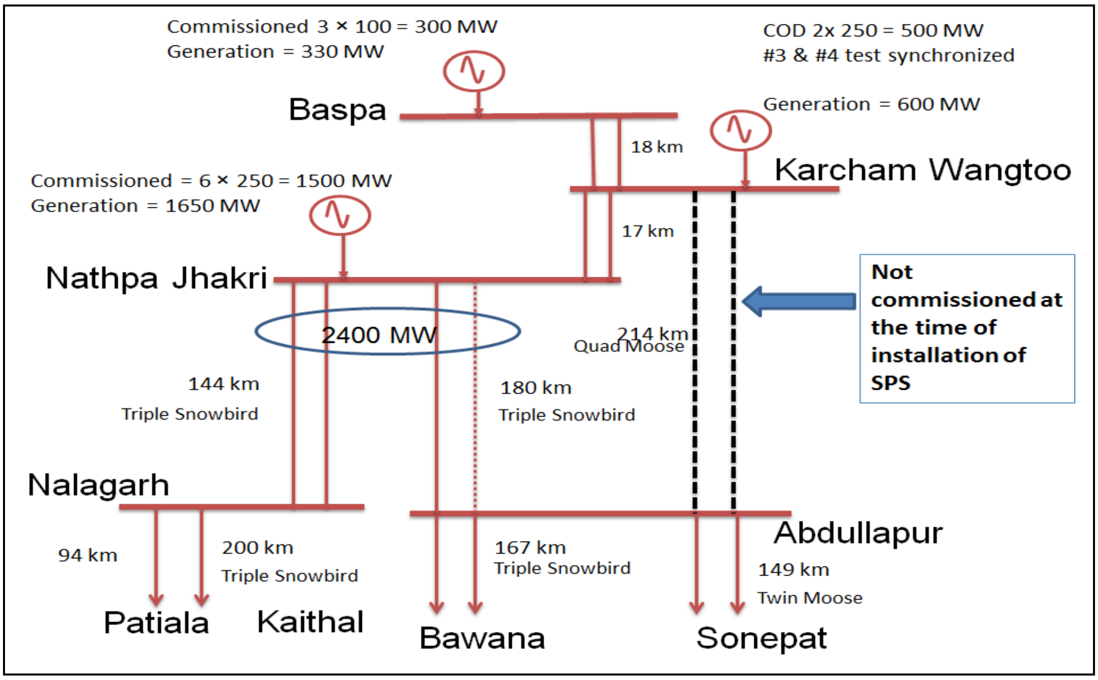


Figure 90: Connectivity diagram of Nathpa Jhakri and Baspa generating complexes

It was anticipated that upon tripping of one of these evacuating lines from Jhakri Hydro station, the load on the remaining three evacuating lines would be around 800MW. Hence a System Protection Scheme was installed at Jhakri HEP which would trip units at Karcham Hydro station based on power flow and number of available evacuation lines from Jhakri HEP.

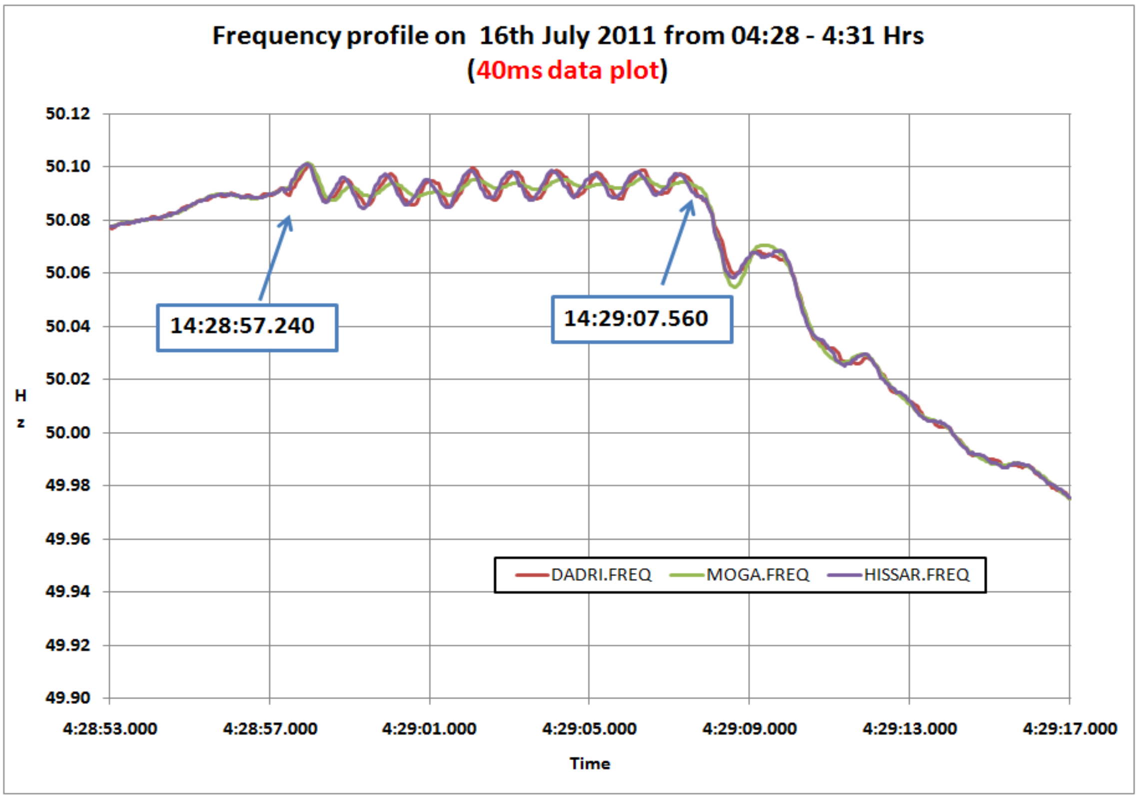


Figure 91: Oscillations in frequency at Dadri, Moga and Hisar

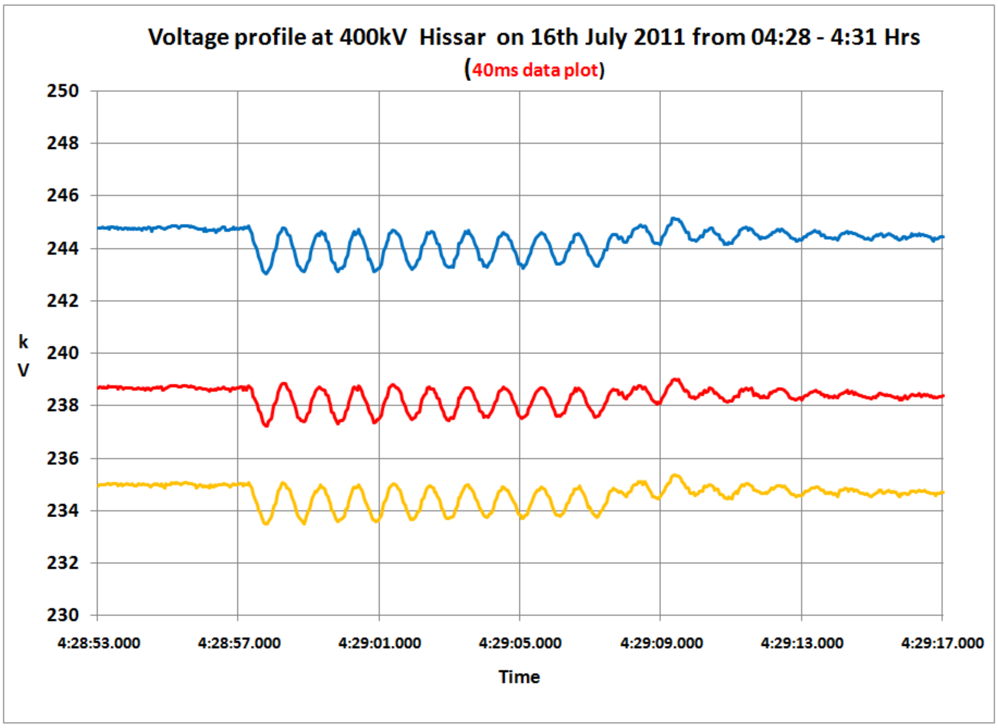


Figure 92: Oscillations in Hisar Voltage

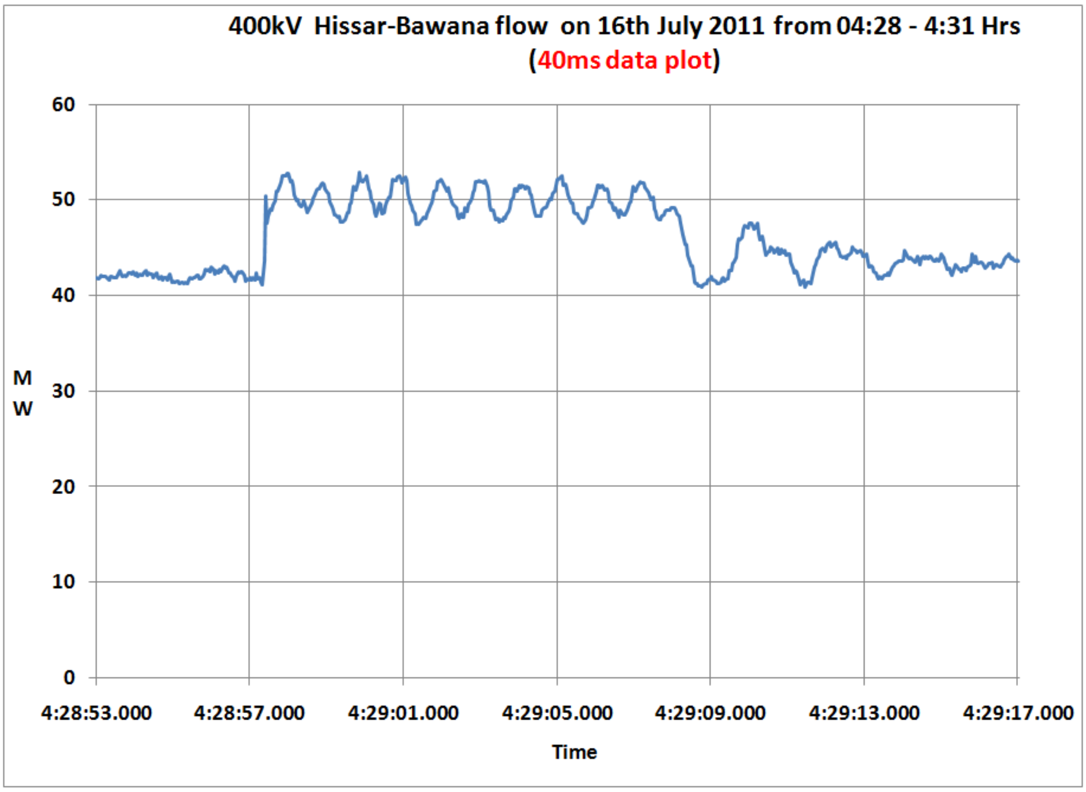


Figure 93: Oscillations in Hisar Bawana flow

Figure 91, 92, 93 shows the PMU plots for frequency, 400kV Hisar bus voltage and 400kV Hisar-Bawana power flow. One of four outgoing lines from Jhakri complex had tripped on 16th July 2011 at 4:28 hrs and the SPS operation got delayed by around 10 seconds. Oscillations were observed for around 10 seconds when the flow on the remaining three evacuating lines was around 800MW. Upon operation of SPS after 10 seconds i.e., tripping of units at Karcham Hydro station (frequency dip) the oscillations died down. Hence PMU data validated the transfer capability and installation of SPS for reliable evacuation of power from the Jhakri-Baspa-Karcham generation complex.

5.6.2 Case Study-30: Oscillation with single ckt of 765 kV Tehri-Meerut D/C

Tehri HEP had reported that oscillations were observed at their station whenever only one out of the two circuits of the 765kV Tehri-Meerut line (charged at 400 kV) is in service and the generation at Tehri HEP exceeded 700 MW.

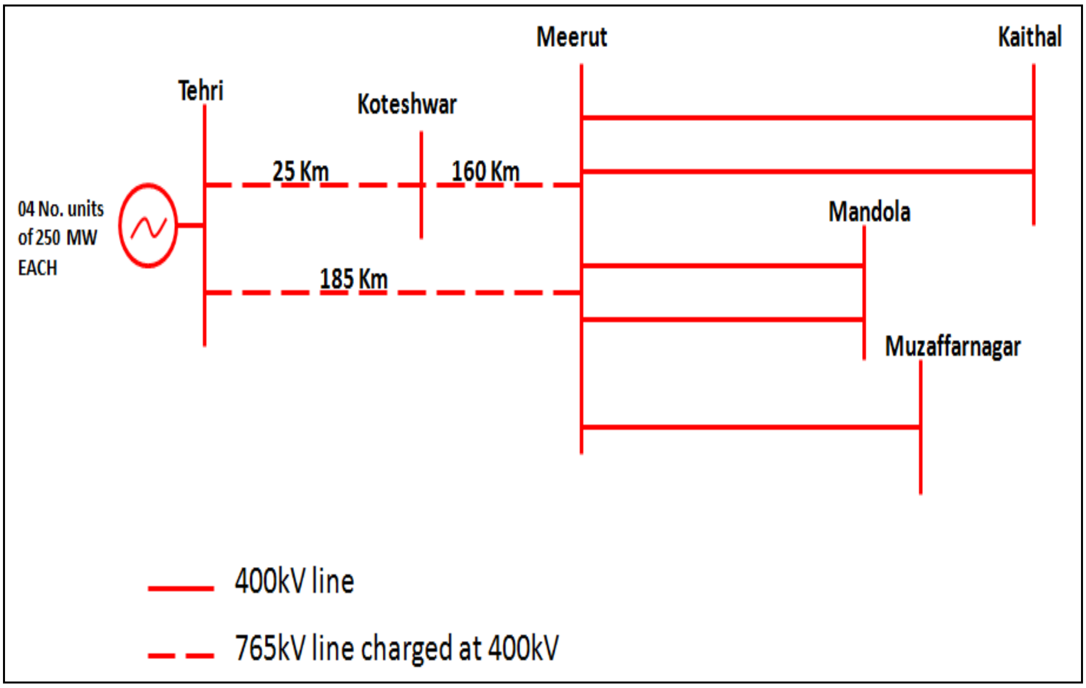


Figure 94: Connectivity diagram of Tehri Hydro station

Figure 94 shows the connectivity diagram of Tehri Hydro station in Northern region

An exercise was carried out on 3rd Feb 2011 from 11.25 hrs to 11.35 hrs to examine the oscillation phenomenon and ascertain the loadability of the line. Unit # 4 of Tehri HEP was synchronized at 11:25 Hrs of 03rd February 2011. The 765 kV Tehri-Koteshwar-Meerut ckt#1 was out of service and only 765kV Tehri-Meerut ckt # 2 was in service. Generation at Tehri HEP was increased to increase the power flow of this line upto 1050 MW. The synchrophasor data was analyzed for the event.

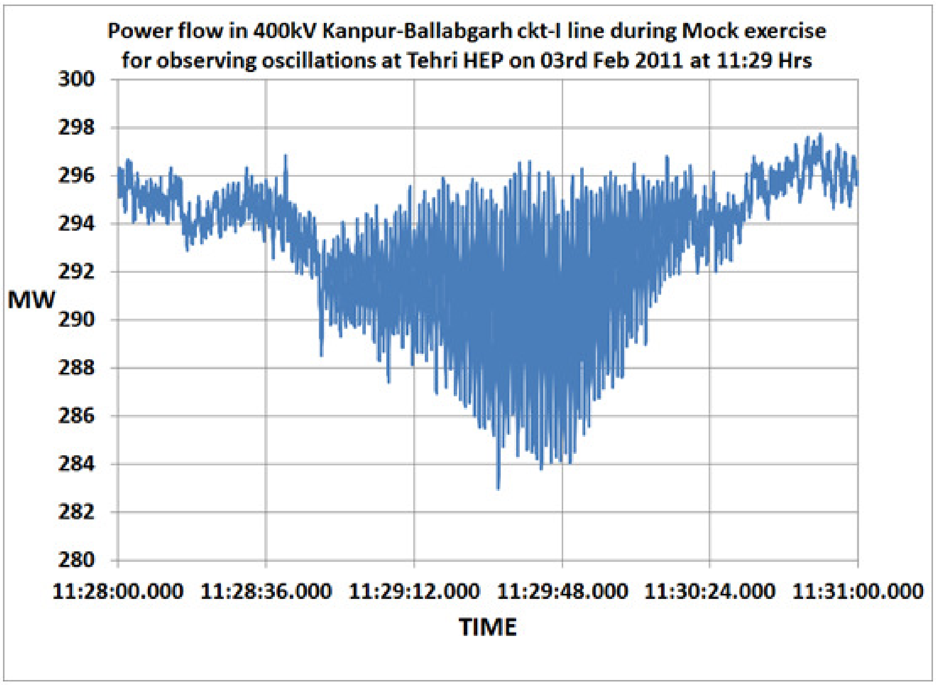


Figure 95: Oscillations in Kanpur-ballabhgarh flow due to increased flow in Tehri-Meerut

Figure 95 shows the power flow in 400kV Kanpur-Ballabgarh line. Oscillations of 0.833 Hz were observed when power flow in 765kV Tehri-Meerut Ckt#2 was varied in the range of 740-1050MW. Figure 96 shows the oscillations observed in frequency during the exercise.

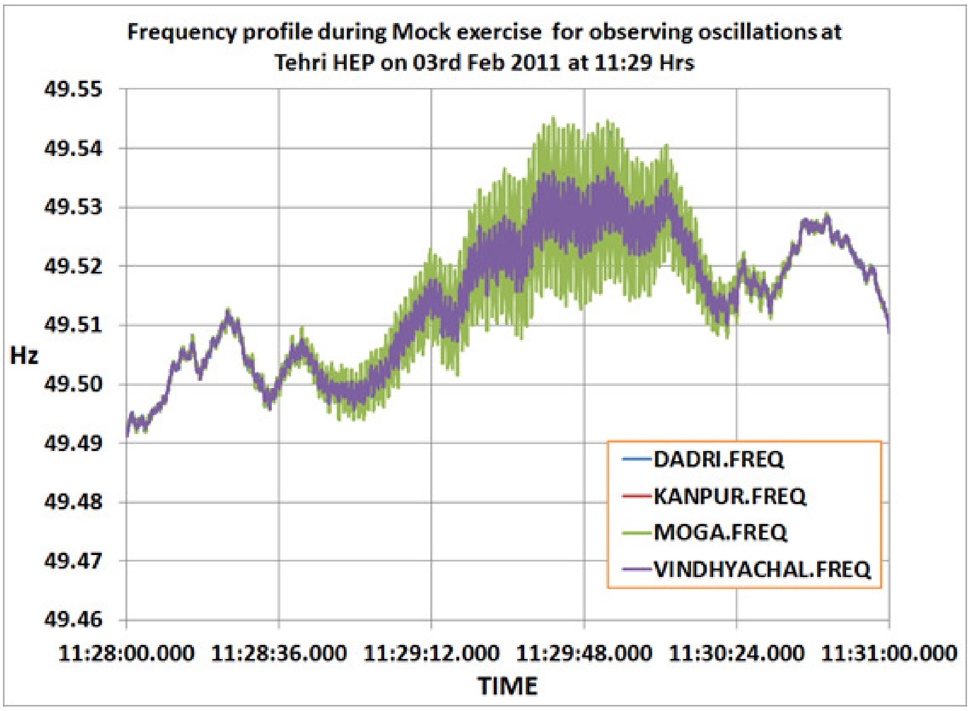


Figure 96: Oscillations observed in frequency during increase in flow on Tehri-Meerut

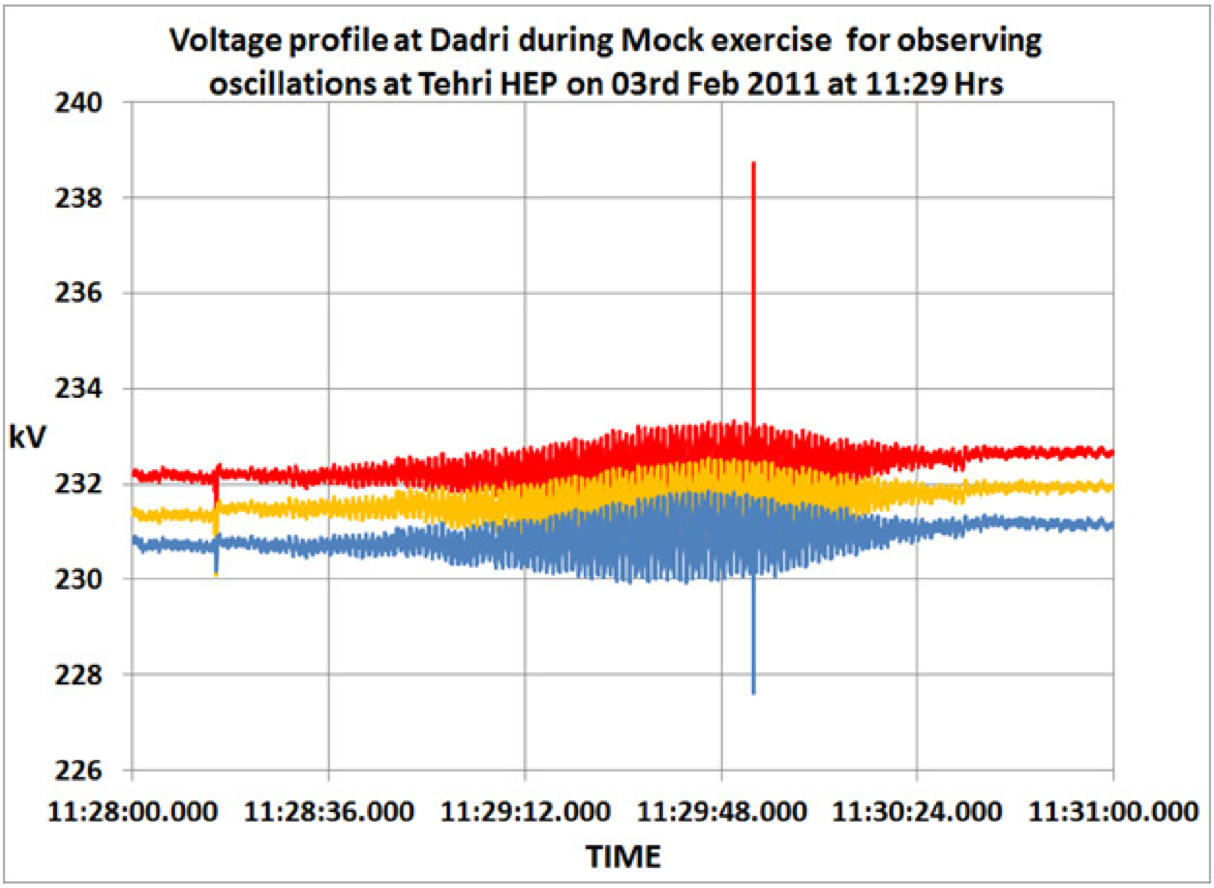


Figure 97: Oscillations observed in Dadri during increase in flow on Tehri-Meerut

Figure 97 show the oscillations observed in 400kV Voltage at Dadri during the exercise. The Power System Stabilizers (PSS) at Tehri was tuned and the same problem has not been experienced again. Thus the issue of line loadability / transfer capability could be resolved with the help of synchrophasors.

5.6.3 Case Study-31: Low frequency oscillations in NEW grid on 30-Nov-2011

Low frequency oscillations were observed in NEW grid at 22:09:34 to 22:14:40 on 30th Nov 2011. It was learnt that there was an event at Rihand Stage-II power station in the morning hours of 30th Nov 2011 when the Digital Control System (DCS) of both the 500 MW units crashed (a software crash). Due to Software crashing of DCS in stage-II, Unit-1 and Unit-2 tripped at 10:20 hrs.After reloading of software, Rihand Stage-II Unit-1 was synchronized at 21:34 hrs. From 2209 hours, hunting from 30 MW to 250 MW observed for five minutes apparently due to control system problem.

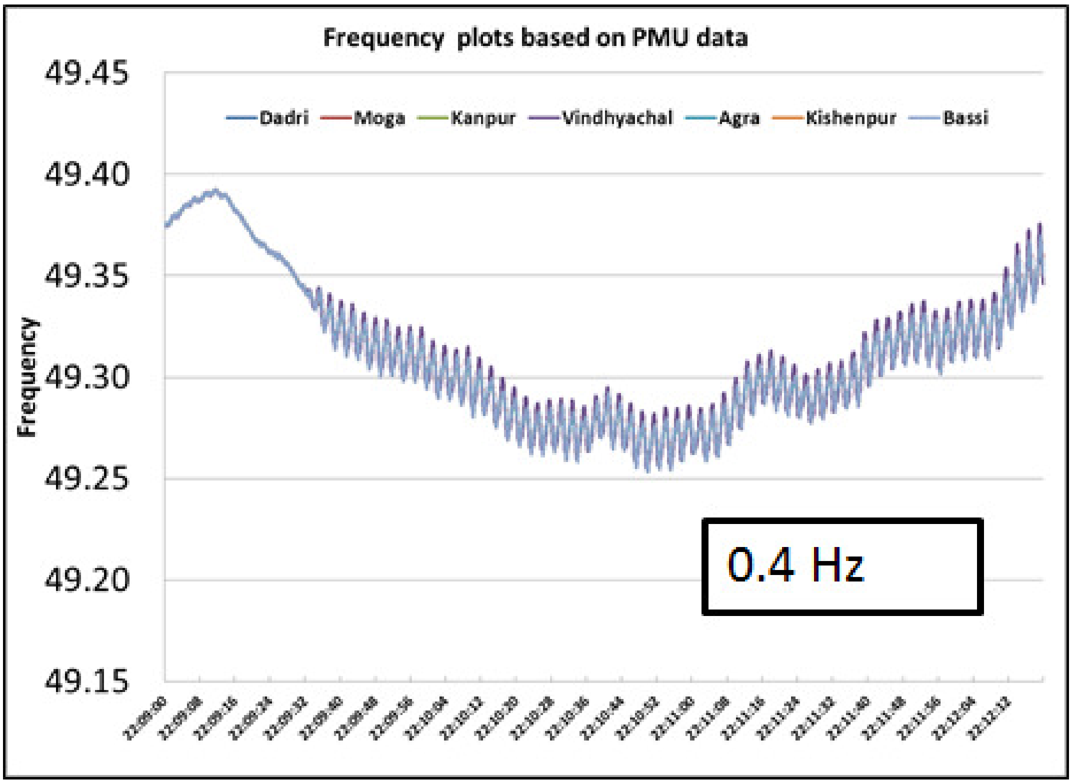


Figure 98: Low frequency oscillations in Dadri frequency

Figure 98 shows the frequency plot. It can be seen that low frequency oscillations were observed at all the eight locations i.e. oscillations were propagated in the entire NEW grid.

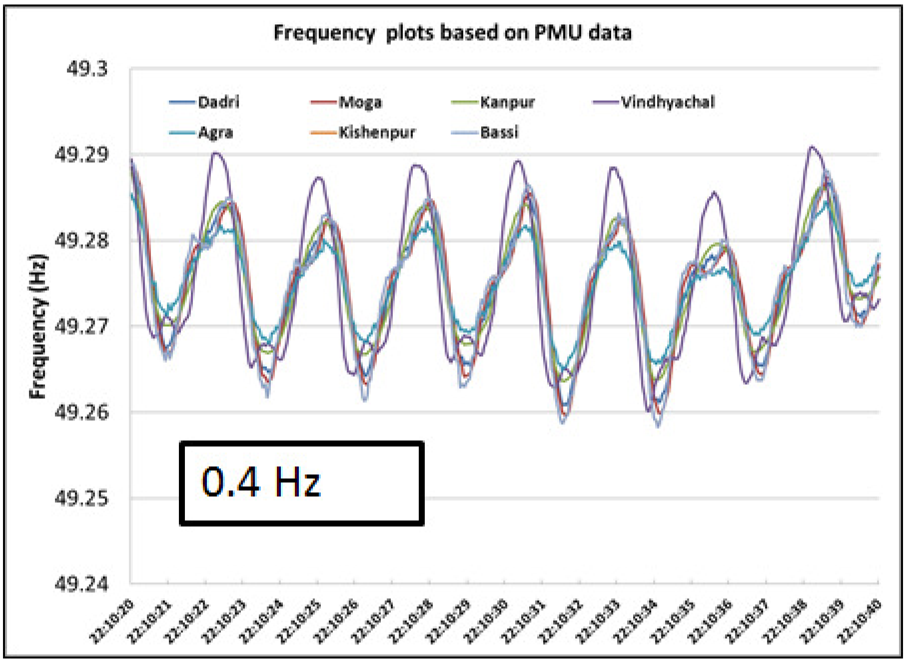


Figure 99: Frequency plots on 30th November 2011

Figure 99 shows the zoomed view of the lot shown at figure. It can be observed that the oscillation frequency was 0.4 Hz.

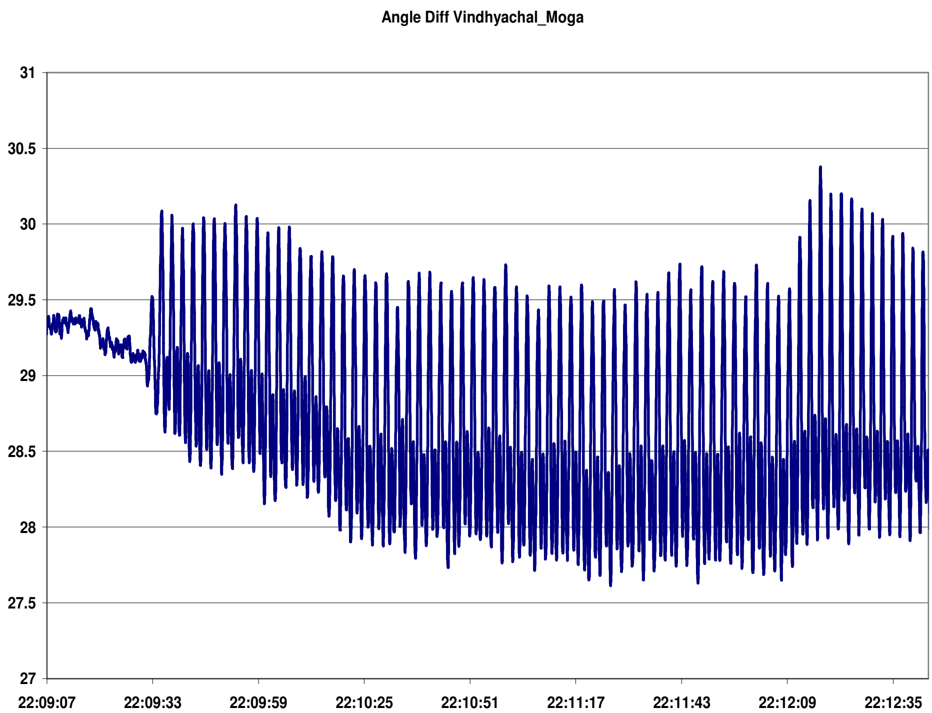


Figure 100: Oscillations in angular difference between Vindhyachal and Moga

5.6.4 Case Study-32: Oscillation analysis (Northern Region, 1-Jun-10)

The oscillations observed during 2000 MW generation loss at Rihand STPS on 1st June 2010. Analysis of these oscillations was carried out with help of IIT, Delhi.

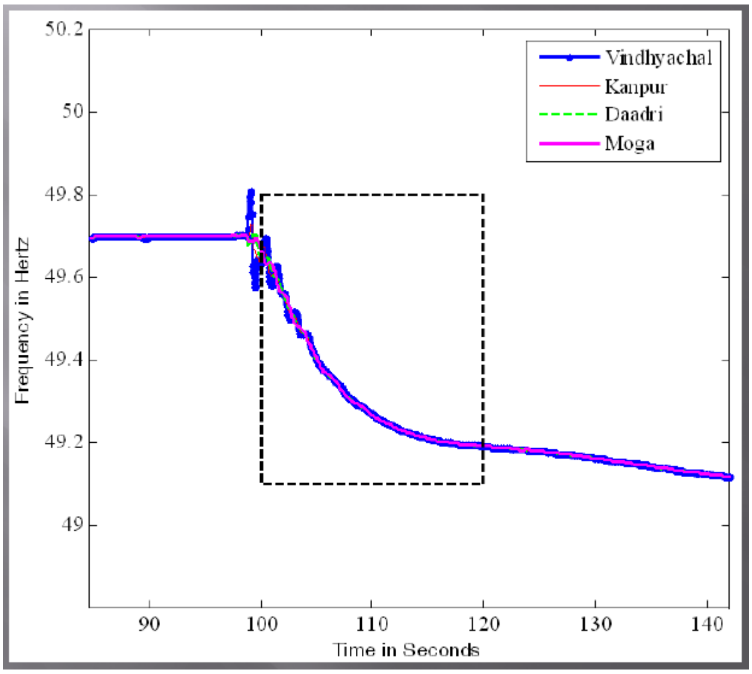


Figure 101: Frequency data recorded by Vindhyachal, Kanpur, Dadri & Moga PMUs

Figure 101 shows the frequency data recorded by PMU at Vindhyachal, Kanpur, Dadri and Moga during the generation loss at Rihand STPS.

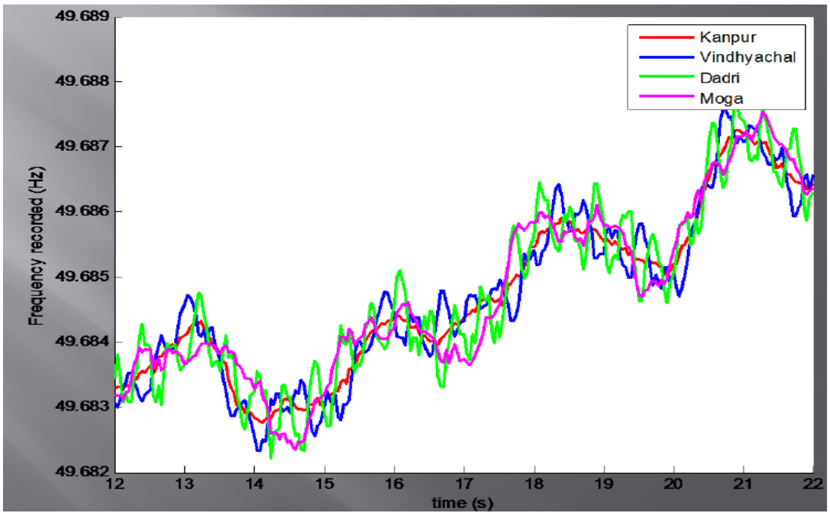


Figure 102: Frequency data recorded by Vindhyachal, Kanpur, Dadri & Moga PMUs

Figure 102 shows the frequency window taken in figure.

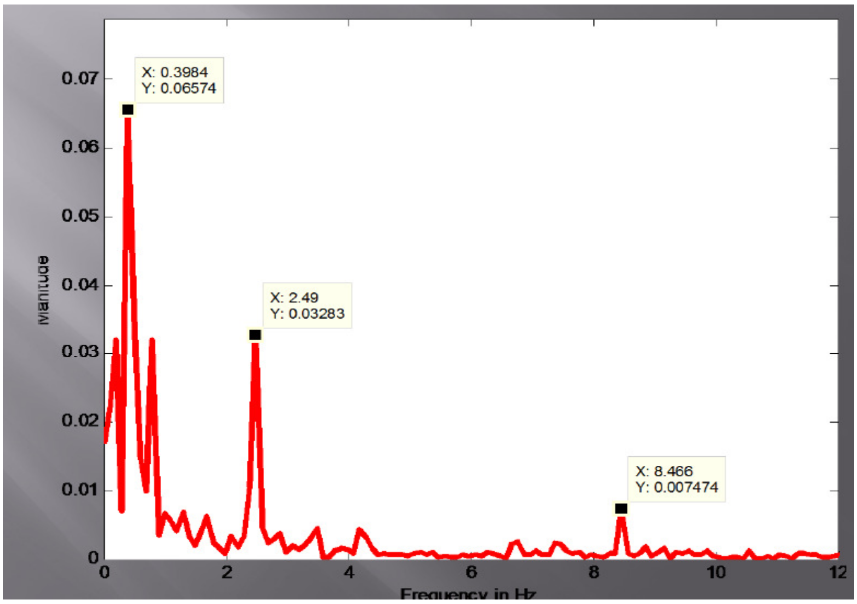


Figure 103: FFT of frequency recorded by Vindhyachal PMU

Figure 103 shows the FFT of frequency recorded by Vindhyachal PMU

Frequency	0.3984	2.49	8.466
Magnitude	0.0657	0.0328	0.0074

5.6.5 Case Study-33: Identification of coherent group of generators

Knowledge of coherent group of generators during inter area oscillations is important for taking appropriate measures for suppressing the inter area oscillations.

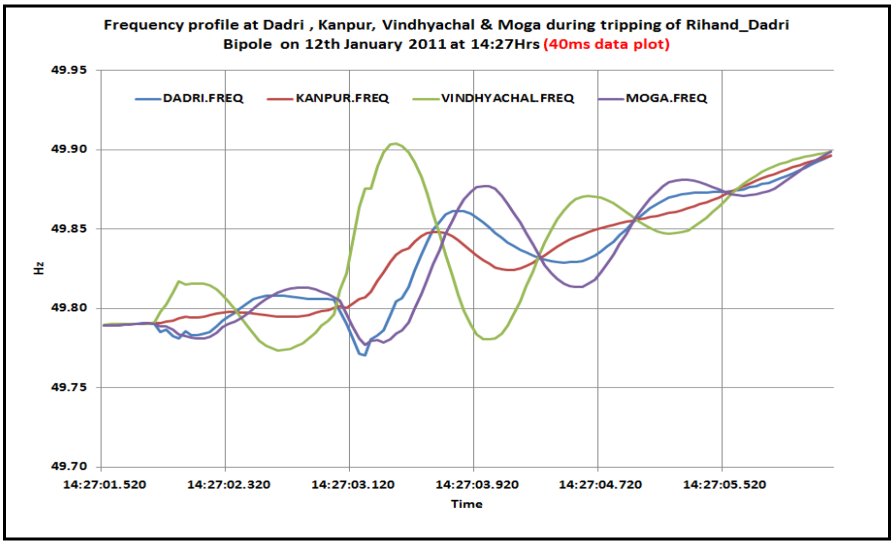


Figure 104: Swing in frequency during tripping of Rihand-Dadri bipole

Figure 104 shows the frequency profile recorded by PMUs during the tripping of HVDC Rihand-Dadri bipole carrying 1400 MW. It can be observed that the generators near Vindhyachal are swinging with respect to generators located near Dadri.

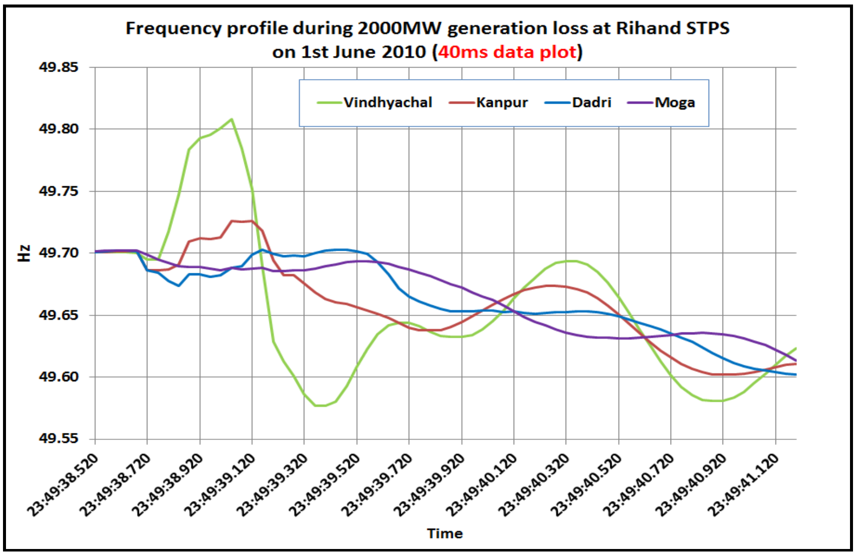


Figure 105: Swing in frequency during generation loss at Rihand STPS

Figure 105 shows the frequency profile recorded by PMU's during incident of 2000MW generation loss at Rihand STPS. Similar patterns of swinging of generators as seen above are observed.

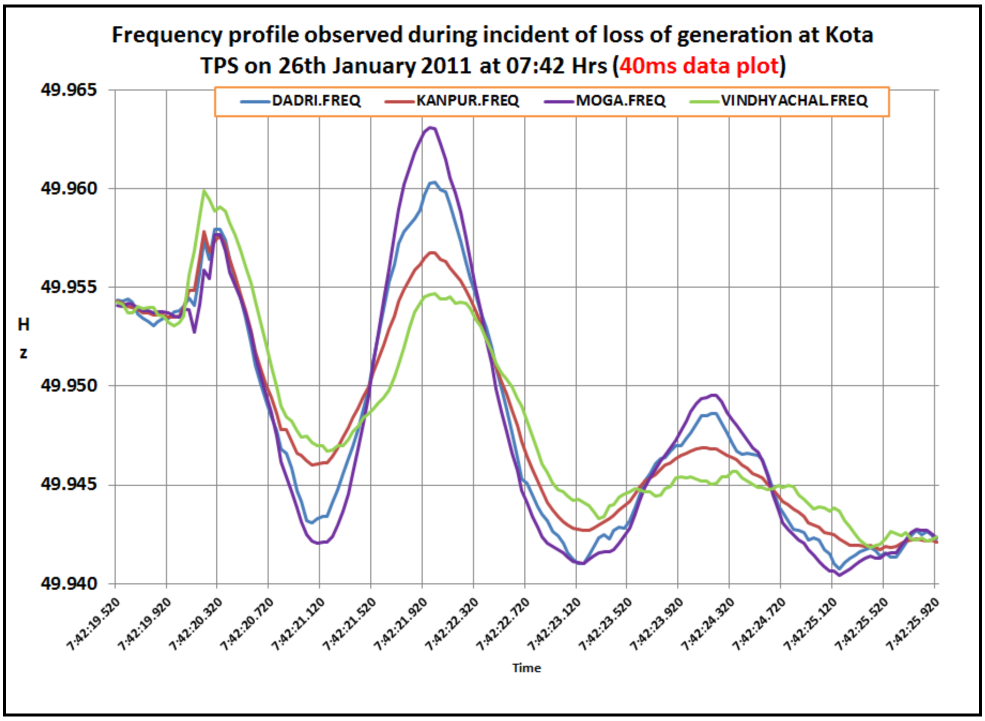


Figure 106: Swing in frequency profile during generation loss at Kota TPS

Figure 106 shows the frequency profile recorded by PMU's during incident of generation loss at Kota TPS in Rajasthan. It can be observed that all the frequencies are swinging in the same direction.

5.6.6 Case Study-34: Oscillations analysis (Southern Region, 22-Apr-2012)

Indian grid is demarcated into 5 regional grids namely North, East, West, North East and South. The first four grids are synchronously connected whereas Southern Region (SR) is asynchronously connected with the rest of India grid through HVDC links namely Bhadrawati back to back, Gazuwaka back to back and Talcher-Kolar bipole. Oscillations have been reported from Ramagundam (NTPC) generating station in SR whenever the power-flow from the western region to southern region through HVDC Bhadrawati is increased to 900MW and above. This can be established with the help of figure no 107 and 108. As power flow in Bhadrawati is increased, oscillations can be seen in flow on Hyderabad-Ramagundam.

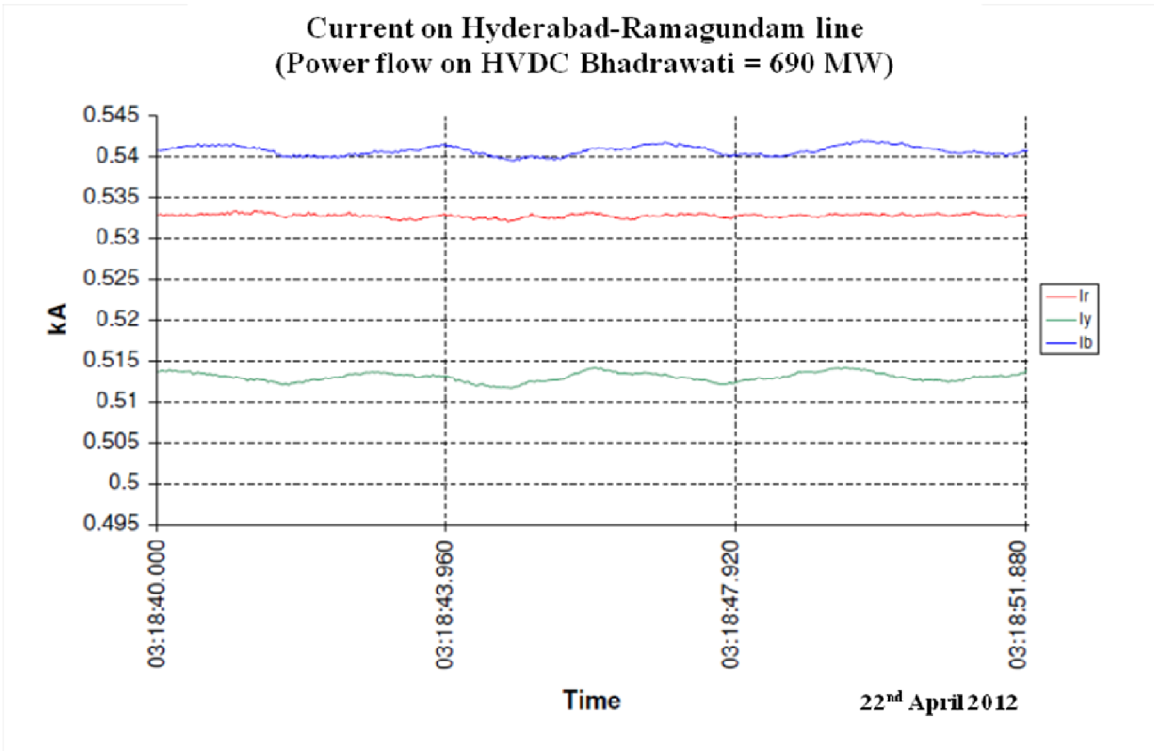


Figure 107: Flow on Hyderabad-Ramagundam (HVDC Bhadrawati = 690 MW)

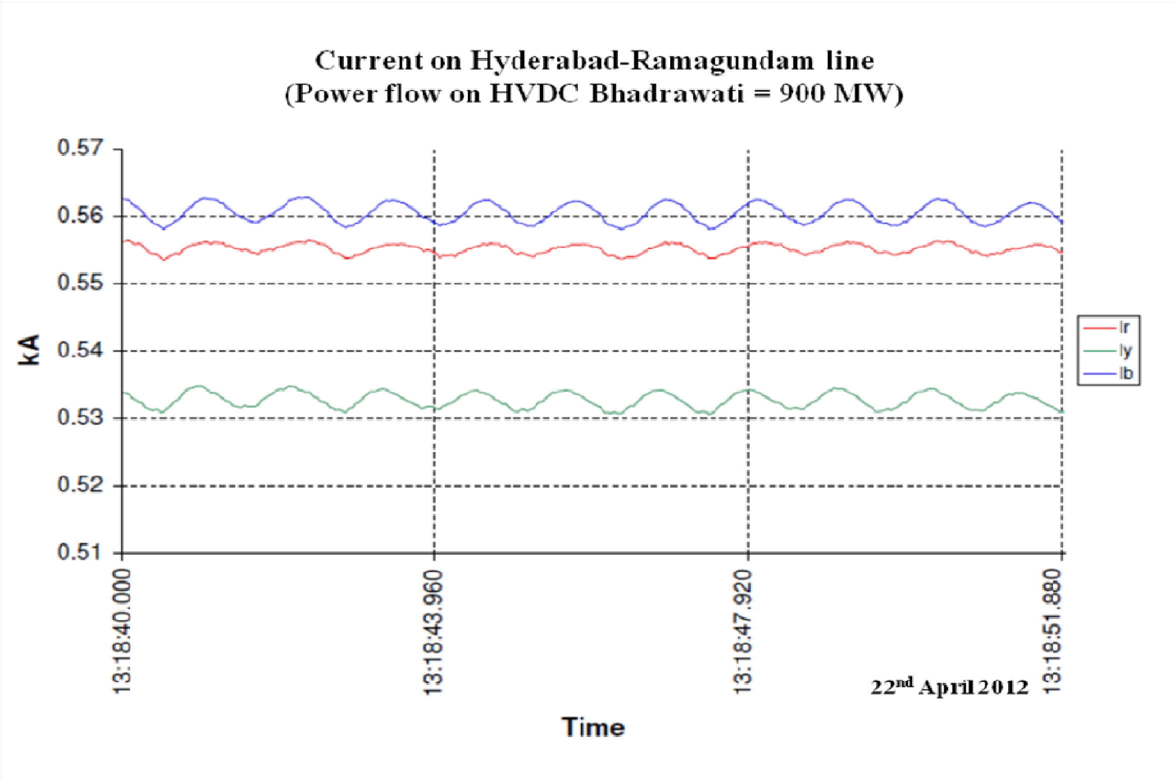


Figure 108: Flow on Hyderabad-Ramagundam (HVDC Bhadrawati = 900 MW)

5.6.7 Case Study-35: Oscillations analysis (Western Region,18-Apr-2012)

Oscillations under high power flow at Bhadrawati were also studied in Western region. Real time field testing was conducted on 18-April 2012 by increasing the power order of HVDC Bhadrawati back to back to 900 MW towards SR at 0930 hrs. The frequency and voltage profile during the testing are shown below:

- <u>Scenario 1: HVDC Power Order < 900MW</u>

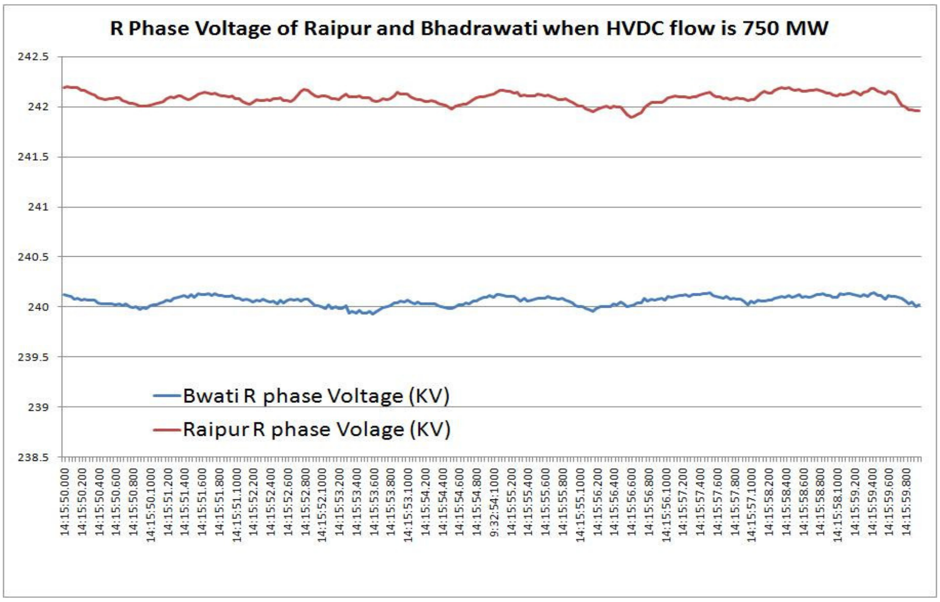


Figure 109: R phase voltage of Raipur and Bhadrawati when HVDC flow is 750 MW

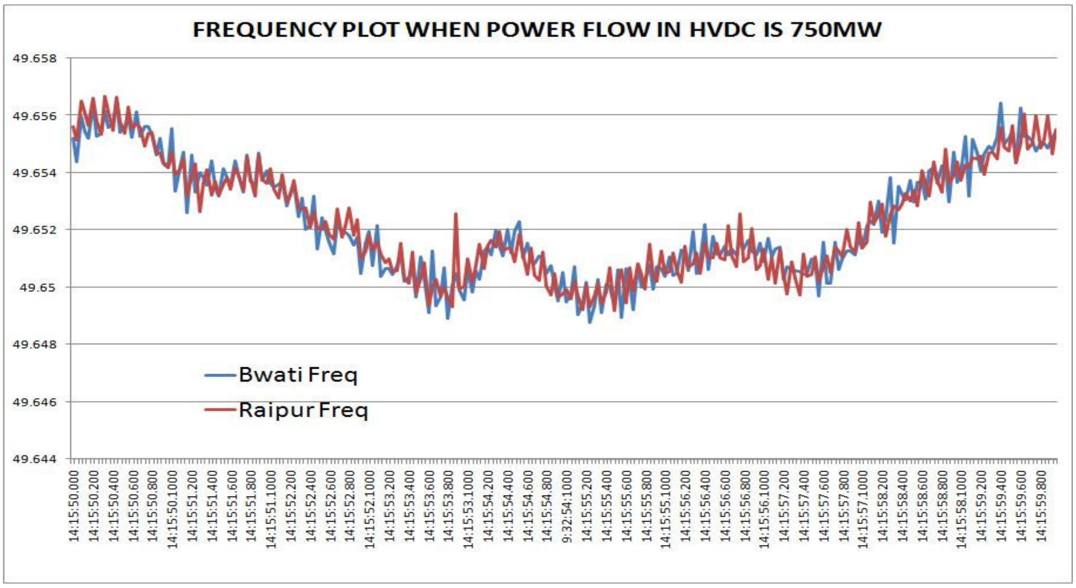


Figure 110: Frequency plot when power flow on HVDC Bhadrawati is 750 MW

- Scenario 2: HVDC Power Order = 900 MW

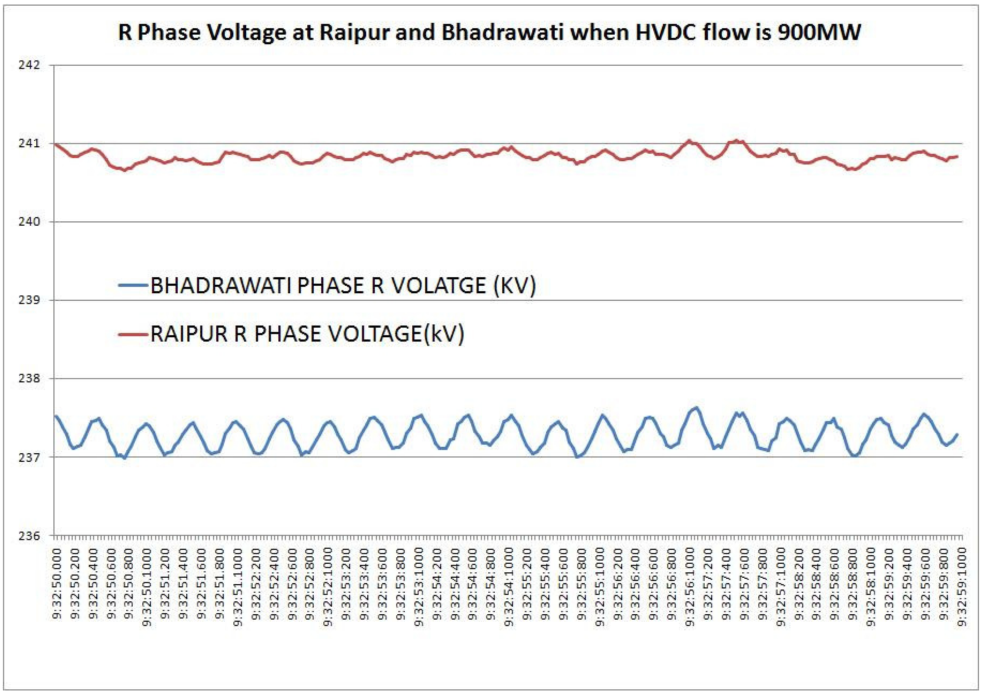


Figure 111: Oscillations seen in Raipur and Bhadrawati when HVDC flow is 900 MW

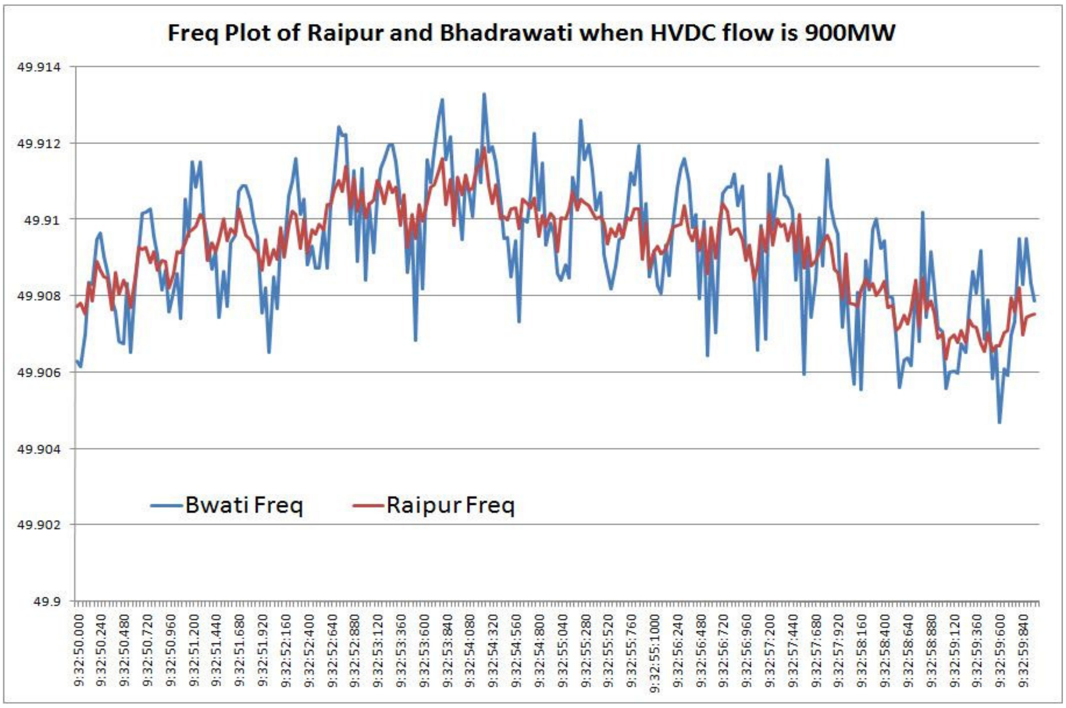


Figure 112: Oscillations in frequency when power flow on HVDC Bhadrawati is 900 MW

It is evident from above plots that oscillations are clearly captured when the HVDC power order is increased to 900MW and oscillations are prominently observed at Bhadrawati end. From the available literature on Power System, oscillations observed can be broadly classified as:

- Electromagnetic Oscillation (Typically of the order of kHz)
- Electromechanical Oscillation (Typically of the order of .2- 46 Hz)

The above scenario exposed the following possibilities:

- Oscillations generated by the HVDC Link due to inadequate damping by HVDC Control System.
- Inter-Area Oscillations.
- Intra-Plant Oscillations in Western Region.
- Intra-Plant oscillations in Southern Region.

PMU plots of second scenario (inter-area oscillations) were further analysed to identify the mode of low frequency oscillation.

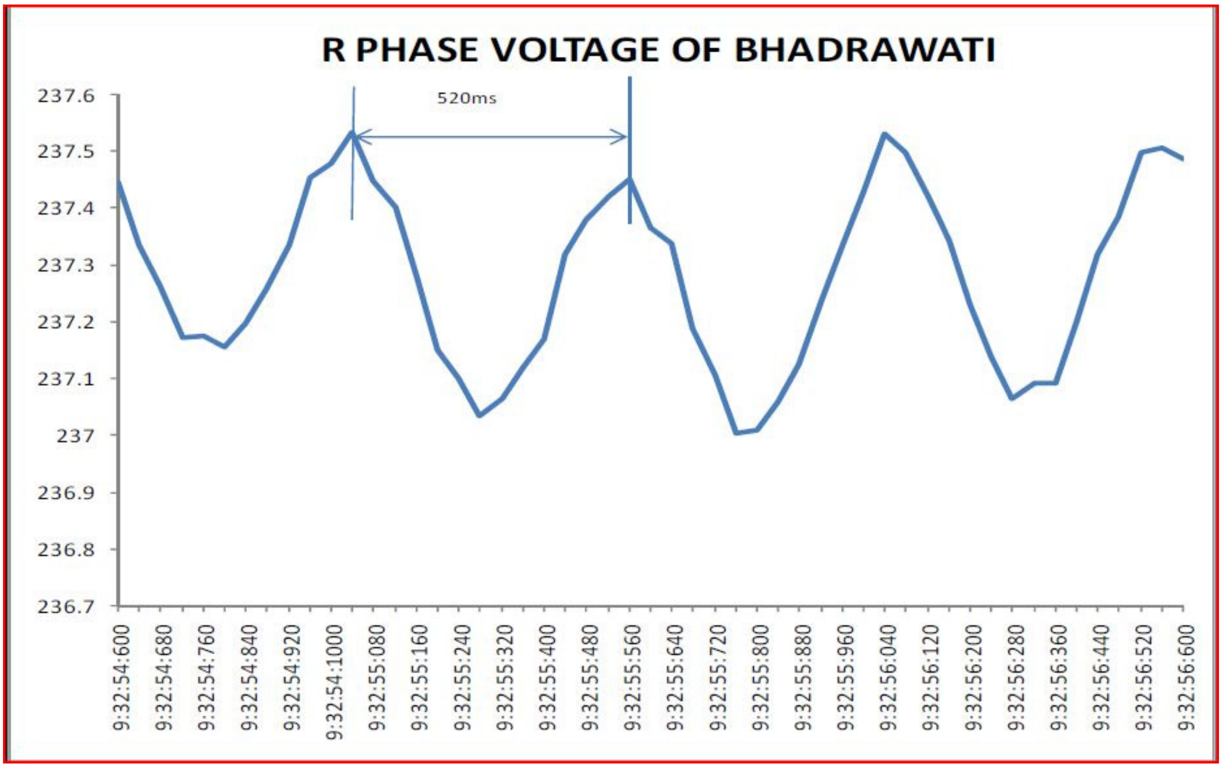


Figure 113: R phase voltage at Bhadrawati showing frequency of oscillations

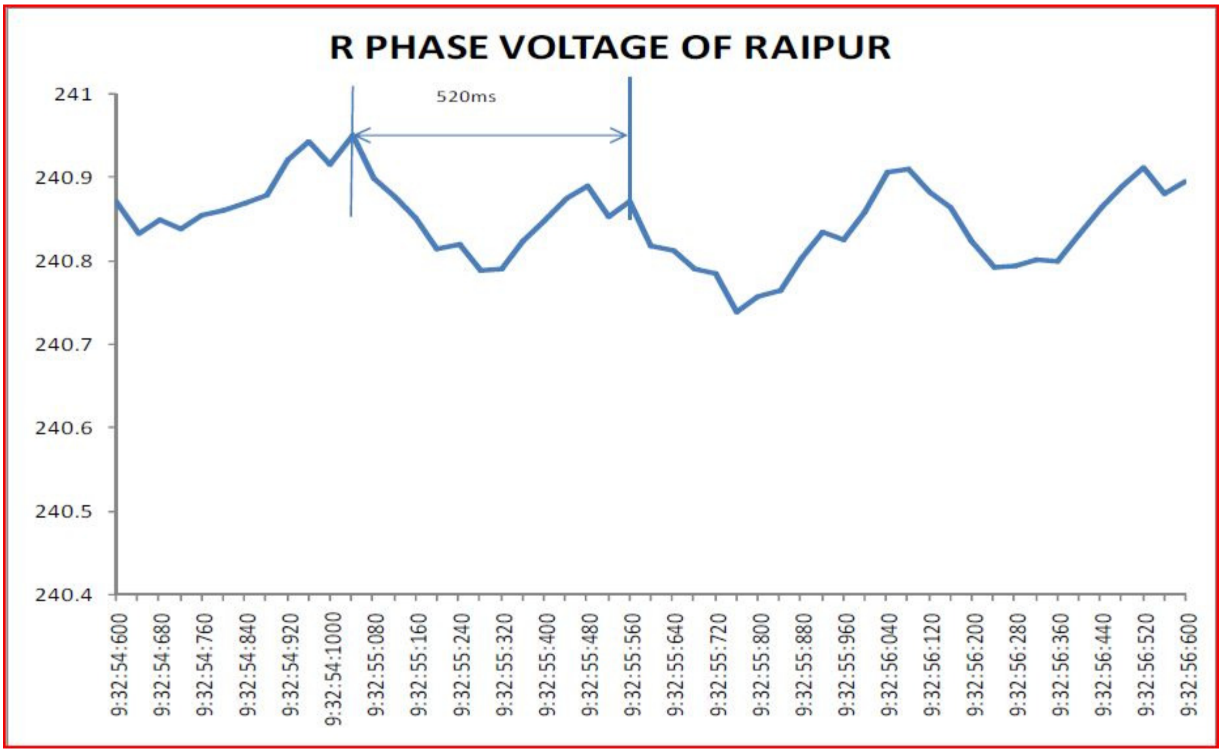


Figure 114: R phase voltage at Raipur showing frequency of oscillations

Above plots indicate presence of low frequency oscillations of 1.923 Hz which falls under the category of Intra-Plant Mode of Oscillations.

Oscillations reported from NTPC Ramagundam may be reflected in HVDC Bhadrawati West-Bus indicates that these oscillation were not damped out by the existing HVDC controllers (Thyristor firing angle control) and may have their origin in SR. Moreover no other generator in SR has reported oscillations during the corresponding period. This strengthens the possibility of Intra-Plant mode (1.2 Hz to 2.1 Hz) of Oscillations originating from NTPC Ramagundam.

Further based on the analysis of PMU data at WRLDC the following observability status can be established.

SUGGESTIONS FOR CONTROLLABILITY

- As the oscillations seems to be originating on account of intra-plant oscillations at Ramagundam, it is suggested to take up tuning of PSS at Ramagundam at the earliest. This is all the more relevant in view of the proposed trial synchronization of NEW Grid with SR Grid planned in July'12.
- Damping controllers which are normally provided at HVDC Bipole stations may be proposed for HVDC B2B Bhadrawati which will help to address inadequate damping.

5.6.8 Case Study-36: Spectral Analysis using Fast Fourier Transform (18-Apr-2012)

The spectral analysis of oscillations observed in Western Region on 18th April 2012 was carried out using Fast Fourier Transform. The inferences are elaborated below. The duration of plots is 10 seconds.

- Scenario 1: HVDC Bhadrawati back to back power order < 900MW

Date: 18-04-2012 TIME: 1415Hrs-1425Hrs Power Flow to SR: 750MW

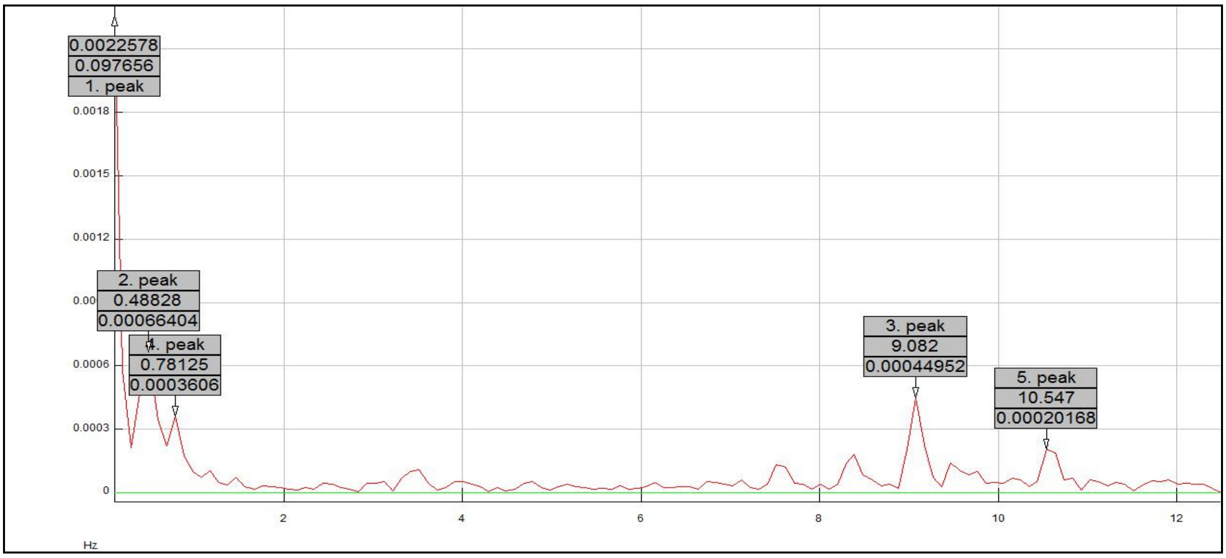


Figure 115: FFT of frequency at Bhadrawati (HVDC B'wati flow 750MW)

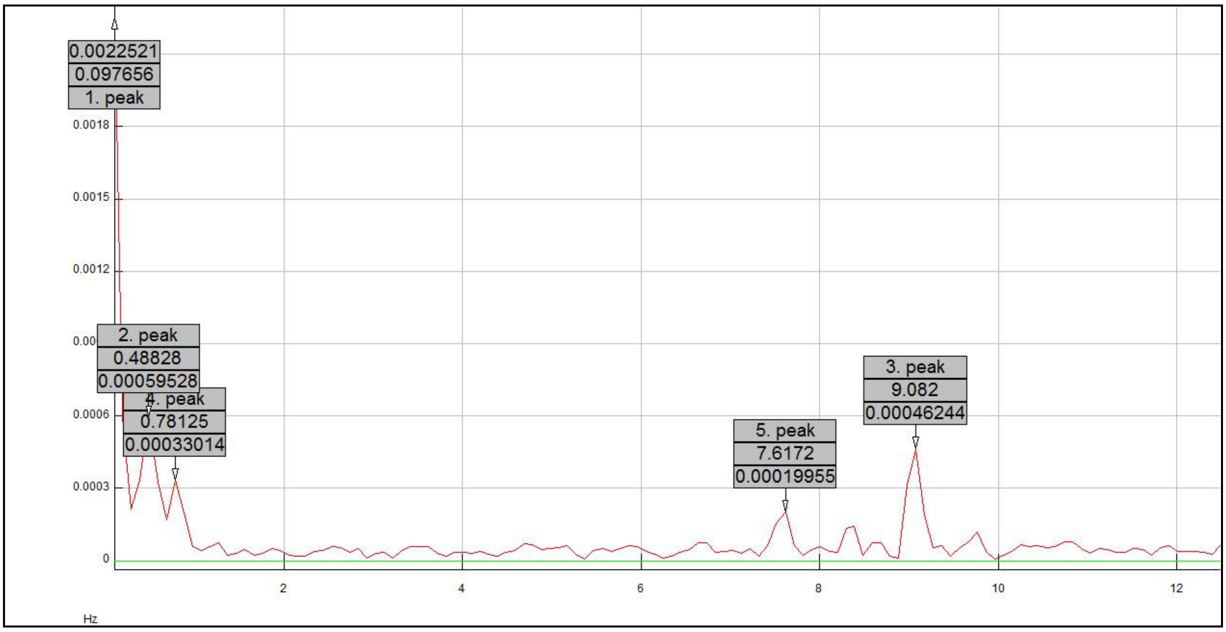


Figure 116: FFT of frequency at Raipur (HVDC B'wati flow is 750MW)

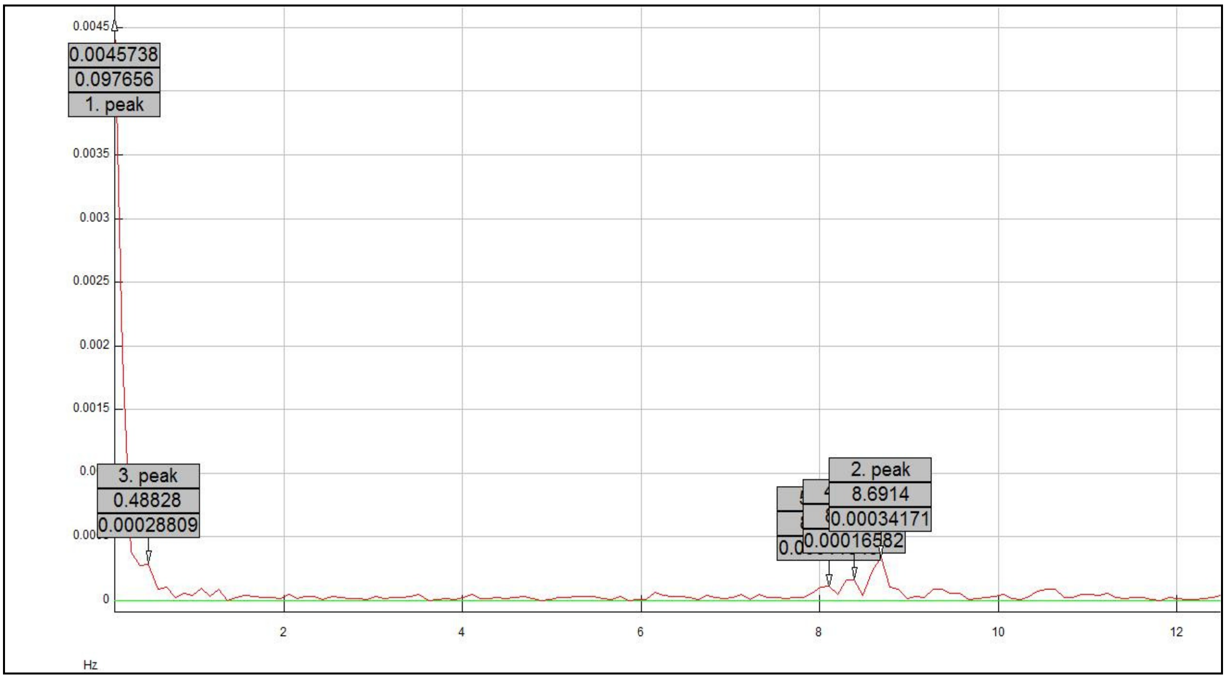


Figure 117: FFT of frequency at Hyderabad (HVDC B'wati flow 750MW)

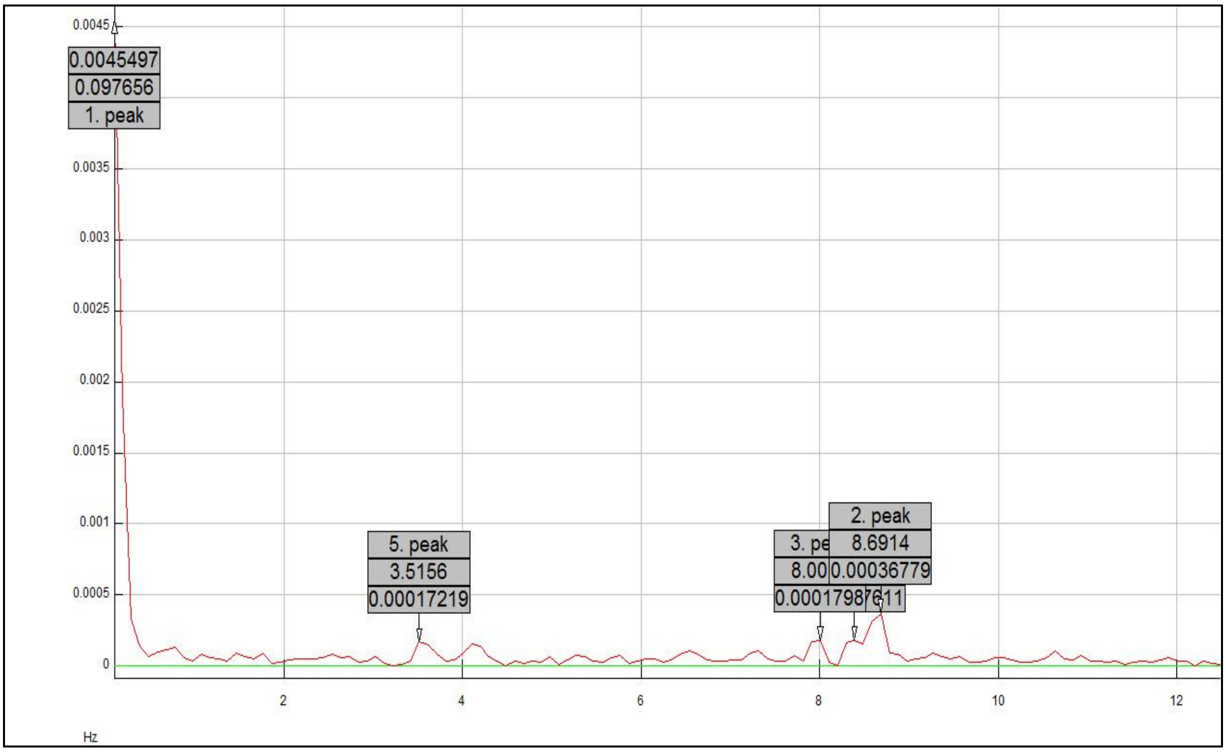


Figure 118: FFT of the frequency at Bangalore (HVDC B'wati flow is 750MW)

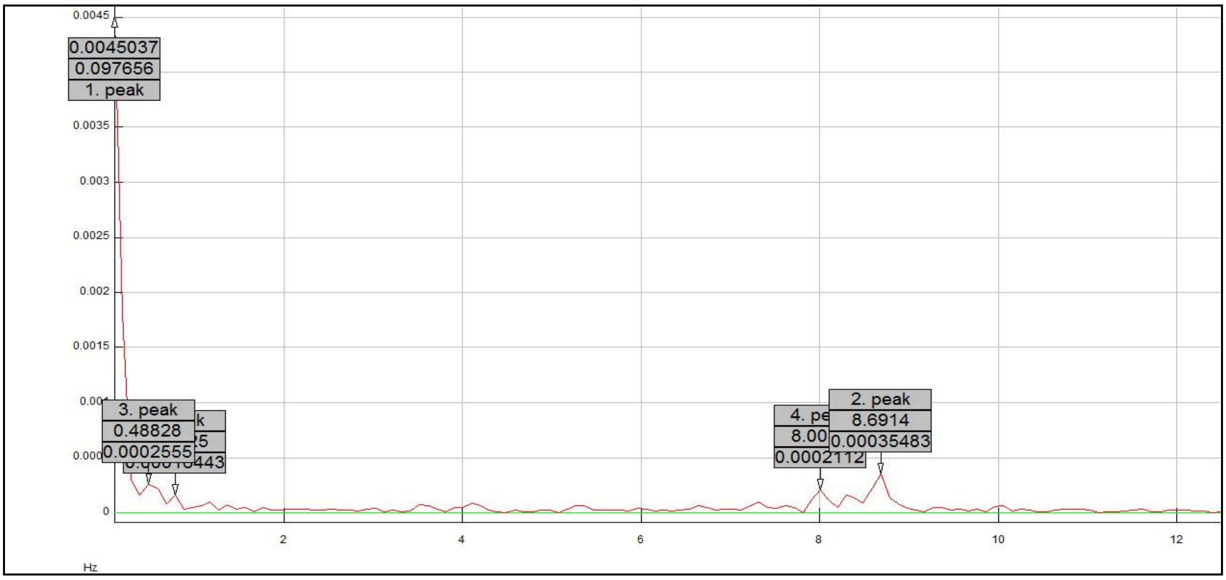


Figure 119: FFT of the frequency at Salem (HVDC B'wati flow is 750MW)

Table 12: Frequency of Oscillation modes with HVDC power order on Bhadrawati 750 MW

<table>
<tr><th colspan="4">Western Region</th><th colspan="5">Southern Region</th></tr>
<tr><th rowspan="2">S. No</th><th rowspan="2">Frequency of different modes of Oscillation (Hz)</th><th colspan="2">Magnitude of Oscillation from FFT</th><th rowspan="2">S. No</th><th rowspan="2">Frequency of different modes of Oscillation(Hz)</th><th colspan="3">Magnitude of Oscillation from FFT</th></tr>
<tr><th>Bhadrawati</th><th>Raipur</th><th>Hyderabad</th><th>Salem</th><th>Bangalore</th></tr>
<tr><td>1</td><td>0.097</td><td>0.002258</td><td>0.002252</td><td>1</td><td>0.097</td><td>0.004574</td><td>0.004504</td><td>0.00455</td></tr>
<tr><td>2</td><td>0.488</td><td>0.000664</td><td>0.000595</td><td>2</td><td>8.6914</td><td>0.000314</td><td>0.000354</td><td>0.000315</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">9.082</td><td rowspan="2">0.000449</td><td rowspan="2">0.000462</td><td rowspan="2">3</td><td>8.0078</td><td>-</td><td>-</td><td>0.000179</td></tr>
<tr><td>0.488</td><td>0.000288</td><td>0.000255</td><td>-</td></tr>
<tr><td rowspan="3">4</td><td rowspan="3">.7815</td><td rowspan="3">0.000360</td><td rowspan="3">0.000330</td><td rowspan="3">4</td><td>8.3984</td><td>-</td><td>-</td><td>0.000176</td></tr>
<tr><td>8.3007</td><td>0.000165</td><td>-</td><td>-</td></tr>
<tr><td>8.0078</td><td>-</td><td>0.000212</td><td>-</td></tr>
<tr><td rowspan="3">5</td><td>10.547</td><td>0.000201</td><td>-</td><td rowspan="3">5</td><td>3.5157</td><td>-</td><td>-</td><td>0.000172</td></tr>
<tr><td rowspan="2">7.6172</td><td rowspan="2">-</td><td rowspan="2">0.000199</td><td>8.1054</td><td>0.000115</td><td>-</td><td>-</td></tr>
<tr><td>0.7812</td><td>-</td><td>0.000164</td><td>-</td></tr>
</table>

From the FFT analysis the frequency of oscillation with maximum magnitude are given in Table1.In the table the top 5 frequencies having highest magnitude is shown. Majority of modes lie in the range of Inter-Area Oscillation. All the modes detected have insignificant amplitude and of not much of consequences. During 750 MW flow through HVDC B'wati link to SR no Intra-Plant mode of oscillation was observed either in NEW Grid (at Bhadrawati and Raipur) or in SR Grid (at Hyderabad, Bengaluru and Salem).

- Scenario 2: HVDC Bhadrawati back to back power order > 900MW

Date: 18-04-2012 TIME: 0925Hrs-0935Hrs Power Flow to SR: 900MW

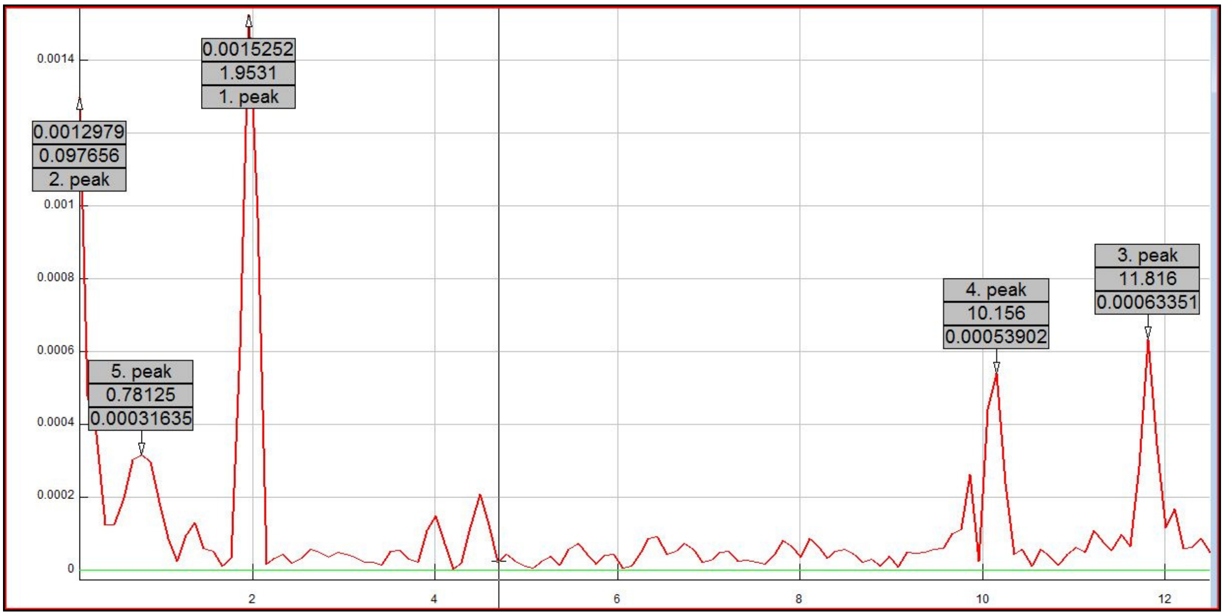


Figure 120: FFT of the frequency at Bhadrawati (HVDC flow is 900 MW)

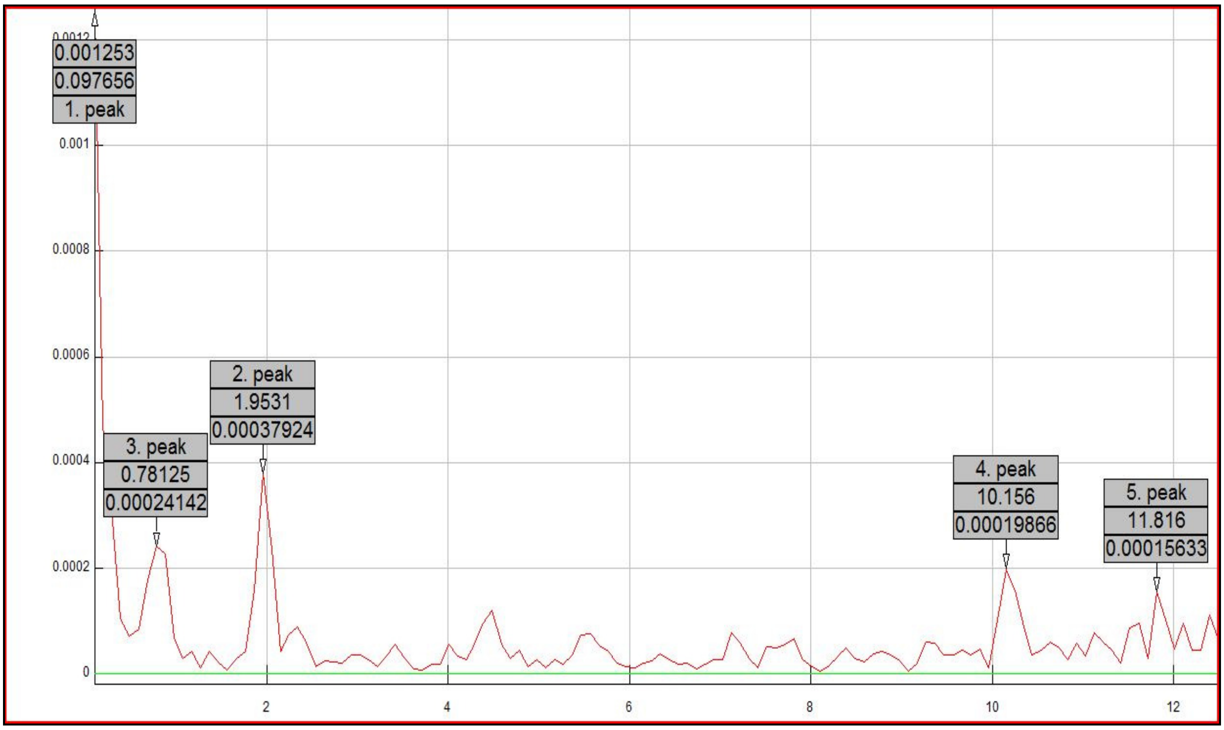


Figure 121: FFT of the frequency at Raipur (HVDC flow is 900 MW)

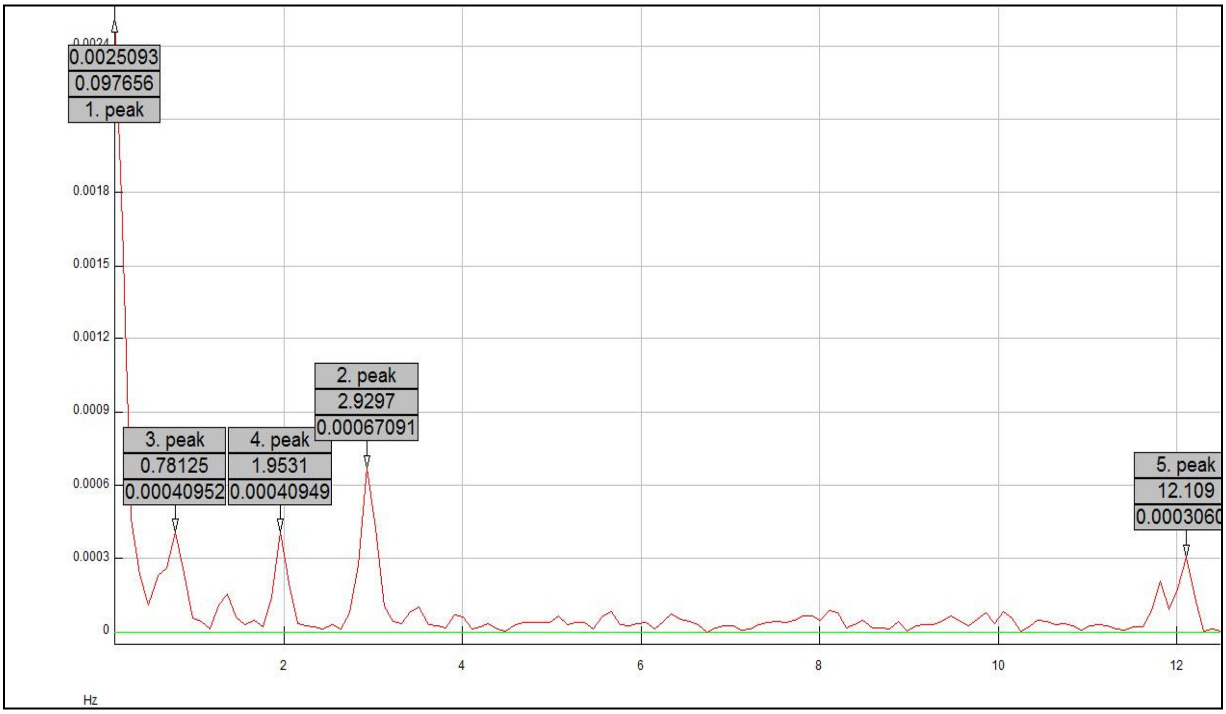


Figure 122: FFT of the frequency at Hyderabad (HVDC flow is 900 MW)

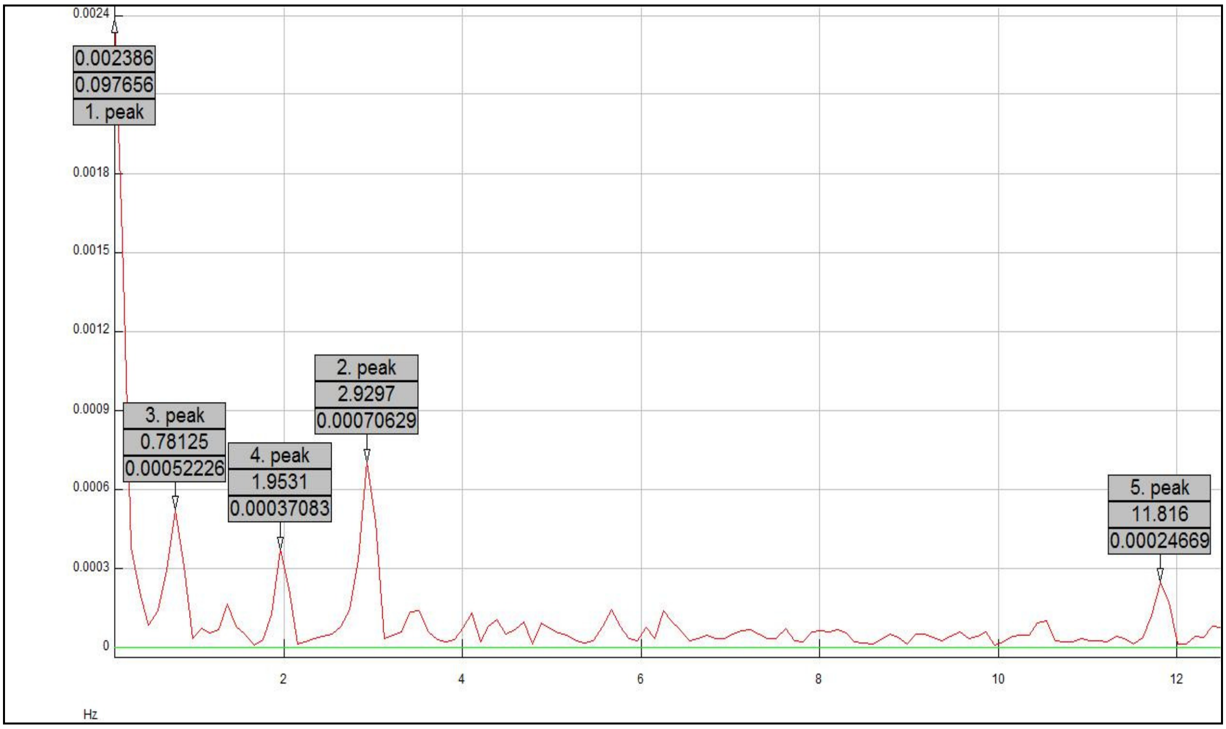


Figure 123: FFT of the frequency at Bengaluru (HVDC flow is 900 MW)

Table 13: Frequency oscillation modes with HVDC Bhadrawati power order 900 MW

Western Region				**Southern Region**				
Sl.No	Frequency of different modes of Oscillation	Magnitude of Oscillation from FFT		Sl.No	Frequency of different modes of Oscillation	Magnitude of Oscillation from FFT		
		Bhadrawati						
1	1.953	0.001501	-	Raipur 1	0.097	Hyderabad	Salem	Bengaluru
2	0.097	-	0.00127	2	2.929	0.00251	0.00241	0.00239
	1.953	-	0.00036					
3	0.097	0.00131	-	3	0.7812	0.00067	0.00061	0.0007
	11.816	0.00062	-					
4	0.7812		0.000226	4	4.1016	0.00040	0.000281	0.0005
	10.156	0.00052	0.000192					
5	11.816	-	0.000149	5	1.953	-	0.000228	-
					1.953	0.00040	-	0.00037
	0.7812	0.00032	-		11.816	-	0.000220	-
	0.7812	0.00032	-		12.109	-	-	0.00025

Spectral analysis using FFT was also done to analyze the low frequency oscillations at Bhadrawati. It was observed that there is a significant change in the magnitude of the oscillations when the power flow in HVDC link is 900 MW towards SR.

- From PMU data of WR it can be inferred that 1.953 Hz mode of oscillation is present along with inter –area oscillation of 0.7812 Hz mode.
- From PMU data of SR it can be inferred that possibly exciter mode 2.929 Hz and Intra-Plant mode (1.929 Hz) of oscillations are found to be significant along with Inter-Area mode 0.7812 Hz.
- No exciter mode of oscillation is observed on WR side.
- Torsoinal mode of oscillation (11.816 Hz) is present on both sides with very low amplitude.
- Magnitude of Intra-Plant mode (1.953Hz) decreases drastically while moving from Bhadrawati end to Raipur end in WR.
- The intraplant mode can be named as South-West Mode –I(SWM-I) for future reference.

5.6.9 Case Study-37: Study of Ringdown oscillations during event on 19-Apr-2012

The case was examined by studying the Ringdown oscillation due to tripping of Anpara and Rihand units in the early morning of 19th April 2012. The total generation loss was around 1600 MW with the tripping of Anpara 1, 2, 3(3x200 MW) and Rihand 1, 2 (2x500 MW) units. The drop in frequency was from 50 Hz to 49.2 Hz.

From the SOE it was observed that following incidences occurred:

- 400kV Anpara-Varanasi line-2 - 0 3:24:43.916 hrs (Varanasi end)
- Unit#1 at Rihand STPS - 03:29:02.393 hrs
- Unit#2 at Rihand STPS - 03:30:53:626 hrs

Tripping of Anpara TPS could not be confirmed from U.P SOE. NRLDC SOE does not reveal any tripping at above mentioned time. Anpara TPS informed that tripping of Anpara-A units occurred at 03:29hrs but did not substantiate.

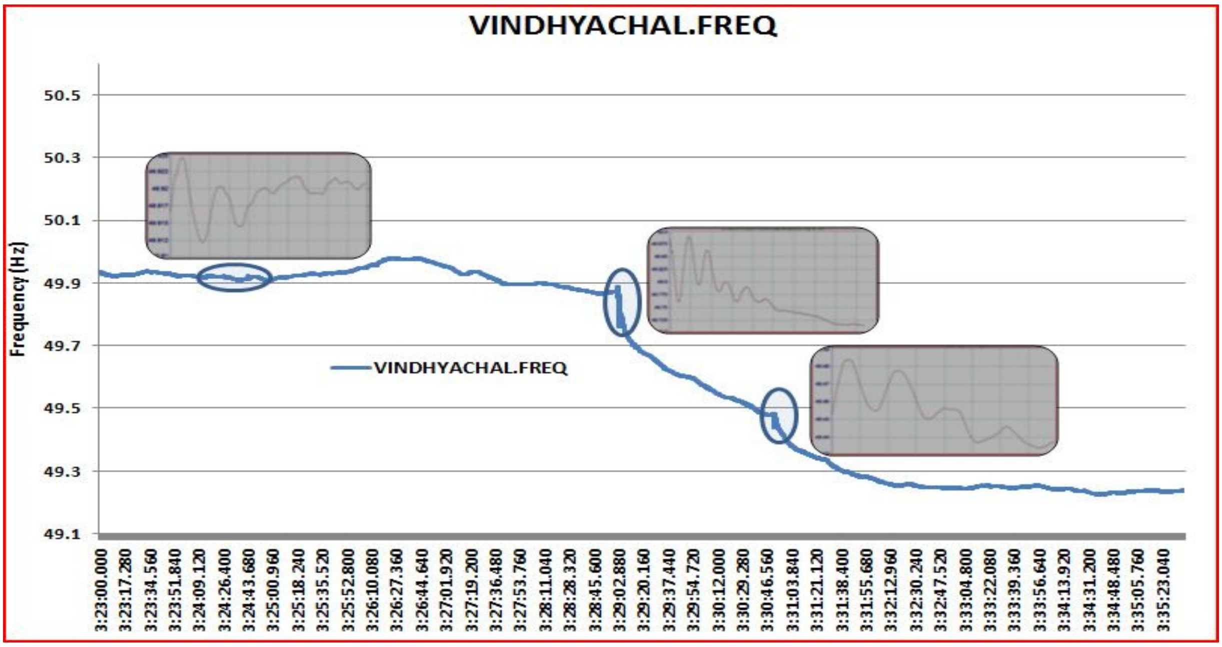


Figure 124: PMU plot for Vindhyachal frequency showing the three incidences

From the SOE and PMU plot shown above, three time intervals has to be analysed for proper investigation of Ringdown oscillation.

Duration 1 : 03:24:44.000 Hrs - 03:24:48.960 Hr (Tripping of 400kV Anpara-Varanasi line-2)

Duration 2 : 03:29:02.600 Hrs - 03:29:11.960 Hrs (Tripping of Rihand Unit 1)

Duration 3 : 03:30:52.000 Hrs - 03:30:55.960 Hrs (Tripping of Rihand Unit 2)

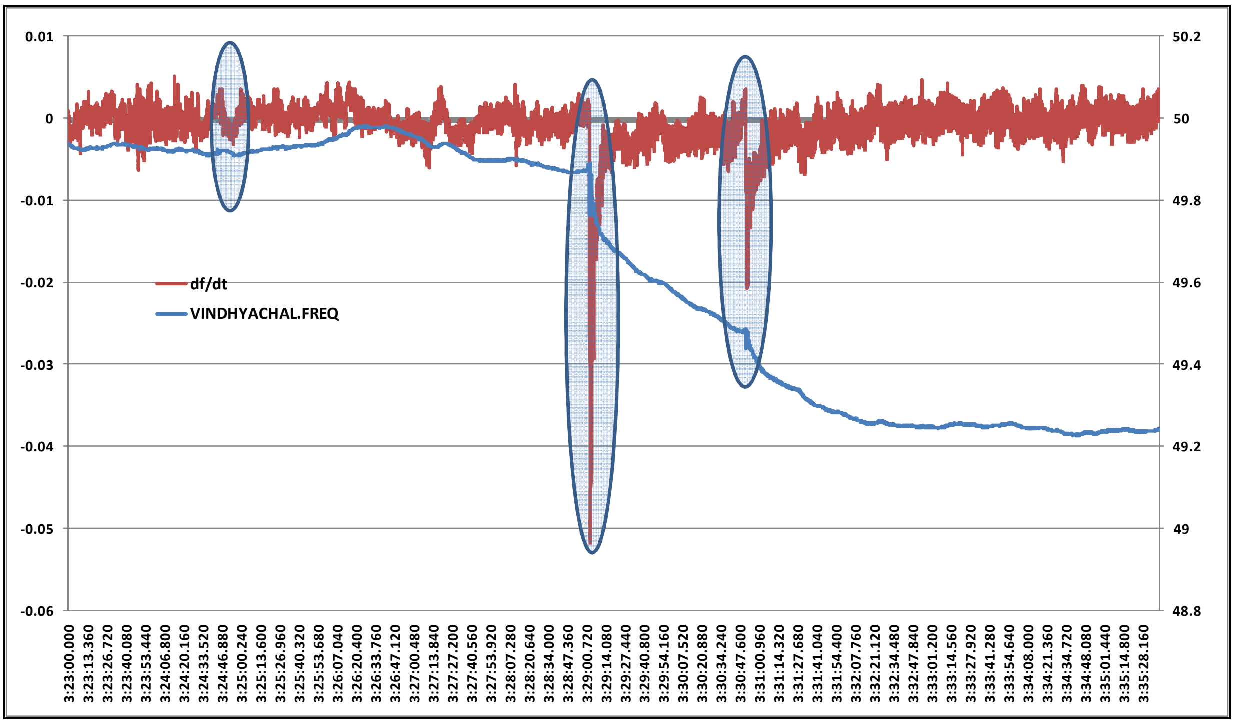


Figure 125: df/dt observed from Raipur PMU

The df/dt value during the second duration is more compared to third duration as shown in figure 125. It may be due to the tripping of Anpara unit 1, 2, 3 along with the tripping of Rihand Unit 1 which was not recorded in the SOE.

- <u>Duration 1: 03:24:44.000 Hrs - 03:24:48.960 Hrs</u>

As reported breaker of 400kV Anpara-Sarnath (Varanasi) line at Anpara end was under Lock-out. It seems that while transferring the line to transfer breaker line got tripped.

From PMU voltage plot it is clear that no-fault had occurred at 3:24:43.900 hrs.

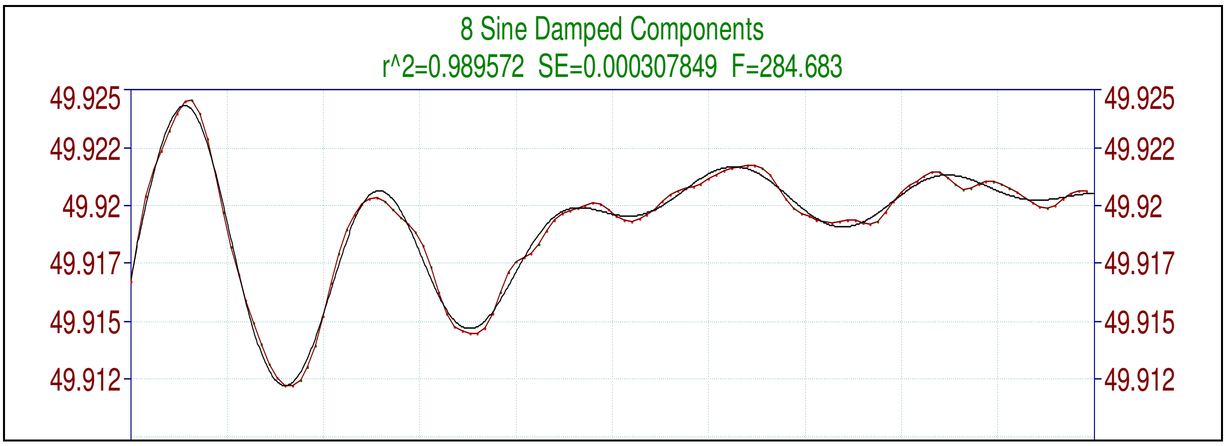


Figure 126: Prony Analysis of Frequency using 8 exponentially sine damped case

Table 14: Prony Analysis for duration 1

Duration 1						
Frequency	Amplitude	Phase	Damping	Power	%	Damping Ratio
0.268056	64.89061	6.10728	0.428132	2762.681	42.05589	0.246340742
0.506594	47.88857	0.480918	0.507842	994.5288	15.13957	0.157539237
0.740993	29.69791	0.982771	0.461709	427.1927	6.503091	0.098674959
0.998874	19.18257	1.099747	0.409642	208.5957	3.175421	0.065125069
1.26131	33.22245	0.990928	0.621605	410.0982	6.242865	0.078187745
1.483538	52.13898	1.811218	0.842068	834.5671	12.70449	0.089962476
1.705713	47.59308	2.843419	0.863031	688.9935	10.48845	0.080259218
1.922993	30.81344	4.154074	0.910696	242.4137	3.690228	0.075152545

- Duration 2: 03:29:02.600 Hrs - 03:29:11.960 Hrs

Rihand Unit 1 (500 MW) Tripped

Possibility of Anpara unit 1,2,3 (3x200 MW) Tripping in same interval

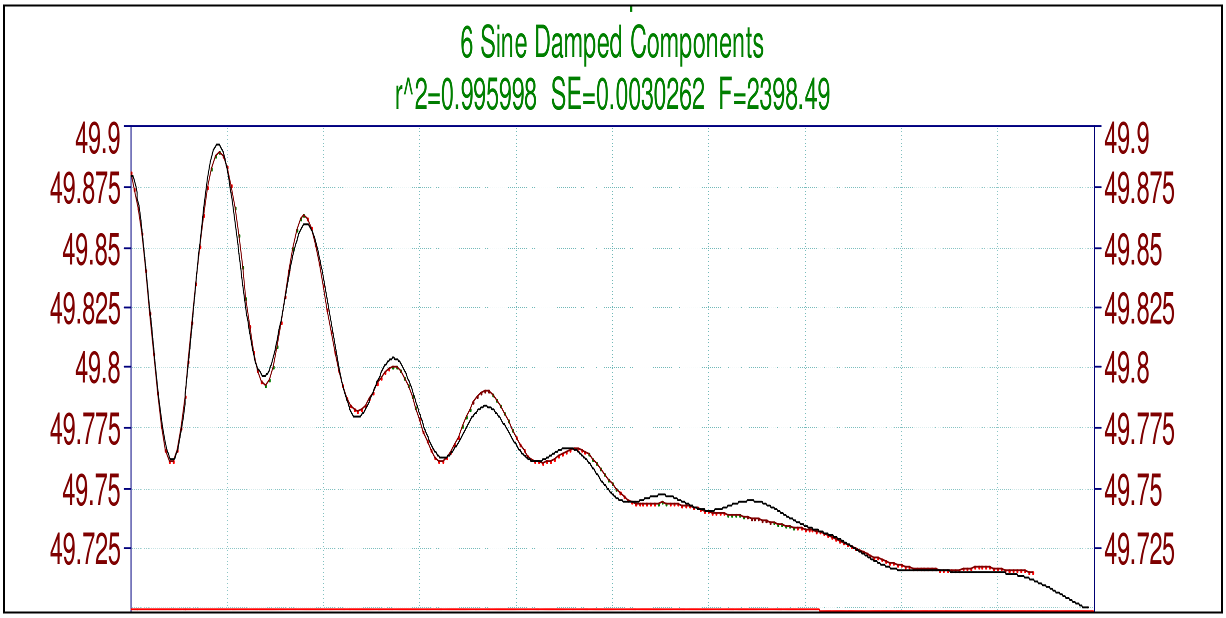


Figure 127: Prony Analysis of Frequency using 6 exponentially sine damped case

Table 15: Prony Analysis for duration 2

Duration 2						
Frequency	Amplitude	Phase	Damping	Power	%	Damping Ratio
0.397995	8.940054	4.341222	-0.04151	545.377	8.851019	-0.016595877
0.801764	35.84076	6.121129	0.505462	661.3904	10.73382	0.099826299
0.982584	74.80438	0.828222	0.712059	1739.611	28.23246	0.114565676
1.107195	57.67048	2.603614	0.701553	1294.976	21.01638	0.100326809
1.375815	16.55803	3.131538	0.528765	130.2619	2.114043	0.06104769

Duration 3: 03:30:52.000 Hrs - 03:30:55.960 Hrs

Rihand Unit 2 (500 MW) Tripped

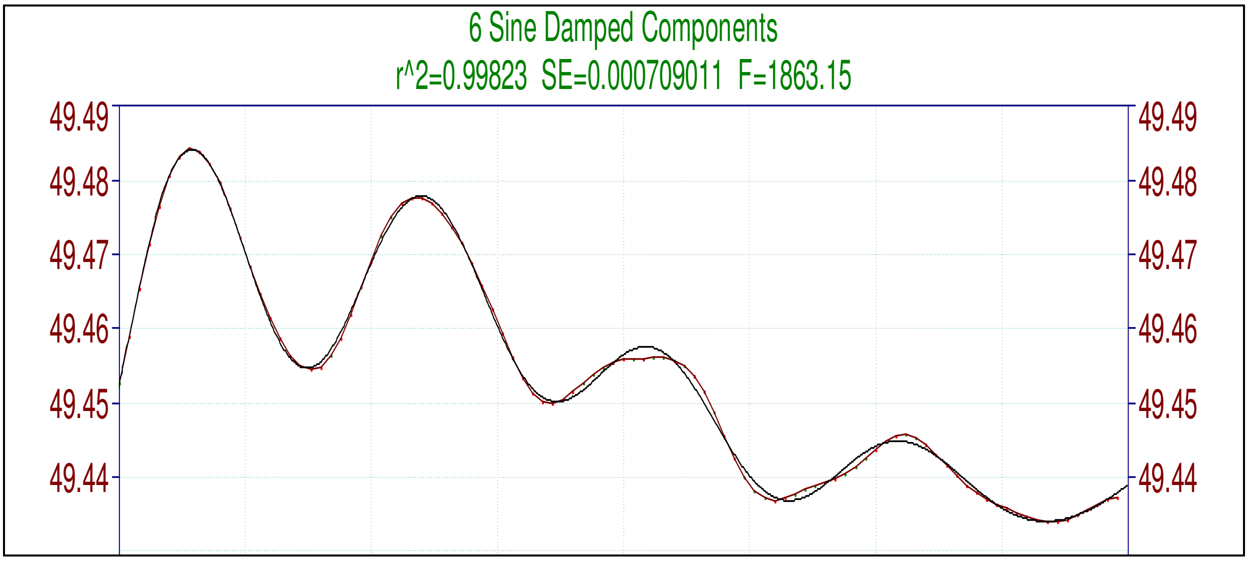


Figure 128: Prony Analysis of Frequency using 6 exponentially sine damped case

Table 16: Prony analysis for duration 3

Duration 3						
Frequency	Amplitude	Phase	Damping	Power	%	Damping Ratio
0.318698	116.2077	5.965598	0.706363	6081.439	52.62514	0.332632026
0.54125	117.8068	1.026222	0.866201	3038.756	26.29558	0.24680378
0.77882	68.71509	2.157672	0.796674	1680.56	14.54256	0.160672538
1.05334	28.44156	2.608701	0.552388	389.5986	3.371354	0.083166121
1.34561	24.41949	2.84787	0.646304	240.0798	2.077507	0.0762132
1.609696	20.23916	3.80039	0.755064	125.7144	1.087857	0.074440763

Inferences that can be drawn from the analysis are listed below:

i. The LFO of 0.39 Hz (0.4 Hz mode) was observed with negative damping (near to zero) when the Rihand unit 1 tripped. It was having negative damping but eventually got damped with time with change of state of the power system moving towards to a stable state. This mode was earlier observed in the grid during the LFO study submitted as "Report of LFO observed in NEW grid on 30th November 2011". This mode is observed all the time during analysis of LFO with adequate damping (always under monitoring). Its presence in NR suggests its universal nature in the Indian grid.

ii. The df/dt value is more when the tripping of Rihand unit 1 occurred compared to tripping of Unit 2 which suggests a possibility that tripping of Anpara units also occurred in duration 2.

iii. 1.1 Hz mode is also observed in all the three durations with adequate damping.

iv. 0.8 Hz mode (0.74 Hz in duration 1, 0.80 Hz in duration 2 and 0.78 Hz is duration 3) is present with adequate damping.

v. Apart from that it was observed that SWM-1 Mode was present and in duration 1 but has adequate damping in all the other durations.

5.7 Computation of System parameters

5.7.1 Case Study 38: Computation of System Inertia constant

An incident of multiple tripping of lines & loss of generation of 1580 MW occurred at Dadri (NTPC) complex on 10th July 2011 at 13:55hrs. The rate of change of frequency (df/dt) recorded by PMU's was utilized to calculate the inertia constant of NEW grid.

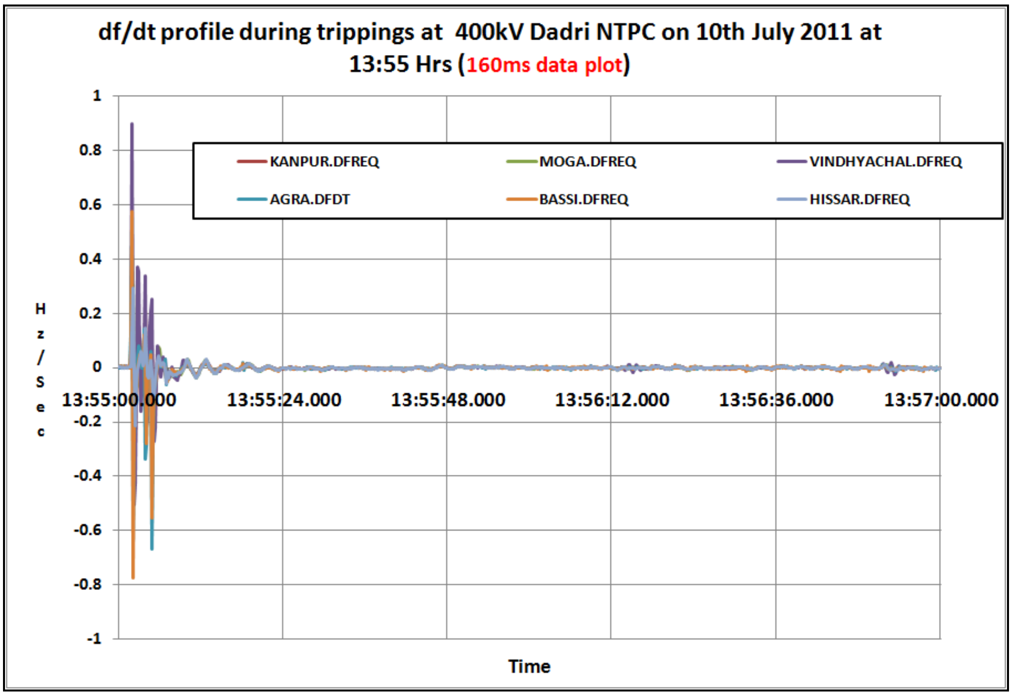


Figure 129: df/dt profile during tripping of Dadri NTPC on 19th July 2011

Inertia Constant (H) = (ΔP / P) x f_0/(2 x df/dt)

Where,

ΔP – Generation loss

P – Size of N.E.W grid

f_0 – frequency before disturbance

H = (1580 / 65300) x 50.02 / (2 x 0.08)

H= 7.5 sec

Note: for the purpose of calculation of df/dt the noise observed during initial period of disturbances were ignored. The df/dt was computed based on 160ms PMU data.

5.7.2 Case Study-39: Computation of Frequency Response Characteristics

Synchrophasor frequency data has been used for computation of frequency response characteristics. The frequency, prior and after the event, is accurately obtained with the help of PMU frequency data.

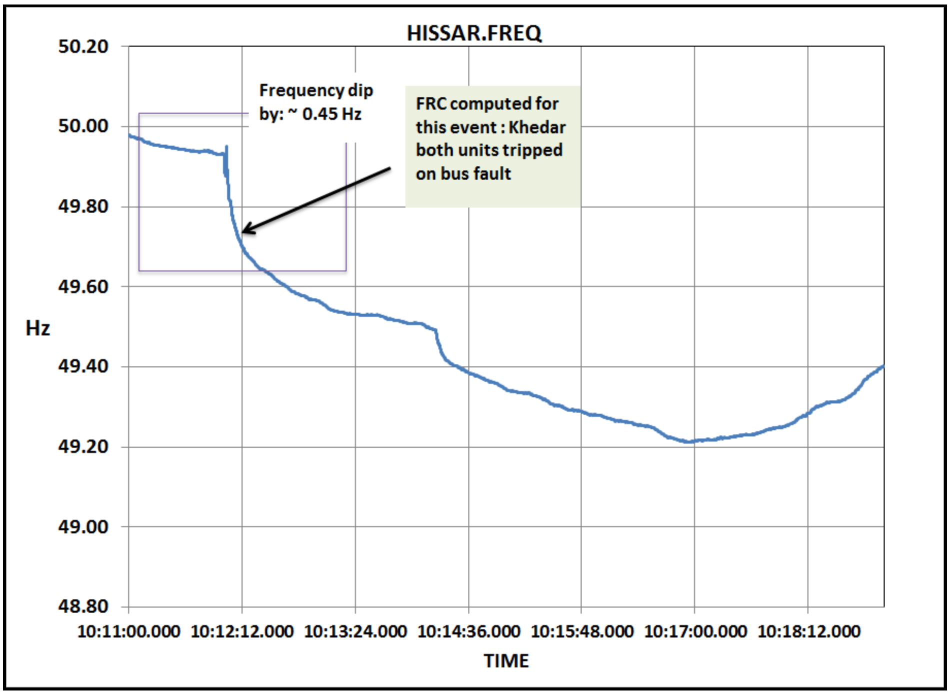


Figure 130: Hisar frequency during generation loss of 1100MW at Khedar TPS in Haryana

Figure 130 shows the frequency recorded by Hisar PMU during event of generation loss of 1100 MW at Khedar TPS in Haryana. The frequency profile indicates a generation loss. Frequency, before and after the incident, was obtained from PMU frequency plot for computation of FRC. In this particular event the FRC for the interconnected system is 2444 MW/Hz.

CHAPTER 6: SUMMARY OF APPLICATION OF SYNCHROPHASORS

6.1 Utilization of Synchrophasor in real-time

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

i). Situational awareness through real time monitoring of frequency, df/dt, angular separation and voltage.

ii). Occurrence of transmission line tripping/ revival within a flowgate by observing:

- Step change in angular separation, voltage magnitude
- 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 autoreclosure 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

Table 17: Real-time applications of PMU data

Time frame	Application	Description	Case Study No.
Real-time	Enhancing situational awareness	Visualization of - Magnitude, angle of all three voltage/current phasor - Sequence components of voltage/current phasor - Frequency & Frequency difference - Rate of change of frequency - Angular separation between pair of nodes - 1-phase auto reclosing in EHV transmission line	Case Study-1 to 5

6.2 Desirable real-time applications in India

S No.	Application for improving Situation awareness	Suggested Actions
1	Transmission Line tripping/synchronization	Alarm
2	Generator trip	Alarm / SPS for load shedding
3	Load throw off due to ICT trip/ Islanding	Alarm / SPS for generation run back
4	Island formation/synchronization	Alarm
5	Abnormal Angle separation	Alarm
6	Off nominal voltage	Alarm / Shunt reactor or capacitor switching or SVC ref change
7	Off nominal frequency	Alarm / SPS for load shedding or generator run back
8	Abnormal Line loading	Alarm /SPS for generation or load regulation
9	Abnormal phasor angle	Alarm
10	Fault Induced Delayed Voltage Recovery	Alarm
11	Detection of uncleared fault	Alarm
12	Detection of faulted phase	Alarm
13	Inter-area System Oscillation detection	Alarm
14	System Oscillation monitoring	Oscillation frequency spectrum Oscillation Magnitude Damping ratio Mode frequency histogram Locus plots showing mode decay time vs mode amplitude
15	Enhanced State Estimation in SCADA	
16	Computation and trending of dV/dt	Alarm

6.3 Suggestions for improved visualization

- Contour display of voltage, angle and frequency for easy comprehension by the operator. It would also facilitate easy detection of off nominal voltage and location of islands.
- Playback facility to view data for past few hours

6.4 Utilization of Synchrophasors in offline

- 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, synchrocheck etc.
- Extensive utlization 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 misoperation 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 centre.
- Used in computation of Frequency Response Characteristic
- Delay of 8 cycles was introduced in the df/dt relays in Northern Region to reduce misoperations.
- 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 powerflow 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

Offline application of Synchrophasors in India is tabulated below.

Table 18: Offline application of PMU data

<table>
<tr><th>Time frame</th><th>Application</th><th>Description</th><th>Case Study No.</th></tr>
<tr><td rowspan="4">Off-line</td><td>Forensic analysis of faults/grid incidents</td><td>Detection of
- Grid events within / other region
- Type of fault viz. LG, LL, LLG, LLL, LLLG
- Nature of fault (Dead short circuit or high resistance)
- Time of the fault and sequence of events
- Fault clearance time, probable location of fault
- Summary of element on fault or otherwise
- Voltage recovery post fault clearance
- Possible protection operation / misoperation
- 1-phase auto reclosing in EHV transmission line</td><td>Case Study-
6 to 19</td></tr>
<tr><td rowspan="2">Post-dispatch analysis of grid operation</td><td>Validation of
- Steady state network model
- Transfer Capability declaration
- Simulated short circuit current
- Substation disturbance record
- Substation event log
- Performance / utility of System Protection Scheme
- Measurement cycle used in df/dt relay</td><td>Case Study-
20 to 29</td></tr>
<tr><td>Computation of
- System inertia constant (H) using df/dt
- Frequency Response Characteristics (in MW/Hz)</td><td>Case Study-
38 to 39</td></tr>
<tr><td>Detection and analysis of oscillations in the power system</td><td>Detection of
- Time, duration, amplitude, frequency of oscillations
- Type of oscillation viz. inter area or local
- Nature of oscillations viz. damped or un-damped
- Modes present, their amplitude and damping factor
- Coherent group of generators</td><td>Case Study-
30 to 37</td></tr>
</table>

6.5 Desirable offline applications in India

- Daily event trigger reporting, atypical state measurement reporting
- Protection mis-operation analysis
- Power System Stability Assessment
- Power quality analyzer
- Dynamic model validation
- PSS tuning
- 3D contour plot of phase angle on all-India map showing crests, troughs and null point

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CHAPTER-7: CHALLENGES

The experience with synchrophasors has been a roller coaster ride full of exhilaration and excitement. Though the synchrophasors data is presently available only from a few locations in the Indian grid, yet it has dramatically raised visualization and the level of understanding of the power system within the control centre within few months of its commissioning. It has now become an indispensable part of the data resource available at the load dispatch centre. The two years of experience has revealed several challenges [Reference 2, 4, 5 and 6] that need to be addressed during the full fledged project. These challenges and difficulties have been discussed below:

7.1. Challenges with respect to visualization tools in real-time

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 &offline applications. However analysis is being done with limited number of available resources. With more number of syncrophasors being installed, new type of displays need to be developed which are more user friendly so that they help in better visualization of the system. These would present a better picture of the dynamic situation of the grid to the operator.

7.2. Reliability of synchrophasor data

Data loss occurs due to communication problem between PMU and control center. There is complete loss of data from one or more location or sometimes intermittent data loss for shorter period.

time stamp	DADRI MW	KANPUR MW	MOGA MW	VINDHYACHAL MW
02:10:45.000	471.2094116	185.571991	-210.5343018	-46.28055954
02:10:44.640	473.1492004	185.677063	-210.9846497	-46.26158905
02:10:44.680	472.7745972	185.5851593	-210.9572296	-46.42945099
02:10:44.720	472.8919067	185.99086	-210.9763641	-46.23189545
02:10:44.760	474.2996521	0	-211.1510925	-46.26906586
02:10:44.800	475.730896	0	-211.3757172	-46.50784302
02:10:44.840	477.2459717	0	-211.3547668	-46.30398178
02:10:44.880	474.0444336	0	-211.3584595	-46.29066086
02:10:44.920	470.9476318	0	-211.4505157	-46.25654984
02:10:44.960	470.5641479	0	-211.6245422	-46.13803482
02:10:45.000	469.4535828	0	-211.7223816	-46.40017319
02:10:45.040	471.7424316	0	-211.9296112	-46.19468307
02:10:45.080	474.8150024	0	-211.8474884	-46.45886612
02:10:45.120	474.2498169	0	-211.8370972	-46.27110672

Figure 131: Data loss of Kanpur PMU on 1st April 2011

Figure 131 shows the data loss of Kanpur PMU on 1st April 2011.

7.3. Abnormal drift and spike observed in data

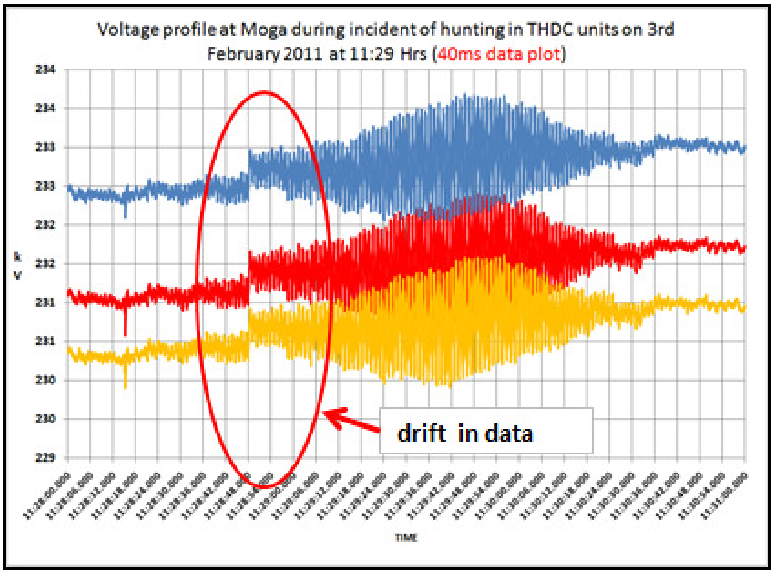

Figure 132: Drift seen in voltage plot during oscillations on 3rd February 2011

Figure 132 shows a case where a drift in data was observed.

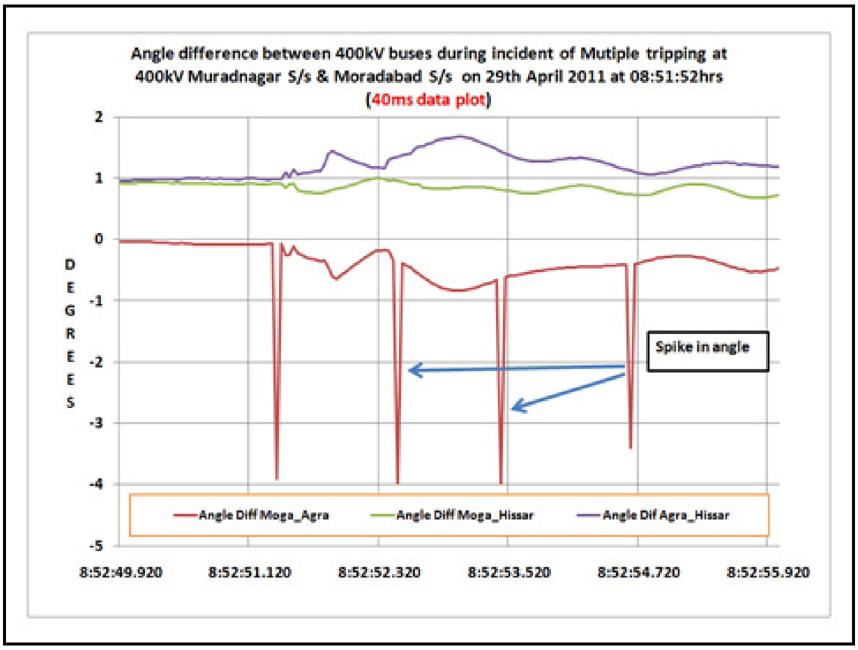

Figure 133: Spikes seen in angular difference during a grid event

Figure 133 shows the spikes observed in angle data plots.

7.4. Challenges in data retrieval from the historian

Retrieval of data from historian is possible only for duration of 3 minutes. Hence retrieval of longer duration data is quite time consuming. Tags required for data retrieval need to have a proper format. While retrieval of data the tags have to be referred from tag database and used during its retrieval. This will get cumbersome with more number of PMUs.

7.5. Challenges in analysis of synchrophasor data

Microsoft excel is being used for plotting and analyzing of synchrophasor data. There is limitation with excel that only 35000 data points can be plotted. Hence better plotting techniques needs to be explored for plotting of data for larger duration.

7.6. Challenges in storage of data

Huge volume of synchrophasor data gets accumulated in the control center over a period of time. Presently installed historian storage capacity is two terra byte. The data has to be shifted from historian to other storage devices in-order to have sufficient storage for incoming data and to prevent data loss. With more number of PMU's being planned to be installed, the capacity of historian needs to be increased and proper mechanisms need to be devised for storage of data.

7.7. Challenges in communication infrastructure

Adequacy of communication infrastructure is one of the biggest challenges in executing the synchrophasors project. In India, the availability of communication between the EHV substation and the Regional Load Despatch Centre was one of the deciding factors for identifying the location of PMUs. Fiber optic links have been used to transfer PMU's data from respective station to control center. It has been observed that there is loss of data due to breakage of fiber optic links. Redundant communication path needs to be provided to counter such problem.

7.8. Summary of Challenges

- Philosophy for placement of PMUs – strategic vis-a-vis optimal
- Validation of the accuracy/quality of synchrophasor data
- Adequacy of communication infrastructure
- Customization of real-time and offline displays
- Intelligent alarms for alerting the operator against grid events in real-time
- Real time tools to further enhance the situational awareness in control centre
- Innovative tools to tag grid events to the synchrophasor data
- Seamless integration of synchrophasor data in SCADA/EMS displays
- Data retention/storage policy for Indian conditions (Trigger based or 100%storage)
- Data retrieval from the historian
- Analytical tools for performing in depth post dispatch analysis
- Interaction between utility, academia and application developers

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CHAPTER 8: SUGGESTIONS

The synchrophasor pilot project 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. The gestation and payback period of investment in synchrophasors is very small compared to the benefits. It is desirable that adequate PMUs are installed to capture the information from each and every bay in an EHV substation. The possibility of installing PMUs at the LV side of generators and FACTS devices may be explored because it might facilitate monitoring the performance of generating units and FACTS controllers under system dynamics. In fact PMUs could become a part of the total substation package.

The population of Phasor Measurement Units is likely to grow. Considering the technological future innovations it would be important to take care of issues related to scalability and interoperability. Customized applications of synchrophasors in the operation and well as planning domain need to be quickly developed. Based on the historical information of load angles, the operational limits in respect of line loadability and angular separation of 30 degree between adjacent substations as specified in transmission planning criteria could be reviewed. All-India load angle contour could be used as an input for planning transmission line between two areas or siting a generating station. In the operational time domain, there is a need for developing customized applications to realize the potential of the technology particularly in view of its utility for large scale integration of renewable energy sources and reliable operation of the large synchronous pan India/SAARC grid.

Few suggestions regarding future scope of work are as under:

- Ramp up all activities related to synchrophasor initiative
  - Integrate regional pilot projects at the national level
  - Identify possible solutions to suitably address the challenges faced
  - Formulate policy for retention and storage of synchrophasor data
  - Ensure compliance to relevant standards
  - Deploy Common Information Model
  - Establish Quality of Service (QoS) norms for in Indian conditions
  - Tailor made displays and customized applications for real-time and offline application for facilitating comprehension of high speed, voluminous data
  - Determine thresholds and operating limits from historical data
  - Develop intelligent alarms to alert the operators in real-time

- Explore application of synchrophasor data in
    - Adaptive protection and control
    - Dynamic model validation
    - Tuning of Power System Stabilisers (PSS)
    - Real time dynamic stability analysis
    - Enhanced state estimation
    - Transmission planning and generation siting
    - Calibration of instrument transformers
- Capacity building for improving comprehension/interpretation of synchrophasors
    - Create a library of grid incidents and events characterized in phasor data
    - Establish a policy / mechanism for sharing synchrophasor data
    - Institutional mechanism for collaboration between industry and academia

REFERENCES

1. **Agrawal V K, Raghuram P R and Kumar S P** Load Angle Measurement using SCADA [Journal]. http://www.nrldc.org/docs/documents/Papers/Load Angle Measurement using SCADA.pdf

2. **Soonee S K, Narasimhan S.R., Porwal R.K., Kumar S., Kumar Rajesh and Pandey Vivek,** Application of phase angle measurement for real time security monitoring of Indian Electric Power System- An Experience [Journal] // CIGRE. – 2008, http://www.nrldc.org/docs/documents/Papers/CIGRE2008_C2-107.pdf

3. **Mishra Nripen and Joshi Mohit** A Near Miss: 200911281326 [Journal] // Transica. - 2010. http://www.nrldc.org/docs/documents/Papers/A Near Miss: 200911281326.pdf

4. **Agrawal V. K. and Agarwal P. K.** Challenges faced and Lessons Learnt in Implementation of First Synchrophasor Project in India http://www.nrldc.org/docs/documents/Papers/Challenges_Final_As%20Submitted.pdf

5. **Agrawal V. K., Agrawal P.K. , Porwal R. K. , Kumar Rajesh., Pandey Vivek, Muthukumar T., and Jain Suruchi** Operational Experience of the First Synchrophasor Pilot Project in Northern India [Journal]. - New Delhi : CBIP, 2010. http://www.nrldc.org/docs/documents/Papers/OperationalExperienceofSynchrophasorPilotProject_CBIP_Conference_5_PA.pdf

6. **Agrawal V. K., Agarwal P. K. and Kumar Rajesh** Experience of commissioning of PMUs Pilot Project in the Northern Region of India [Journal]. - [s.l.] : POSOCO. http://www.nrldc.org/docs/documents/Papers/Experience_of_commissioning_of_PMUs_Pilot_Project_in_The_Northern_Region_of_India_NPSC_2010.pdf

BIBLIOGRAPHY

1. **Adamiak Mark, Premerlani William and Kasztenny Dr. Bogdan** Synchrophasors: Definition, Measurement, and Application [Journal].

2. **California ISO** Five Year Synchrophasor Plan [Journal]. - 2011.

3. **Electric Power Group** Using Synchro-Phasor Technology to Detect and Manage High Frequency Oscillations Caused by HVDC Pacific Intertie [Journal]. - [s.l.] : North American Synchrophasor Initiative.

4. **Farmer Richard G.** Power System Dynamics and Stability [Report]. - [s.l.] : Arizona State University, 2001.

5. **Flerchinger Bill** Using Synchrophasor Measurements for Wide-Area Situational Awareness to Improve System Reliability [Journal]. - [s.l.] : North American SynchroPhasor Initiative.

6. **IEEE Power Engineering Society** IEEE Standard for Synchrophasors [Report]. - New York : [s.n.], 2006.

7. **Johnson Anthony [et al.]** Static Var Compensation Controlled via Synchrophasors [Journal]. - 2007.

8. **K Seethalekshmi, Singh S.N. and Srivastava S.C.** Wide-Area Protection and Control: Present Status and Key Challenges [Journal]. - [s.l.] : National Power Systems Conference (NPSC), 2008.

9. **Lawrence Berkeley National Laboratory** Real Time Grid Reliability Management [Journal]. - [s.l.] : California Energy Commission, 2008.

10. **Liu Guoping, Quintero Jaime and Venkatasubramanian Vaithianathan "Mani"** Oscillation Monitoring System Based on Wide Area Synchrophasors in Power Systems [Journal]. - [s.l.] : School of EECS, Washington State University, 2007.

11. **Martinez C. [et al.]** Real Time Wide-Area Monitoring, Control and Protection Applications [Journal]. - [s.l.] : EIPP – Real Time Task Team, 2005.

12. **Martinez Carlos A., Eto Joseph H. and Dyer Jim** Real Time Performance Management Tools for Wide Area Operations in Competitive Electricity Markets [Report].

13. **Martinez Carlos A., Mo Jianzhong and Whitehurst Hugh** Multi View, Geo-Graphic Visualization for Wide Area Real Time Performance Monitoring [Journal].

14. **Mills-Price Michael and Flerchinger Bill** Smart Anti-Islanding Using Synchrophasor Measurements [Journal]. - [s.l.] : North American Synchrophasor Initiative.

15. **NASPI** Guidelines for Siting Phasor Measurement Units [Journal]. - [s.l.] : NASPI, 2011.

16. **NERC** Real-Time Application of Synchrophasors for Improving Reliability [Report]. - 2010.

17. **Parashar Manu, Dyer Jim and Bilke Terry** EIPP Real-Time Dynamics Monitoring System [Journal].

18. **Prasertwong K., Mithulananthan N. and Thakur D.** Understanding low frequency oscillation in power systems [Journal].

19. **Singh Bindeshwar [et al.]** Applications of phasor measurement units (PMUs) in electric power system networks incorporated with FACTS controllers [Journal]. - [s.l.] : International Journal of Engineering, Science and Technology, 2011.

20. **Tate Joseph Euzebe and Overbye Thomas J.** Line Outage Detection Using Phasor Angle [Journal]. - [s.l.] : IEEE Transactions on Power Systems, 2007.

21. **VLPGO Working Group 1** Application of PMU technology with emphasis on early detection and prevention of cascading events, 2007

Website Links

1. https://www.naspi.org/
2. Washington State University GridStat, http://www.gridstat.net/trac/
3. Power Systems Engineering Research Center, http://www.pserc.wisc.edu/documents/general_information/presentations/smartr_grid_executive_forum/
4. Electricity Infrastructure Operations Center (EIOC), http://eioc.pnnl.gov/research/synchrophasor.stm
5. Western Electricity Coordinating Council (WECC), http://www.wecc.biz/library/default.aspx
6. Bonneville Power Administration Transmission, Serviceshttp://www.transmission.bpa.gov/orgs/opi/system_news/index.shtm
7. http://openpdc.codeplex.com/
8. http://www.selinc.com/synchrophasors/
9. GE Multilin, http://www.gedigitalenergy.com/multilin/index.htm
10. Macrodyne Inc. , http://www.macrodyneusa.com/
11. LinkedIn Group: Synchrophasors and WAMS
12. LinkedIn Group: Smart Grid-Energy and Water

Presentations

1. *Western Interconnection Phasor Monitoring Network and Visualization*. **Dave Hawkins**: WECC Performance Work Group; February 3, 2005
2. *Islanding Protection System based on Synchronized Phasor Measurements and its Operational Experiences*. **Teruo Ohna et el**.: Tokyo Electric Power Company; June 23, 2008
3. *Primer Discussion on Cyber Security: What do the CIP Standards Mean for SynchroPhasors in the future?*. **Scott Mix**: NERC; February 5, 2009
4. *Lessons Learned Integrating Synchrophasors into EMS Applications*. **Dr. Naim Logic Bill Robertson**: Salt River Project-Synchrophasor Team; February 4, 2009
5. *Eastern Interconnection Wide Area SynchroPhasor Angles Baselining Study*. **Mahendra Patel**: PJM
6. *Wide Area Monitoring and Control at Hydro Quebec*. **Inncocent Kamwa**: Hydro Quebec Technology Group; June 2006
7. *SynchroPhasor use at OG&E*. **Austin D. White P.E. and Steven E. Chisholm**: Oklahoma Gas & Electric
8. *North American Synchrophasor Initiative Phasor Applications Update NERC OC Briefing*. **Bob Cummings, Bharat Bhargava, Tony Johnson, Manu Parashar, Alison Silverstein**: NASPI; March 17, 2009
9. *Performance Monitoring and Model Validation of Power Plants Leveraging Synchrophasors*. **Dmitry Kosterev**: Bonneville Power Administration; December 7, 2010
10. *Oscillations in Power Systems*. **Dmitry Kosterev**: Bonneville Power Administration

ANNEX-I Terms of Reference for the Task Force

Power System Operation Corporation Limited
National Load Despatch Centre
New Delhi

10th May 2012

Sub: Experience in application of synchrophasor technology and Wide Area Measurement Systems (WAMS) to power system operation.

The interconnection of regional grids in India has led to the formation of a Very Large Power Grid leading to complexities in system operation. Improved visualization of the power system and Situational Awareness (SA) is important in ensuring reliable operation of such a large system. Energy Management Systems (EMS) installed at different RLDCs and NLDC has provided one tool to the system operators. Synchrophasor technology has been introduced in 2010-11 and by the end of 2012 we would have a fairly extensive foot-print of Phasor Measurement Units (PMUs) over the all India grid.

A need has been felt for documenting the experience of Indian system operators so far in utilizing synchrophasor technology. For this purpose, a Task Force is constituted with the following members:

1. Shri Vivek Pandey, Manager, NRLDC................convener
2. Shri S. K. Saha, Manager, WRLDC
3. Shri T. Muthu Kumar, Deputy Manager, NRLDC
4. Shri Abdullah Siddiqui, Engineer, SRLDC
5. Shri Nripen Mishra, Engineer, NLDC

The Task Force would submit its report within fifteen (15) days of the date of issue of this order. The report would cover:

- Features available in the present projects installed in different regions
- Applications available and used in real time as well as offline analysis.
- Case studies for each application
- Further analytics that would be required.
- Road map

This issues with the approval of CEO POSOCO.

Narasimhan
(S. R. Narasimhan) 10/5/12
Deputy General Manager, NLDC

Copy to:

1) **Individual executives nominated above**
2) **General Manager NRLDC/WRLDC/SRLDC**
3) **General Manager, NLDC**
4) **CEO POSOCO**

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