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Application of phase angle measurement for real time security monitoring of Indian Electric Power System- An Experience

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SUMMARY

The Indian electric power system has expanded manifold and is on a high growth phase. The five synchronous separate geopolitical grids, which developed independently, have been integrated gradually. In August 2006, the 25 GW Northern grid was synchronised to the "North East-East-West" grid to form the North East--East-West grid now designated as the "N-E-W grid" having installed capacity of around 90 GW (peak 60 GW). The 25 GW South India grid (installed capacity of over 36 GW), is presently connected asynchronously to the N-E-W-grid through 4 GW of HVDC links Fig-1.

The power system in India is operated on a regional basis through its regional control centres that are equipped with conventional SCADA/EMS system. With the above developments, there has been a paradigm shift in power system operation in India. Knowledge of the "neighbouring system" became as important as the knowledge of the host region for real-time security assessment and monitoring of the integrated system. However as the National control centre is yet to be commissioned, the real-time data exchange between the regional control centres is extremely limited. This limitation was overcome through a novel use of phase angle measurement at strategic locations.

In the Indian grids, phase shifters have not been deployed. However, hybrid system of AC and DC interregional ties provides an opportunity to modulate power flow on the AC links. The two HVDC back-to-back stations within the NEW grid enables us to measure phase angle between the two AC buses on either side of the HVDC blocks. The AC buses on either side of the HVDC back-to-back blocks are geographically at the same substation but were separated thousands of kilometres electrically after formation of N-E-W grid. Measurements of phase angle difference between these two adjacent (buses) points provide a signature of the system state. The phase angle measured in the manner described above is telemetered to the regional control centres. World over Synchrophasor technology is being considered for such wide area monitoring. This has been exhaustively documented in international literature [1-8]. Monitoring and assessment of system state using phase angle measurement with the help of SCADA system would not give system behaviour for low frequency oscillations (inter-area oscillations) but it is still a good visualization tool as it captures several quantities to indicate the 'pulse' of the system.

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The phase angle differences across different nodes are a measure of static stress across the grid and its proximity to instability and therefore can be monitored with respect to predetermined stability threshold limits. These threshold limits are being put based on the past experiences of system separation and off line simulations. The novel approach has improved system visualization and situational awareness of the system operators in the "NEW-grid." The paper describes the deployment of direct phase angle measurement for monitoring the security of a large grid and would be a precursor to the deployment of Synchrophasor technology in the Indian electric power systems.

KEYWORDS

Synchrophasor technology, Phase angle measurement, Phasor Measurement Unit, System Operation, Visualization, Situational awareness, Security Monitoring

1. BACKGROUND

The Indian Grid consisted of small isolated systems in 1947. Gradually the systems around urban and industrial areas grew into full-fledged State (provincial) power systems. In 1964, the concept of regional power system was formulated leading to five regional grids viz. Eastern (ER), Northeastern (NER), Northern (NR), Western (WR) and Southern (SR). Presently four out of five regional grids (Northeast, East, West and North) have been interconnected into one large synchronous power system of nearly 90 GW (60 GW peak). The Southern Regional Power System continues to be asynchronously connected to this "N-E-W" grid with the help of HVDC and radial AC tie lines. It would be interesting to note that the Southern Region operated in synchronous mode with Western Region (total combined size of 25 GW) during September-October 1991 on a trial basis. However in the absence of adequate tools for real-time monitoring and control, the operation had to be suspended in spite of 150 hours (08^{th} to 14^{th} Oct 1991) of continuous successful operation [9].

While the physical grids were being integrated the power sector in India was also undergoing rapid changes. A decentralized market mechanism with floating frequency and freedom to deviate from interchange schedule was adopted in the country. The Electricity Act 2003 introduced competition in the sector by allowing open access in transmission system.

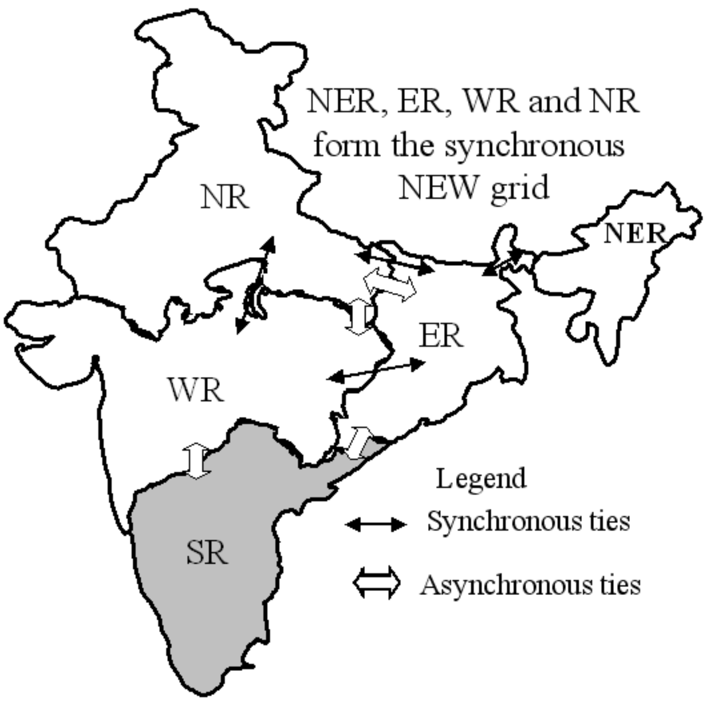


Figure 1: Two synchronous power systems in India

2. MOTIVATION FOR PHASE ANGLE MEASUREMENT

Formation of synchronous "N-E-W" grid brought a paradigm shift in grid operation in India. Long haulage of power from pithead to load centre, huge diversity in terms of weather, time, load pattern, and machine availability got reflected as large interregional flows. Free flow of power across regional boundaries resulted in stabilization of the system frequency but caused large variations in bus voltages and line loadings. The conventional SCADA/EMS with only regional visibility was suddenly found to be inadequate to meet the requirements of system operation as a part of a large interconnection.

Further the performance of the newly formed synchronous system was expected to set the course for the future of power system and electricity market in India in terms of technology deployment (generation as well as transmission) and interconnections, both national and international. There was pressure to make it a success and avoid the experience as in case of trial synchronization of Southern and Western regional system in 1991. With the liberalization of the Indian power sector and growing competition the pressure to load the power system to its limits had been growing. This pressure achieved its crescendo after the formation of N-E-W grid because the integration of the physical network had also merged four large electricity markets and the market players wanted to exploit the newfound access to such a large market.

The physical systems and the market mechanisms were in a state of transition. Even the system operators had to undergo a process of unlearning and relearning the nuances of system operation in the changed scenario. The National Load Despatch Centre (NLDC) with the provision for sharing of data among Regional Load Despatch Centres (RLDCs) is yet to be commissioned. Under these circumstances power system visualization with the help of "Phase angle measurement" was a breakthrough.

3. METHODS FOR PHASE ANGLE MEASUREMENT

It is understood that SCADA technology does not have phase angle as an analog measurement. State estimator uses the SCADA inputs (analog and digital measurands) to estimate the system state viz. node voltage and angle. State estimator (SE) results are used for monitoring the angular separation between buses in the power system. However SE has its limitations. It runs periodically as well on change of circuit breaker status and any monitoring based on SE output is very sluggish. Moreover the SE results are often inaccurate and unreliable in a rapidly growing power system due to limited network observability and bad data. Deployment of synchrophasor technology for improving the SE output and for real time security assessment is being studied worldwide. Exploratory studies are also being carried out in India.

Phase angle measurement is commonly used in auto synchronization of hydro station and check synchronization relays used at substations either for three phase auto-reclosures or closing of lines. All these applications are at the local level. At control centre level this analog value is normally not considered as measurable in SCADA system and hence does not form a part of the database. In order to move ahead and to take the advantages of the wealth of information stored in phase angle measurements two different approaches as discussed below were adopted in India:

1. Real time calculation of phase angle based on actual line flow, node voltage and line reactance
2. Measurement of phase angle using a voltage / phase angle transducer

Both the approaches were highly successful and they proved to be excellent tools for real time network security monitoring and assessment in conjunction with conventional SCADA/EMS system.

4. REAL-TIME PHASE ANGLE CALCULATION - WITHIN REGION

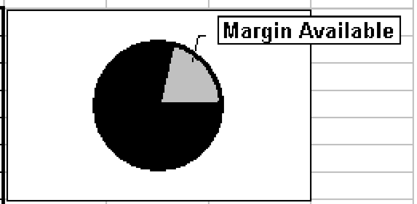
Northern Region has a large thermal generation complex of about 6000 MW in southeastern part while the load centre is located in the Western part of the region. These two pockets are separated by more than 800 kilometres and connected via a number of parallel 400 kV AC lines and an HVDC bipole between Rihand (in the south eastern pocket) and Delhi (in the western pocket). In the past there had been several incidents of separation of these two pockets under skewed load despatch and or due power swing. Therefore it was essential that the angular separation between these two pockets be monitored in real-time. Since it was not possible to telemeter the phase angle separation between two distant nodes in the grid with conventional SCADA system the angular separation between Rihand and Delhi was calculated at the control centre with the help of real time power flow, bus voltages and network reactance using standard equation $\boldsymbol{\delta = \sin^{-1} (P*X/V_1*V_2)}$. Calculations were validated along multiple parallel paths and prominently displayed before the system operator in real time.

The system operators made efforts to maintain this separation within the limits derived from past experience of system separations. Similar initiatives were taken in Southern Regional Load Despatch Centre. Actions taken based on these phase angle displays probably prevented occurrence of several grid disturbances [10].

This method of phase angle calculation has limitations due to uncertainty in data availability from RTU stations and updation time of 10-15 seconds, which is considerably large from the point of view of power system dynamics. Phase angle calculation is also affected by availability of lines along the path chosen for estimating the angular separation.

Phase Angle Calculation Between Rihand & Delhi

Along Path-1	Volt (End-1)	Volt (End-2)	Line Flow	Angle
Rihand-Singrauli	414	419	238	1.1
Singrauli-Allahabad	419	429	409	9.0
Allahabad-Kanpur	429	415	421	9.8
Kanpur-Agra	415	416	405	12.6
Agra-Ballabgarh	416	406	186	3.8
Ballabgarh-Maharani Bagh	406	415	-160	-0.4
Maharani Bagh-Delhi	415	409	-162.12054	-0.4
	delta (Rihand-Delhi)			**35.6**
Along Path-2				
Rihand-Singrauli	414	419	238	1.1
Singrauli-Lucknow	419	417	424	19.2
Lucknow-Unnao	417	400	361	1.6
Unnao-Agra	400	404	385	12.6
Agra-Muradnagar	404	405	88	1.5
Muradnagar-Delhi	405	409	26	0.1
	delta (Rihand-Delhi)			**36.2**



Rihand Delhi Angle Range
0-45 degree.

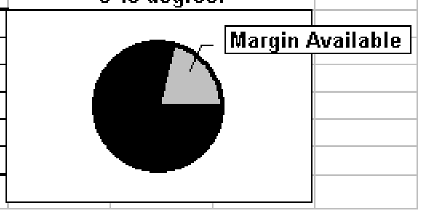


Figure 2 Phase Angle Calculation at Control Center using SCADA measurands

5. PHASE ANGLE MEASUREMENT USING VOLTAGE / ANGLE TRANSDUCER

After the formation of N-E-W grid there was a need to monitor angular separation between coherent group of generators located in different regions within a synchronous system. However there was a limitation with the SCADA system with only regional visibility. Since the Regional control centres receives measurands in the network located within the region, the calculation of angular separation between two buses located in different regions was not possible through SCADA system. The problem would have been solved if the data from all regions could be made available at a centralized location. The proposed National Control Centre with those features is under development. This difficulty was however circumvented by measurement of angular separation with the help of voltage or phase angle transducers [11] installed at strategic location and then having it telemetered through conventional SCADA system.

Northern Region has multiple synchronous as well as asynchronous links with neighbouring regions. As shown in the Figure 1 there is a HVDC back-to-back station at Vindhyachal located in the southwest corner of Northern region connecting it with Western Region. Two huge coherent group of generators (6000 MW) exists on either side of the back-to-back station. AC link between these complexes has not been done from fault level considerations. Electrically the two 400 kV buses are far away (geographical distance in the range of 2000 to 2500 km depending on AC line route chosen).

Since the back-to-back station at Vindhyachal was located at a unique position within the synchronous system, voltages at the North bus of Vindhyachal and the West bus of Vindhyachal had the same reference and hence could be compared with the help of a simple voltage transducer. This comparison provided an excellent indication of the angular separation between the two buses located in different regions. This would be evident from the equation $\Delta V^2 = V_1^2 + V_2^2 - 2V_1V_2\cos\delta$. Initially, the magnitude of difference in R phase voltage of North bus and R-Phase of West bus was plotted in the Regional Control Centre. It was observed ΔV at Vindhyachal was highly sensitive to variations in network topology, load distribution, generation dispatch and interregional flows. System operator could immediately sense insecure operating conditions even in the absence of online data from the neighbouring regions. Subsequently phase angle transducer [4] was installed at Vindhyachal back-to-back station to provide accurate phase angle between adjacent buses located close to coherent group of generators in different regions. The observations during the initial days after installation of this transducer was as under:

1. The measured δ was highly sensitive to changes in load profile, generation dispatch and network topology.
2. Variation in δ had a direct correlation with power exchanges at regional boundaries.
3. During contingencies the magnitude of variation increased sharply.
4. Any system separation or disturbances within or across the regions were quickly reflected in the angular separation trend due to loss of reference.

The above method of phase angle measurement has been implemented / proposed in the Indian system at selected locations based on the criteria indicated in Table-1.

Table 1 : Indentification of location for Phase angle measurement

S No.	Location	Criteria
1.	Between two buses across HVDC back-to-back	HVDC Back-to-back within synchronous system (implemented)
2.	Between bus and line voltage	Important tie line within synchronous system (implemented)
		Probable locations for synchronization of subsystems within synchronous system. (proposed)
3.	Between two buses at the same AC substation	Buses normally operating in split mode within system (proposed)

6. PHASE ANGLE DIFFERENCE AS SIGNATURE OF THE SYSTEM

During the initial days the inferences to be drawn from the angular separation plots was not very clear. Few operators were apprehensive about relying on these plots. However it was realized quickly that the angular separation plots were the signature of the synchronous system as evident during system separations that occurred on 15th Sep-06, 22nd Oct-06, 25th Feb-07 and 28th Feb-07.

On 22nd October 2006, Northern Region, Northeastern Region, Bhutan system and parts of Eastern Region separated from rest of the N-E-W grid due to the tripping of 400 kV Jamshedpur-Rourkela D/C. Both the systems survived and they were quickly synchronized back. It was observed that the export from Northern Region to rest of the grid continued to increase along with the angular separation between Vindhyachal North bus and West bus till the tripping point was reached. Fig-4. The range of the phase angle transducer was selected as + 60^{o} based on off-line simulations under various scenarios. It would be seen from Fig-4 that the phase angle transducer reading got clamped at +60o at 1004 hrs.

Based on the R-phase voltage difference the phase angle was estimated as 72^{o} just before system separation at 1029 hrs. This was also borne out by off-line simulations.

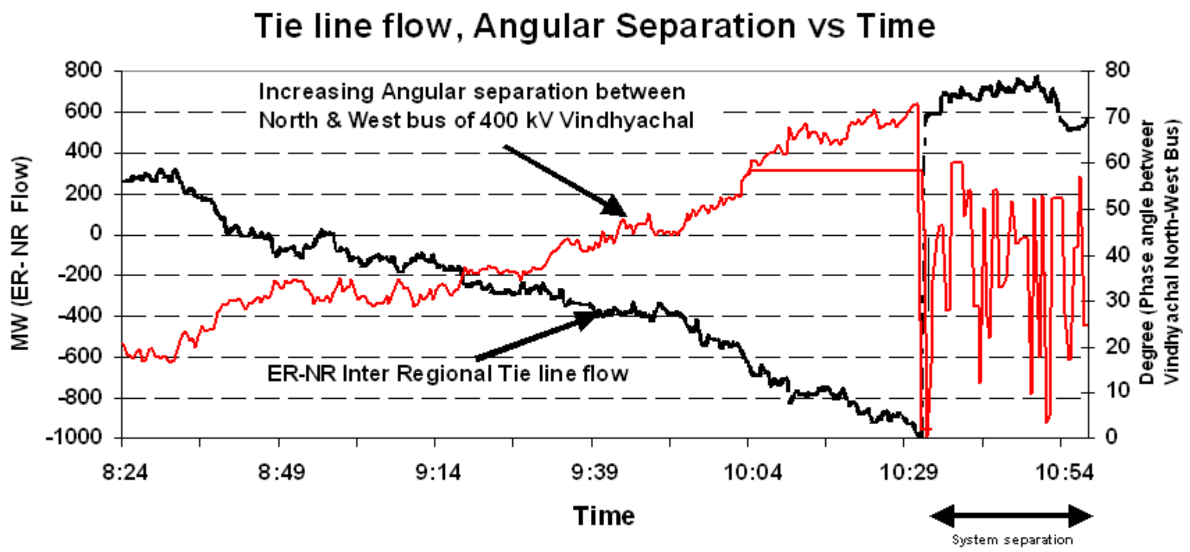


Figure 3 Phase angle trend before and after system separation in NEW grid on 22nd Oct 2006

Although there was no problem with the network in Northern Region, these disturbances emphasized that the angular separation between Vindhyachal_West bus and North bus must be maintained within $\pm 40^{o}$ for stability of the integrated system. Phase angle data available at Northern Regional Load Despatch Centre is also shared with other control centres within and across regions through Internet and through Inter Control Centre Protocol exchange.

7. ENERGIZATION OF THE SYNCHRONOUS TIE LINE BETWEEN NORTH AND WEST

Northern Region and Western Region have been operating in synchronous mode since 26th August 2006 when Northern Region was synchronized with the combined Northeast-Eastern-Western Region through 400 kV Gorakhpur-Muzaffarpur D/C. The direction of powerflow across interregional seams was after synchronous interconnection with Eastern Region is usually from Eastern Region towards Northern and Western Regions. Power exchange between Northern and Western Region before August 2006 was only through 2 x 250 MW HVDC back-to-back at Vindhyachal, 220 kV Auraiya-Malanpur, 220 kV Auraiya-Mehgaon, 220 kV Ujjain-Kota and 220 kV Morak-Ujjain in asynchronous/radial mode.

As a part of the transmission capacity addition 765 kV circuit between Agra (NR) and Gwalior (WR) has been constructed. At the time of energization it was evident that the first direct synchronous lties between NR and WR (which were otherwise in synchronous mode via ER) would introduce interregional loop flows by closing the third arm of the delta connection between NR, ER and WR grids. Off line simulations were carried out. Impact of the power order on the angular separation at HVDC back-to-back between NR and WR as well as between 400 kV Agra and 400 kV Gwalior was studied. It was observed that angular difference between 400 kV Agra and 400 kV Gwalior is 0.9 times of the angle between Vindhyachal North and West bus when the link between Agra and Gwalior is open. It was also seen that this angular separation would translate into around 9 MW flow per degree antecedent angular difference on the link when it was synchronized. Simulations also indicated that the angular separation between Vindhyachal North and West bus reduces to around 50 % of the value before closing the Agra-Gwalior link. This implied that the fluctuations in angular separation at Vindhyachal would reduce thus the safe operating range would also be narrowed down.

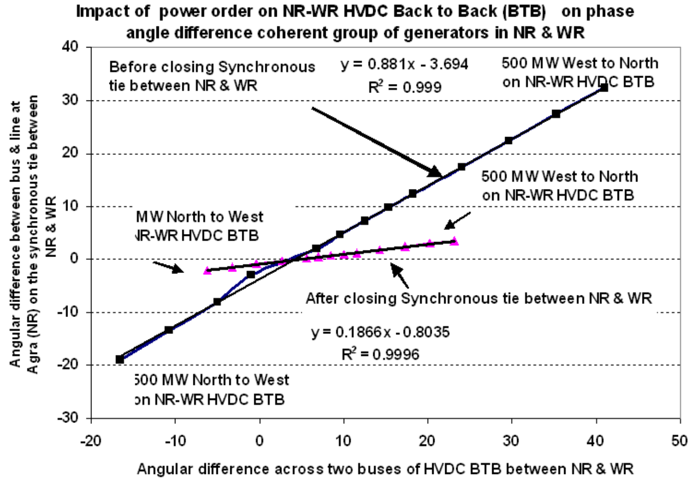


Figure 4 Simulation Results for energisation of synchronous link between NR & WR

8. OPERATION OF WEAK INTER-REGIONAL TIE LINES IN SYNCHRONOUS MODE

There are several inter regional AC tie lines in Indian grid that are either lying dormant or being utilized in radial mode. This is primarily because it is not advisable to operate two large grids in synchronism with weak tie lines. 220 kV Auraiya-Malanpur and 220 kV Auraiya-Mehgaon links between Northern and Western Region have been successfully switched from radial operation to synchronous operation after commissioning of 765 kV (charged at 400 kV) Agra-Gwalior. Similar efforts are going on in case of 220 kV Kota-Ujjain and 220 kV Morak-Ujjain. Likewise, feasibility of parallel operation of 220 kV Sasaram-Varanasi link between ER and NR was examined since the proposed synchronization of NR with ER.

Considering the successful utilization of phase angle transducer in earlier case one such transducer was installed at 220 kV Sahupuri that read the angular difference across the bus coupler that had been kept open to facilitate radial operation. Offline simulations were also carried out to study the technical feasibility of parallel operation of 220 kV Sasaram-Varanasi with other tie lines during different load flow scenarios. The results were highly encouraging and the link was test synchronized on 20th August 2007 but reverted to radial operation pending modification in the distance protection scheme at Varanasi end.

9. ANGLE CONSTRAINED TOTAL TRANSFER CAPABILITY

The phase angle differences across different nodes are a measure of static stress across the grid and its proximity to instability. Therefore this value can be monitored with respect to predetermined stability threshold limits. These limits are kept in mind while assessing the Total Transfer Capability (TTC) of the power system for a future scenario based on the anticipated network topology, load-generation balance, operating criteria and network response. While applying the N-1 criteria on inter-regional tie lines during contingency studies it is ensured that the standing phase angle should not be higher than values where re-synchronization becomes difficult. Operation circulars indicating the threshold values for angular separation for important flow gates have been issued for the benefit of real-time operators.

10. SCOPE FOR FUTURE APPLICATIONS

Indian electric power system and system operators have had the first hand experience of the benefits of phase angle measurement. Scope for deployment exists in all probable locations identified for sub-system restoration after loss of synchronism. Within a synchronous system often there are adjacent nodes that have to be synchronized after long duration of dormancy. In India there are several interstate tie lines that have not been used due to legacy issues. Archival of the standing phase angle between such buses could indicate the most opportune time for synchronization. It is like a virtual synchronization trolley in the control centre. Relevance of Phase angle measurements would increase after future interconnections both national and international. The phase angle threshold limits could also be used as a signal for kicking in congestion management steps. Using the phase angle transducer output at HVDC back-to-back station could be used to trigger modulation of power flow over the HVDC link. Monitoring of phase angle difference between coherent group of generators at the upcoming National control centre would provide valuable insight into the system. This would be of immense help in planning and implementing and use of synchrophasor technology in the future.

11. CONCLUSION

The paper has shared the Indian experience of phase angle measurement with the help of conventional SCADA system as well a through voltage and phase angle transducer. It has been demonstrated that phase angle measurement implemented in Indian grid is very useful and cost effective at less than US$ 100/measurement. It is portable and it works with hardware already installed for SCADA systems. The solution is highly recommended for rapidly growing power systems. This phase angle measurement also helps in validating the network model used for state estimation and offline studies. The phase angle gives very precise information about system state. The paper also opines that the deployment of phase angle transducers for could be effectively used for security monitoring and assessment in a large grid as a wide-area monitoring tool and could be a precursor to the deployment of synchrophasor technology. This technology is also being planned in Indian power system for wide-area security monitoring.

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