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Challenges faced and solutions for Network modelling and implementation of State Estimator at Northern Regional Load Despatch Centre, India

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Abstract

The rapidly changing world of Power System Operations requires advanced, flexible & adaptive software solutions to ensure seamless Transmission Network operations. Thus, suitable tools are used to monitor, assess the security, analyze and optimize the System operations. The tool present at Control Centres to realise above tasks is termed as Energy Management Systems (EMS). State Estimator (SE) forms the front end of EMS system. It is responsible for providing a complete, accurate, consistent and reliable real-time scenario for analysis, control, and optimization of the system. Realization of SE at a control centre monitoring a wide and complicated power system is challenging several times. Major challenges for SE to function consistently are modelling of equipment, equipment operating modes, trade-off between telemetry and network expansion to include parallel network at lower transmission voltages, location of measurement in actual system vrs its location in the EMS model etc. This paper gives details of those challenges faced and their solutions during in course of implementation of EMS in Northern Regional Control Centre of India.

Keywords: *Energy Management System; State Estimator; Model Update; Model Processor; Performance Index*

1. Introduction

Modern Power System Control centres operating as Load Despatch Centre are essentially equipped with State Estimator. The purpose of SE is to provide a complete complex voltage solution that is contiguous to real-time network conditions at all Network buses [1]. SE takes as input the real-time measurements like line power flows, bus voltages, Transformer taps, CB/Isolator status, load schedules, generation and user entries and provides an optimal state of system based on above measurements and assumed system model [2]. SE determines the estimate for the voltage magnitude and angles which best matches the unfiltered measurements information based on measurement redundancy. Once the system state and the system model is known, all the active and reactive power flows in the system can be computed, even if these flows were not measured originally. SE forms a reliable database of the system, on which security assessment functions can be reliably deployed in order to analyze possible contingencies and the required corrective actions.

The paper is organized as follows.

Part I introduces the need of EMS system. Part II comprises basic system information of EMS system at Northern Regional Load Despatch Centre. It includes SE model update and processing, model and input data validation, modification of topology and network truncation, modeling of equipments and Network Parameter Adaptation. Part III comprises of Major issues being faced while implementing EMS and the solutions. Part IV comprises quantitative analysis of improvements shown by SE and future scope in context of new implementations that would further improve the output. The section talks about External Network Equivalency and Hybrid State Estimator and their anticipated affect on quality of SE output. Part V concludes the paper

2. System Information and Modelling

Northern Regional Load Despatch Centre (NRLDC) is the apex body to ensure integrated operation of the power system in the Northern Region of Indian Power Grid. It is responsible for monitoring of system parameters and security, load/generation dispatch etc. for the whole region. The northern grid consists of transmission elements owned by individual transmission utilities that belong to central/state sector or private sector. State Load Dispatch Centres (SLDCs) are responsible for monitoring and dispatch of transmission elements at voltages lower than 220 kV that belong to respective state owned utilities (transmission and generation). It also co-coordinates with NRLDC to control and operationalize state owned transmission elements at voltages of 220 kV and above.

2.1 TNA Model Update/Processing:

TNA uses the Physical model made by Power System Resources organised around the Substation. Typical elements comprising Physical model are Busbar Sections, Generating units, Loads, Shunt/Series compensators, AC/

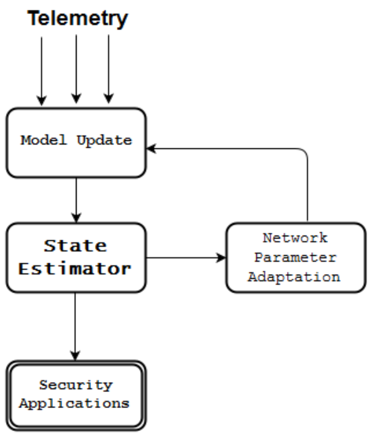

Fig. 1: Steps involved in Model Processing

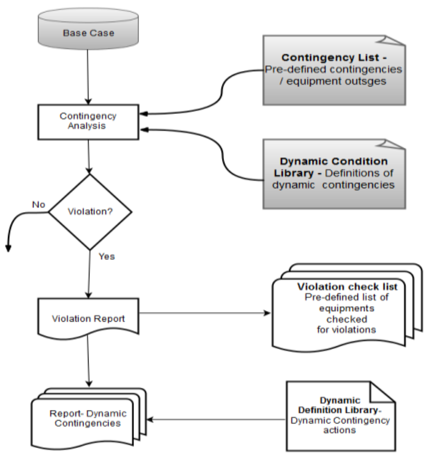

Fig. 2: Steps involved in RTCA

DC transmission lines, Power Transformers, Switching devices etc. Topology processor (TP) or Model Processor (MP) forms the integral part of State Estimation process. SE gathers status data for all the Circuit Breakers (CBs) and switches, and configures the one-line diagram of the system. Figure 1 shows a typical flowchart for SE process flow. The output to SE acts as an input to other TNA applications like Real Time Contingency Analysis (RTCA) often termed as Security Analysis (SA), Security Despatch (SD) & Voltage Scheduler (VS). Steps incurred in RTCA are shown in figure 2. SE uses adaptive parameters that consistently aid in its solution process. The technique used for the purpose is "Parameter estimation" as explained in most of the literature [2, 3].

TNA applications use production database. However, Control parameters for TNA applications like measurement weights, scaling of load/generation, solution technique used, blocking and inverting signs of some measurements can be performed with application interface or by SQL scripts that are integrated with TNA applications.

2.2 Initialisation of TNA database / Input data validation:

TNA database is tailored from SCADA database only. An element that is already a part of SCADA database can be added to TNA network by enabling relevant tag. The newly expanded model is then validated during SE execution. SE sometimes fails to converge due to poor availability of requisite telemetry and database modelling issues. Input data error may occur due to:-

(1) New elements are regularly brought into service in a vast and expanding Indian grid.
(2) Modelling errors related to equipment.

However, these modelling errors in connectivity and parameters are easy to identify and revamp, but database modification may induce a problem of technical feasibility in context to the application that drives various TNA applications. In order to address these issues, the script based application; "TNAInit" which is exercised on ADM server. The same is shown in Figures 3 and 4.

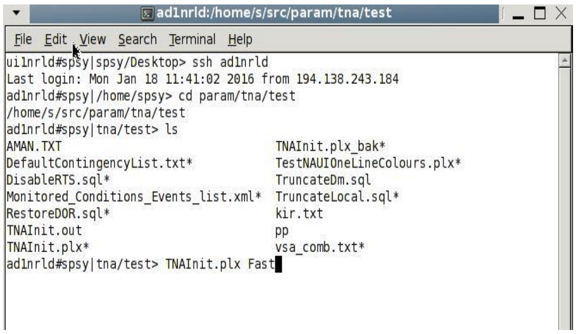

Fig. 3: Initialization of TNA database

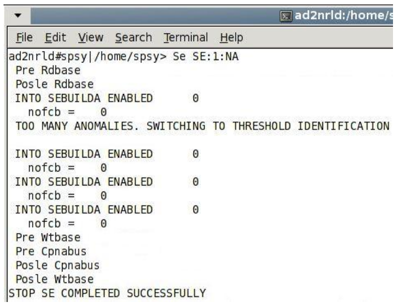

Fig. 4: SE simulation via script

2.3 SE system size at NRLDC

In order to obtain convergence of SE under Full mode, the Network is needed to be tailored based on available telemetry. As of now, network used for SE at NRLDC is truncated at 220 kV buses. Voltage estimate is available for 220 kV buses but estimated flows aren't available for the connected lines at this voltage level. However, generators at all voltage levels are included in the model. Presently, Network size with above true for SE at NRLDC is:

No. of buses:

Voltage (kV)	765	400	220	132	66	**Total**
No. of Buses	19	180	141	2	1	**343**

No. of lines:

Voltage (kV)	765	400	220	**Total**
No. of lines	25	389	78	**492**

Other elements:

Element	Generating units	LTC	Conforming Loads	Reactors	TCSC	SVC	DC lines
Nos.	240	298	502	265	1	2	4

3. Issues faced and solutions implemented

3.1. Creation of Parallel Path at 220 kV to provide evacuation path for power from generators modelled radially in *TNA*

In order to get more precise results for TNA applications, it is thus necessary to include generators and associated critical elements (forming parallel paths for evacuation of power) in the network model. In TNA model of NRLDC most of the 220 kV lines are truncated and modelled as equivalent loads due to inconsistent telemetry at 220 kV and lower side. However, most generators injecting into 220 kV level (or 132 and 66 kV) are modelled in TNA. This attempt has lead to few generators injecting at 220 kV level are modelled as radial node in TNA model. The inherent shortcoming with this model is total outage of such a generator from TNA model in case any critical element in this radial connection trips or is taken under outage. This may lead to formation of two separate Electrical Networks in SE Model Update. However, in actual, only single Network exists since the generator may be connected to the grid via complicated network of 220 kV lines. Thus, TNA model must include parallel paths at low voltage levels for power evacuation from that particular generator based on consistency of telemetry.

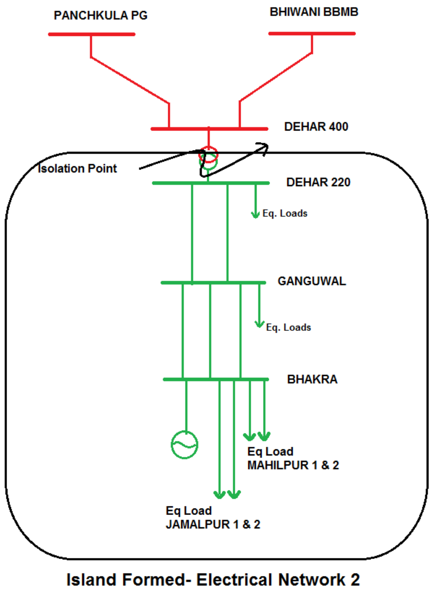

Fig. 5: Island formed-Network 2

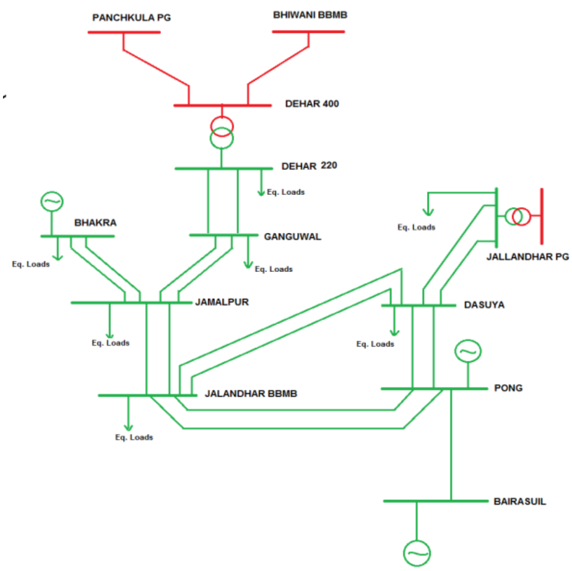

Fig. 6: Expanded network to include parallel 220 kV paths

The subject can be better appreciated with an example of Bhakra generating station. In previous model, Bhakra (BBMB) is connected (radially) to 400 kV network via Ganguwal and Dehar 220 kV bus. The outage of 400/220 ICT at as shown in Figure 5 in such a model, would lead to formation of Island consisting of Bhakra, Ganguwal and Dehar 220 buses. Since adequate generation and loads were available in small network formed, it is solved by SE as Electrical Network 2 as shown in Case 1 of table 1. In order to address the aforementioned issue, TNA network model is expanded in manner as shown in Figure 6. This has lead to creation of parallel path via Jamalpur - Jallandhar BBMB - Pong - Dasya through which Bhakra would still connected to Network 1 after its separation at Dehar. This also has helped in introducing Bairasuil and Pong (both hydel generating ststions) in the TNA network.

Table 1: Island summary for different cases

Island Summary	Network No.	MW Load	MW Load delivered	Losses MW (%)	MW Generation
Case 1	1	29012	28530	481 (1.66%)	26861
	2	967	964	2.7 (0.28%)	967
Case 2	1	29450	28841	608 (2.07%)	27982

Case 2 in table 1 shows that Bhakra is now connected via Jamalpur – Jallandhar BBMB – Dasuya - Jallandhar PG in a single Network 1. However, the telemetry of downstream stations is very important in case of parallel paths. SE output of upstream buses deteriorates if this part of Network becomes unobservable.

3.2 Point of telemetry for reactive power and its mapping:

It's being observed that SE is marking analog measurement set (P,Q) for a transmission line anomalous when a line reactor is bought into operation connected to that line. The reason is disparity between point of telemetry and point of measurements assignment in TNA. The issue can be better appreciated with aid of figure 7.

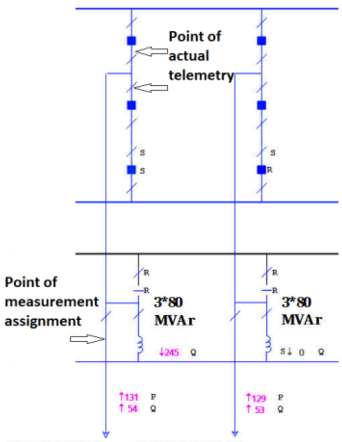

Fig. 7: Point of actual measurement and assigned measurement

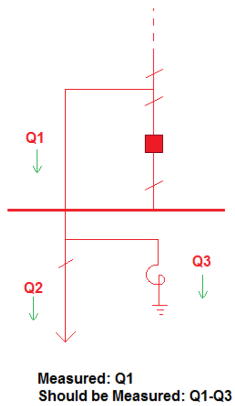

Fig. 8: Understanding the proposed solution

In case, line reactor is connected, the actual and mapped measurement for Reactive Power flowing over the line would differ significantly. The issue can be better appreciated from Figure 8. The actual MVAr measurement that should be considered in TNA is Q2 i.e. Q1-Q3. However, the telemetry mapped into TNA at end of line is Q1. Hence, TNA marks the measurement set (P1,Q1) as anomaly since it assumes that the measurement is taken at end point or precisely due to unavailability of actual MVAr measurement i.e. Q2. To address the issue, a Calculated analog point has been defined for value of MVAR i.e. Q1-Q3 in SCADA and has been mapped to TNA instead of Q2. It means that a calculated value of MVAr will be assigned to that terminal of line having line reactor connected. The gradual improvements are being observed in SE output by use of calculated MVAr. Table 2 shows measured vs. estimated flows and value of normalized residuals for an AC branch LKN_BAR1 when telemetered and calculated MVAr is used respectively. A steep reduction in values of normalized residuals is observed.

Table 2: Measured vs Estimated flow over LKN_BAR1 under two conditions

	MW meas.	MW est.	Normalized Res	Meas. status	MVAr meas.	MVAr est.	Normalized Res	Meas. status
Case 1	-424.35	-457.34	1.65	ok	-110.8	-294.96	9.21	**Anomaly**
Case 2	-402.18	-419.70	0.88	ok	-304.67	-306.52	0.09	ok

The MVAr measurement which was an anomaly is now included in measurement set and hence adding to redundant measurements. Value of PI (Performance Index) has also got improved since it depends upon values of normalized residuals. Lower the value of PI, better are the results.

3.3 Variance in sign convention for Inter Connecting Transformer (ICT) loadings:

One major challenge faced was non-uniform sign conventions for ICT flows followed by different utilities of NR grid. The widely followed convention is to take P, Q at high voltage side negative and P, Q at low voltage side positive if P or Q is flowing from high voltage to the lower voltage. This is illustrated in figure 9.

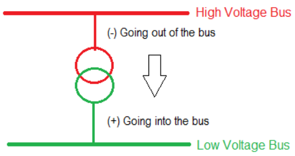

Fig. 9: Convention for P, Q flows across ICT

The above convention deviates from normally accepted convention in which power going out of bus is considered positive while that going into the bus is considered negative. The reason being measurements for ICT flows have generally being made available at low voltage side which is responsible for calculation of loads being served at sub-control area of a larger control area. The problem is addressed with implementation of SQL script that has uniformized the sign conventions across all ICTs present in NR grid. The improvement shown by SE output after implementation of script can be visualized in table 3. Estimated values against measured values along with normalized residuals are shown for LT side of 400/220 kV transformers FE_T1 & FE_T2 under two different scenarios. Case 1 depicts large values of residuals, and hence PI when the sign of MW/MVAr deviates from followed convention. Case 2 depicts disappearance of anomalies and gradual reduction in residuals, and hence improvement in PI after uniformization of signs.

Table 3: Estimates with wrong and corrected sign convention

Transformer		**CASE 1**				**CASE 2**			
		measurement	**estimate**	**Residual**	**Status**	**measurement**	**estimate**	**Residual**	**Status**
FE_T1	**MW**	-112.68	86.87	19.95	**Anomaly**	116.3	113.14	-0.32	Ok
	MVAr	11.71	16.32	1.63	Ok	11.23	11.46	0.09	Ok
FE_T2	**MW**	-108.72	86.87	19.56	**Anomaly**	111.98	113.14	0.12	Ok
	MVAr	12.16	16.32	1.63	Ok	11.97	11.46	-0.11	Ok

3.4 Reference bus issues with PMU data used as input:

The formulation of estimation problem requires a reference bus where voltage phase angle is always equal to zero. With no Phasor measurements available, SE engine uses the prescribed reference bus during formulation and calculates the phase angle at all other buses wrt the reference bus. When PMU measurements are used in input, one of the buses with PMUs is taken as reference bus. This also means the values of phase angles obtained from PMU output at different buses are first calculated wrt to reference bus and then to be used as input to SE. However, if the measurement from reference PMU consists of error, the output of SE gets biased. Various techniques have been reported in literature to address the aforementioned issue. Eastern Interconnection Phasor Project (EIPP) has implemented a technique where average of phase angle measurements located nearby of chosen bus is calculated and the value is assigned to a virtual bus that would be considered as reference bus [4-5]. However, this technique is useful only when measurements from several PMUs are available in the system.

The SE at NRLDC uses data from 4 PMUs located at Dadri, Balia, Bassi and Hissar. As mentioned earlier, the calculated angular separation of Balia, Bassi and Hissar wrt Dadri is coursed with other inputs of SE. In this way PMU input is made consistent with SE problem formulation. Since PMU provides absolute value of phase angle at buses, a standard calculation rule is used to calculate the relative values in SCADA system.

As mentioned in [2], enough redundancy should be there in PMU measurements to detect and identify the errors in Phasor measurements for an observable island. It calls for a provision to mark erroneous PMU measurements anomalous and hence to be removed from the measurement set. However, the situation arises when the PMU measurements from chosen reference bus, say Bus A become erroneous. In order to prevent SE output to become biased, the PMU measurements from chosen reference bus also need to be removed from measurement set. As an outcome, a new reference bus, say B is required to be chosen for SE problem formulation. The problem has been recognized and the Bus with PMU nearest to reference Bus takes over as the new reference Bus. This resolution may yet bring up another issue since phase angle output at all buses previously calculated wrt to A is now being calculated wrt B, corresponding plots will also get changed and thus may offer inconsistency in visualization of output by operator. It is thus required that SE must give the final values of phase angles wrt to bus A, even the phase angle at current ref bus B should also be calculated wrt A. The same has been recognised and is under implementation.

4. Improvements and future contrive

As mentioned in section 3.1, careful inclusion of parallel paths in TNA model for evacuation of power generated at low voltage levels will serve twin purpose of increase in system size and addition of good data. Table 4 shows the resulting Performance Index (PI) with inclusion of parallel paths.

Table 4: PI with network expansion at 220 kV

S. No.	N/W Expansion	System Size in SE	No. of measurements added	**PI**
1	BBMB-Pong	32800	59	**4563**
2	UPPTCL-Harduaganj	33300	67	**4328**
3	RRVPNL-Sakatpura	34500	43	**4084**
4	NPCIL-Narora	35030	84	**3886**
5	NHPC-Dhauliganga	35310	71	**3670**

It can be observed how, as more generators are added along with parallel path at voltages, lower values of PI are obtained, which means more accurate estimates. System size of SE in beginning was around 32400 MW and actual system load was near to 38000 MW. The value of PI before network expansion and inclusion of parallel paths was 4800. Different generations brought into network via creation of parallel paths at 220 kV are stated in front of their owning utilities. Number of good measurements acquired is also stated. Subsequent improvement in PI is observed. Another factor that has shown a substantial improvement is the amount of transmission losses (TL) occurred in the system as solved by SE. With the system size approaching close to actual system load, a more absolved idea of system TL will be obtained. Figure 10 shows the resulting TL over a day as a result of adding generators at low voltage levels and creation of parallel paths.

It is remarkable that Transmission Losses calculated by SE, though following a same pattern differ by a significant amount from actual losses in the system. It can be observed that with the inclusion of generators and parallel paths at 220 kV, the mismatch between actual system TL and SE calculated TL has reduced considerably. Further improvements could be done by including generators and parallel paths at lower voltages of 132 kV and 66 kV.

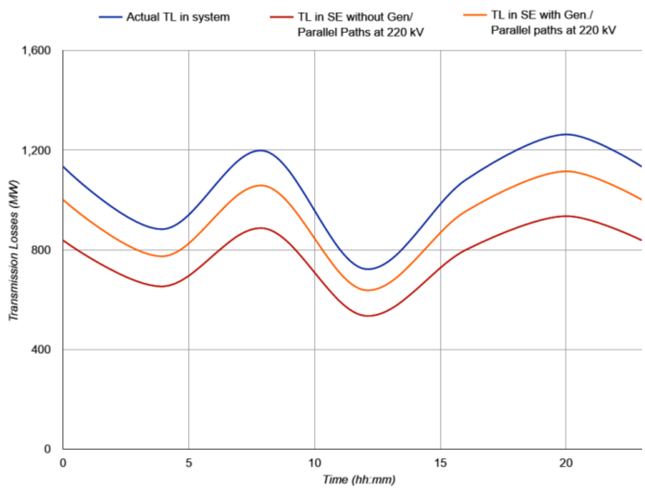

Fig. 10: Transmission losses over a typical summer day in NR

As was discussed in section 3.2, improper point of telemetry for reactive power may result in high MVAr mismatch at a bus in presence of shunt reactors. It also results in wrong estimate of the voltage at that bus. With more mismatches, higher values of PI are obtained, which means less accurate estimates. The proposed calculation rule was realised at bus-line pairs at 765 kV, where the line reactors are present. The number of line reactors present at this voltage level is more than 50. Table 5 shows the improvement in PI with calculation rule applied.

Table 5: Values of PI

Network Scenario	**PI**
Before	**4800**
After	**4100**

Voltage profiles at 765 kV level in the evening of a typical summer day are drawn. Figure 11 shows the voltage profile with wrong point of telemetry. The average deviation is calculated as 1.62 % in this case. Figure 12 shows the voltage profile after calculation rule is applied to take care of improper point of telemetry. Th average deviation in this case is being reduced to 1.2 %.

The major impact can be seen in a zone 765/PGCIL/WR, which represents the connected bus of neighbouring control area. The estimated voltage at this bus got reduced from 807 kV to 772 kV which of course makes more sense. The problem of high MVAr mismatch at boundary stations is common among many utilities, and improper point of telemetry could be one of the reasons.

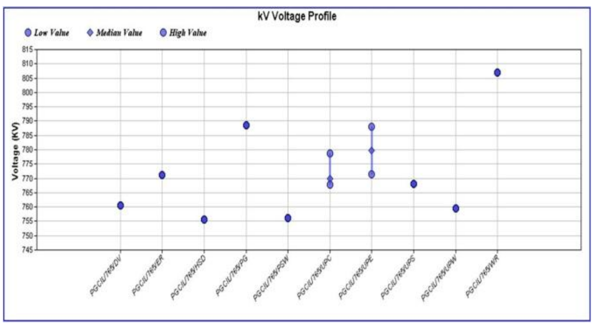

Fig. 11: Voltage profile at 765 kV with improper point of telemetry

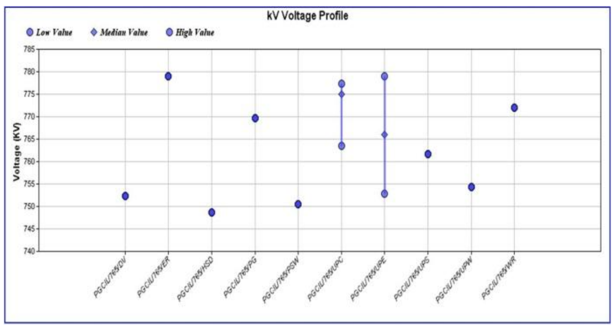

Fig. 12: Voltage profile at 765 kV after MVAR calculation rule

The improvement in quality of SE output by incorporating PMU phase measurements data in a conventional SE has been assessed. A quantitative analysis of output with two different scenarios, i.e. with only conventional measurements and with both conventional and PMU measurements has been done. The following scenarios have been considered to monitor the quality of SE output:

1) *SCADA measurements only*: The measurements which are varied are Bus Voltage-angle pair. The standard deviation for these measurements in SCADA has been set to 0.45.
2) *SCADA and PMU measurements both*: In SCADA, only bus voltages are monitored in aforementioned measurement set. Phase angles are available for PMU which are considered to be 10 times accurate than SCADA measurements, hence, standard deviation associated with PMU measurements will be 0.045.

A factor S is defined which is the ratio of standard deviation of SCADA measurements and that of PMU measurements.

$S = \frac{\sigma_{SCADA}}{\sigma_{PMU}}$ Where, σ_{SCADA} & σ_{PMU} are std. deviation of SCADA measurements and of PMU measurements respectively. SE output is monitored with different values of S, ranging from 1 to 10. Figure 13 shows the resulting PI for the different values of S.

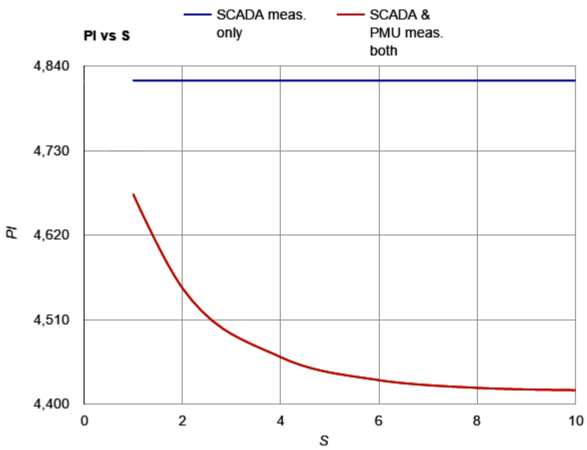

Fig. 13: Simulation results for PI with PMU measurements

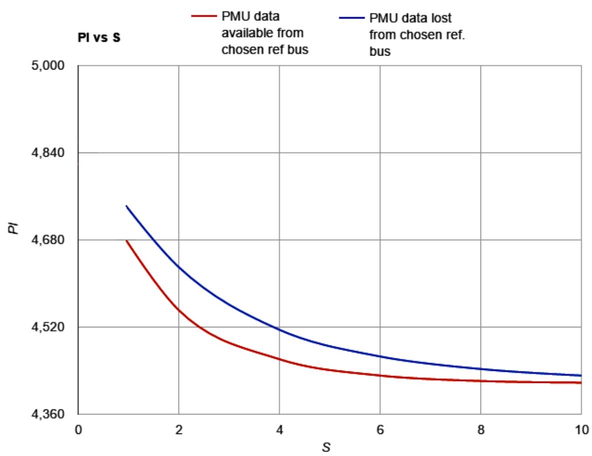

Fig. 14: Simulation results for PI with change of ref. Bus

It can be seen that with increase in value of S, lower values of PI are obtained, which means more accurate estimates. Increase in value of S means that standard deviation associated with PMU measurements is being reduced. It can also be seen that with increasing value of S beyond 10, the quality improvement in SE output somewhat saturates. The affect of loss of data from reference PMU and re-designation of new reference PMU (as discussed in section 3.4) is also assessed. Figure 14 shows resulting PI following change of reference bus with different values of S. It is remarkable that from the point of view of SE output quality; it is plausible to strive in further improving the quality and consistency of PMU measurements rather than increasing the number of PMUs. An offline observability analysis to identify the best locations for PMUs installation is thus necessary. However, robustness against loss of PMU data is higher when a larger number of PMUs are installed.

With the increased use of security Analysis in large interconnected power systems, an adequate representation of the neighbouring power systems is required to take into consideration the system dynamics of neighbouring control areas in order to get more absolved output from SE. Presently, Inter-regional lines are modelled as equivalent load/injection by careful modification or assignment of parameters. However, for unbiased modelling of internal system under all foreseeable conditions, some of the external network (belonging to neighbouring control areas) must be explicitly retained. A comprehensive technique is to reduce external network by lumped equivalent impendance with associated external measurement of external elements [6]. The calculation of network equivalents is performed by using offline program. The following points are considered while performing the equivalency process:-

- Several utilities of Northern Power Grid form a single control area and share the complete network of the voltage levels 220 kV and above
- The network at voltage level of 132 kV and lower is only of interest for the control centre of state owned utilities and not for Regional Control Centre (NRLDC) and hence the 132 kV sides of the connecting transformers is to be modelled as the boundary nodes at NRLDC.
- Control areas external to Northern Power Grid will be reduced to its boundary.

Figure 15 shows the complete network of interest for security applications.

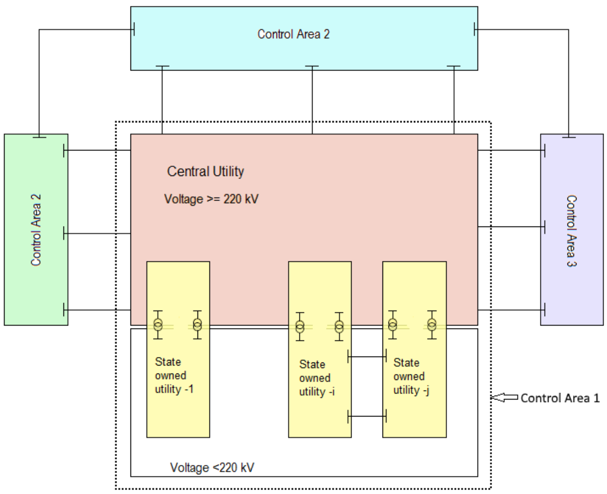

Fig. 15: Network of NR and its utilities

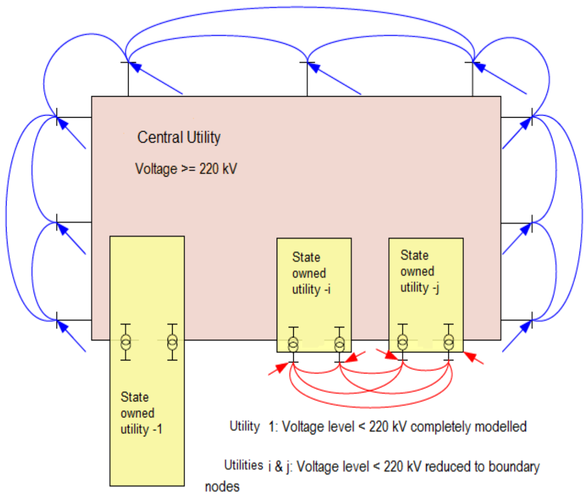

Fig. 16: Reduced network model

Using offline tool, the external network formed by neighbouring control areas and part of Northern Power Grid belonging to state owned utilities at voltage level lower than 220 kV is reduced to the boundaries. The same is done with state owned utilities having no tie lines below 220 kV. However, for a state owned utilities having tie-lines with others at voltage level less than 220 kV, it will be included in that utility's model, as it is seen in Figure 16. The arrow in the figure represents the boundary nodes.The stipulated operation is already performed by using offline program and is scheduled to be implemented after successful modelling of reduced networks of utilities. For further improvements, a technique was proposed in [7] in which equivalent considers the effects of primary voltage and frequency control of neighbouring control areas, including the real scenarios and constraints, as well as the effects of under frequency load shedding or under frequency protection of generator.

With inclusion of more and more PMUs and their successive integration with TNA, the quality of SE output will improve. As a result, major part of power grid will become observable, making feasible the estimation of the state of these observable portions at much faster rates than the traditional state estimator. It will improve statistical as well as numerical robustness of the existing estimator and will pave a way to implemenet Estimator with high scan rate which would be able to capture system dynamics. Presently at NRLDC, a hybrid SE is operational with data from 4 PMUs is being utilized. Since, more PMUs are being installed and under commissioning process, the quality of SE output will eventually improve. This will also pave way for the implementation of Linear State Estimator (LSE) at

NRLDC. However, integration of the LSE to the existing EMS environment will pose some issues like lack of offline observability Analysis before installation of PMUs, lack digital breaker/switch information etc [8].

5. Conclusion

This paper provides the candid assessment of the way State Estimator and associated real-time applications are realized at NRLDC. The modelling of database for SE and its tuning in hierarchical perspective and addressal of related issues occurred over the period is also understood. The identification and inclusion into TNA of parallel path to include generators connected to grid at lower voltage levels is discussed along with associated issues. This exercise is important to match system size in SE to actual load being served in control area and to include operational effects of generators connected at lower voltage levels. The subsequent improvement in quality of SE output is also seen. It is evident that switching of a generator has prominent effect on grid operation when compared to switching of a transmission element. It was shown that how inappropriate point of telemetry has resulted into increase in bad data and values of thresholds, thus adversely affecting the Performance of SE as can be comprehended from a large value of PI. The problem is carefully tackled by assigning calculated measurements resulting into gradual vaporization of anomalies. Also, uniformization of signs across ICTs has resulted in significant reduction in residuals and thus improving PI. It is also demonstrated that atleast three phasor measurements are necessary for identification of bad data associated with any phasor measurement in an observable island where the PMUs are located. It is also discussed that as phasor measurements start populating the systems, the choice of reference bus will no longer be the user’s decision. Heuristic Selection of Reference Angles can be used where in Flat start; initial angles of the observable islands are set to the Median angles of all PMUs of that island. Initial angles of unobservable islands are set to angle reference of the electrical island.

The paper also talks about relevant methodological and practical aspects of forming the external network equivalent that is to be implemented. However, it is yet to consider whether this equivalent takes into consideration changes in both active and reactive power output of generators in external control area. If included, the accuracy of the external network equivalent will further get improved.

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