WAMS and Synchrophasor Experience During Synchronization of Large Grids in India

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***Abstract*— Electricity grid interconnections have played a key role in the history of electric power systems for economic and optimum utilization of resources. Most national and regional power systems that exist today have begun many decades ago as isolated systems. In similar way, Indian grid has also evolved from state grid to regional grid and then their synchronization one after another. On 31st December 2013, the interconnection of NEW Grid and Southern grid in Indian power system has resulted in accomplishing the final stage of Indian grid synchronization. This synchronization was unique in the sense that operator at Regional and National control centre were able to monitor the each phase of synchronization with the help of synchrophasor measurements. This paper describes the experience of System operator gained from NEW-SR grid synchronization with the help of synchrophasor measurements.**

Keywords— Indian Grid, Islanding , Low Frequency Oscillation, Synchrophasor, Synchroscope, System Protection Scheme.

I. INTRODUCTION

Indian Grid is among the largest electrical grid in the world with a total installed capacity of around 250 GW [1]. It has evolved in a long span of time from the state grids era to their synchronization to form the regional grids. This has resulted in five regional grids during year 2000 and named as Eastern Grid, North-Eastern Grid, Northern Grid, Southern Grid and Western Grid. In a phase wise manner first the North-Eastern and Eastern grid were synchronized and it was followed by synchronization with Western grid. This has formed the Central Grid in Indian power system, which existed along with Northern and Southern grid. After this, the Northern grid synchronization with the central grid was completed in year 2006. This has completed the formation of NEW Grid. The final step for Indian grid was the synchronization of Southern Grid with the NEW Grid. This feat was achieved on 31st December 2013 when these two system got synchronized with high capacity 765 kV Solapur Raichur link and thus "One Nation-One Grid-One frequency" has come to realization in Indian power system. During the final step of synchronization, a major role has been played by the Phasor measurement units (PMU) technology. This paper discusses how the synchrophasor measurements have played the pivotal role prior to synchronization of NEW –SR Grid, during synchronization and post synchronization.

II. SYNCHROPHASOR IMPLEMENTATION IN INDIA

Synchrophasor measurements have evolved out as an important tool for power system operator. In India, Pilot project in northern region was the first step towards the synchrophasor technology implementation and sooner rest of the regional grids have started its implementation. At the end of year 2012, each of these regional pilot projects got integrated at national level for use at National Load Despatch Centre for monitoring and control on Indian power system. For the benefit of power system fraternity, the experiences of these pilot projects have been published in form of two reports by the POSOCO, which manages the Indian grid [2-3]. At present over 60 PMUs have been integrated in the Indian grid of various make, which has given insight into the major challenges that is being faced while integration and application development.

Out of the various utilization of the synchrophasor measurements, most promising are fault analysis, oscillation monitoring, islanding and synchronization. Among these, the grid operators at control centers in India are using it for fault analysis in real time operation from the very beginning. With gradual experience, the oscillation monitoring has evolved as a tool for small signal stability issues in the grid. Various real time and offline cases were analyzed which has helped in PSS tuning and other corrective actions to mitigate such problems. The third application is the synchronization experience based on PMUs, which has developed gradually with few occurrences of islanding and their synchronization. The knowledge base gained in this field was the basis for its utilization for the synchronization of NEW and Southern Grid. The next section is about the various lessons learnt from previous occurrences of islanding and their synchronization in Indian power system.

III. Pre-Synchronization Experience

Use of synchrophasor in the field of islanding detection is among the leading research topic in the power system fraternity. Prior to synchrophasor measurements, grid operators use to know about islanding in the system with the state estimator after a long delay. In addition, their role was limited to inertia calculation based on SCADA frequency and information from the field and providing inputs for what action has to be taken to stabilize the various islands and their synchronization. It was not possible to have a view of system dynamics at operator level in real time during the actual synchronization.

With the introduction of synchrophasor in the Indian grid in year 2010, high-resolution time synchronized phasor data was now available at control centre and the islanding of any part of system having PMUs can now be easily observed at control centers in real time. Grid operators can now have an insight into the various aspects of the islands and their characteristic and play the pivotal role in smooth resynchronization of any island with rest of the system.

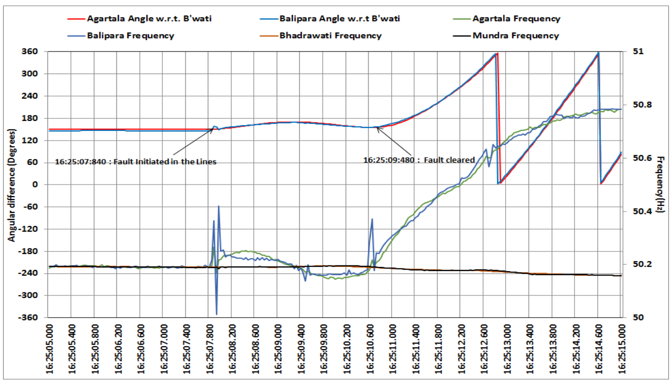

Fig. 1. Angular difference and frequency plot during isolation of NER Grid from the rest of the NEW grid.

After the introduction of synchrophasor units, first of the detailed analysis of system islanding and synchronization was done for the North-Eastern (NER) grid. On 29th August 2013, the North- Eastern Grid was connected to NEW grid by only 400 kV Balipara-Bongaigaon D/C due to the shutdown of 220 kV BTPS-Salakati D/C which is the parallel corridor [3]. Due to power system fault on both the 400 kV lines, NER grid got islanded from the NEW grid. Figure 1 shows the Angular difference and frequency plot when the NER grid islanded from the rest of the NEW grid. It can be monitored that with islanding of the both grids, their frequencies has separated depending up on the inertia and load-generation balance of both grids after separation. In addition, the phase angle difference can be observed to be on increasing trend and went beyond 180 degrees, which means that machines in the two system have gone out of phase and two system have separated. The angular difference after separation is being wrapped within $\pm 180^0$ as the frequency is different for both the grids The angle wrapping observed is dependent on the slip frequency between the two grids [3]. It can be noticed that the frequency of NER grid has increased due to excess generation after seperation. Hence, there is a need of automatic action to control the frequency by limiting the generation when islanding occurs. This case has illustrated the fact that how islanding can be monitored in the grid with the help of synchrophasor measurements. In addition, it signifies that how safe islanding can be achieved during unforeseen events like N-2 contingency in above case and what automatic action is desired for stability of both islands.

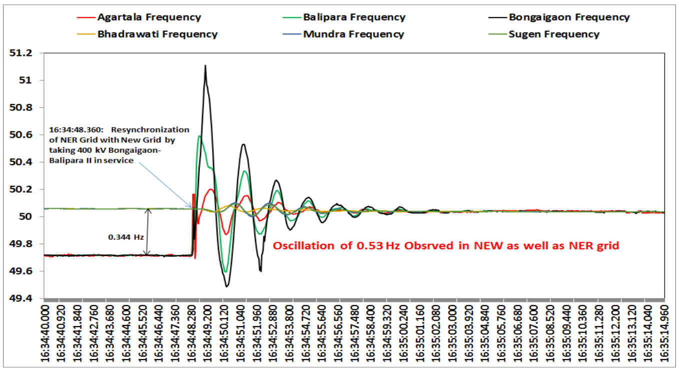

Fig. 2. Synchronization of NER grid with the NEW grid after isolation

After the event, the synchronization of NER Grid with the NEW Grid was done on the same day as shown in figure 2. It can be found that the synchronization was not smooth due to the large frequency difference between the two grids. Due to the synchronization with such large frequency difference, the NER grid has experienced a severe jerk in their system. The synchronization of two grids (Area) resulted in one inter-area mode. In this case, the inter-area oscillation was of 0.53 Hz. Being a low inertia island, it was desired that at time of synchronization NER Grid frequency should have been more than NEW grid so that there is no sudden power inrush. The rough synchronization has also resulted in large magnitude of inter-area oscillation in all the parameters of NER grid, which could have resulted in mal-operation of protection.

So, from this islanding and resynchronization experience, following lessons are learnt:

1. Islanding and synchronization can be easily monitored with the help of synchrophasors data.
2. During synchronization, the criteria for frequency difference between two grids should be less than 0.1 Hz for lower amplitude of inter area oscillation. Larger the frequency difference between the two islands, greater will be the power swing observed in inter-area oscillation mode, which will be reflected across all parameters.
3. A synchrocope can be designed with the help of PMU measurements across the both end of tie lines for Control Centre operator's use. The parameters to be monitored are frequency of both island, angular difference and voltage difference. These data are easily available from the synchrophasor units.

Before discussing the NEW-SR synchronization, a brief about the synchroscope is discussed in the next section for familiarization with development of digital synchroscope at Control center to monitor synchronization.

IV. SYNCHROSCOPE AND ITS FUNCTION

A synchroscope is an equipment that is used to monitor the three synchronizing variables which are frequency difference between the two islands, voltage magnitude and voltage phase angle difference across the synchronization point [4]. A synchroscope has input voltage waveforms from the two sides of the open circuit breaker across which synchronization has to be done. If the angular separation between the two voltages are at the same frequency, the angular difference does not move and shows a fixed difference as reference is same for both grid. This is due the fact that if the relative measurements are taken at same frequency then they will show standing phase angle difference. While if the frequency of two waveforms are different, then the phase angle difference will increase or decrease with the rate of change in frequency difference (slip) between the two waveforms. In case of two grids which are at different frequency, the synchroscope dial of angular separation rotates in proportion to the frequency difference between the two grids [3]. The same can be observed in figure 1 where phase angle difference in the two grid is being wrapped due the different frequencies of the grids after islanding.

During synchronization, the synchronizing variables along with the synchronizing needle should be well within limits to allow the closing of the synchronizing breaker. Now the synchronization is being done with the digital synchroscope, which allows automatic synchronization when the above-mentioned three conditions are within the defined limit [5]. These quantities from the fields are now also available at control centers with the PMUs at field which was used for NEW-SR Grid synchronization by developing a digital synchroscope as explained in next section.

V. SYNCHRONIZATION EXPERIENCE

The final stage of Indian grid synchronization has to be done through 765 kV Solapur-Raichur high capacity link. As there was only one link available at the time of synchronization for such large grids synchronization, so it was necessary to monitor them using the available measurements devices. In view of the above, synchrophasor measurements units (PMUs) were installed at both end of the 765 kV AC tie link. The synchrophasor measurements from both ends of the lines were available at Western and Southern Regional load Despatch Centre along with National load Despatch Centre for monitoring. Based on prior experience, the synchronization was preceded by taking due care of the various contingencies in the both grids by putting system protection scheme for automated action based on the experience gained in the section 3. Similar to NER grid synchronization explained in section 3, it was expected that inter area oscillation will be observed post synchronization of these two large grids.

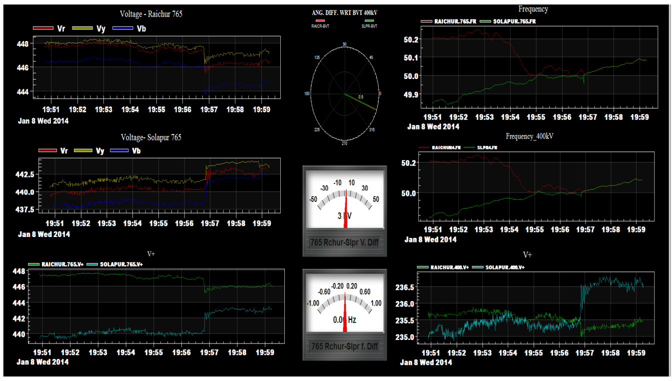

Fig. 3. Synchroscope avavailbe at opeartor desk to montor the synchonization with the help of synchrophasor measurements.

To monitor the synchronization, a synchroscope was made with the help of synchrophasor measurements from both ends. Figure 3 shows the visualization prepared for synchronization at Western Regional Load Dispatch Centre. It consists of voltage magnitude, voltage angle difference and frequency difference dial from both ends of the lines. Each end represents their respective grid characteristic, which is monitored at various control centers. To know how the parameters for smooth synchronization, system studies using software were performed which is described below.

From the stability studies conducted in PSS/E , it was found that synchronization has to be done with frequency difference of 0.1 Hz as this will control the initial power swing within 1000 MW limit on the 765 kV tie line. The accepted standing phase angular separation across the breaker was to be kept within 5 degrees, which will cause smaller swing across various generators. Apart from that, a comprehensive System protection scheme (SPS) was also put in place to ensure the grid stability in case of loss of synchronization between the grids due to loss of the AC tie line. In addition, the SPS has been designed to keep the various stability limit of both grids within the safe limit in case of other major contingencies.

After these preparatory activities and their cross validation, synchronization of the NEW and SR grid was done on 31st December 2014 at 20:25 Hrs. The 765 kV Solapur-Raichur tie line was charged from Raichur end and synchronized at Solapur end, which has resulted in synchronization of these two grids forming Indian Grid. Figure 4 shows the frequency of SR and NEW Grid during first synchronization and the power flow across the AC tie line. As envisaged, Inter area oscillation of 0.2 Hz (0.18-0.22 Hz) was observed post synchronization from synchrophasor measurements as shown in figure 4 which is due to the variation in load generation balance in the two grids.

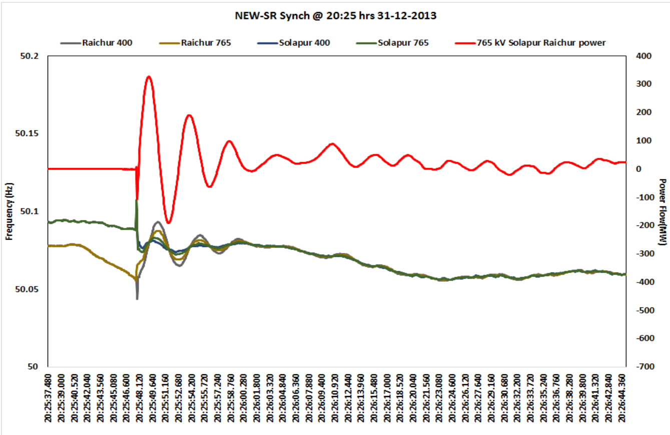

Fig. 4. Frequency of Southern and NEW grid and the AC tie line power flow after the first synchronization .

The key characteristic of the Indian grid observed post synchronization from synchrophasor data analysis are as following:

1. Inter-Area oscillation of 0.2 Hz having a damping of around 8-16 % is observed on various occasions [6].
2. The flow on the tie line is bidirectional as it is sensitive to load-generation variation of the two grids as observed in figure 4, 5, 6 and 7.
3. Power Number of grid has increased to 5000 -7000 MW/Hz, which has improved the system stability during disturbances.

During the operation after the synchronization, the synchrophasor data was helpful in accessing the various aspects of synchronization including the SPS operation if any. It has provided the details, whether the SPS has operated as per the desired set condition or not. This has further helped in improving the SPS design and in providing the feedback to planners and regulators on the synchronization aspect.

During the synchronized operation it was found that the inter area oscillation observed is having good positive damping. There are only few occasions when it has negative damping, which was also controlled with the help of designed SPS operation to reduce generation/load to relieve line loading of the tie line. Out of these cases of negative damping, the first one was observed on 28th January 2014 when modal resonance has resulted in the negative damping of the 0.2 Hz [6]. Figure 5 shows the power flow on the AC tie line during the negative damping of 0.2 Hz mode which got arrested by the SPS operation designed to control rate of change of power flow on the circuit to a maximum of 400 MW/Sec. During this event, the oscillation was felt throughout the new grid. Here the damping observed initially was -3 %, which after SPS operation increased to 4 % and system returned to stable state.

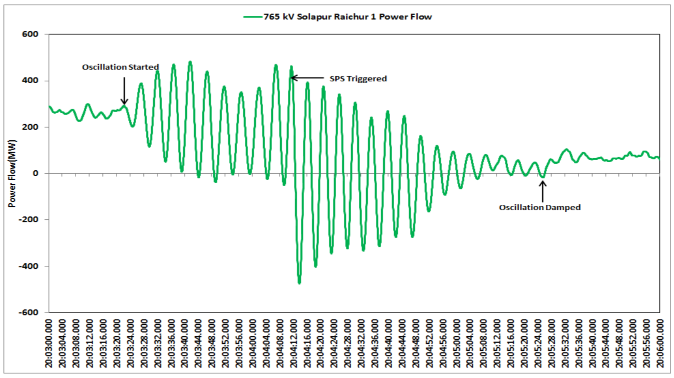

Fig. 5. Undamped oscillation observed in the AC tie line on 28th January 2014 .

The second case of undamped oscillation was observed on 6th May 2014 when one the units in southern grid started hunting due to mal functioning of relay controlling the steam inflows to turbine. The oscillation in the Unit resulted in inter-area oscillation which was felt across the grid. As shown in Figure 6, the power flow on the tie line connecting NEW and SR grid started oscillating with negative damping. Again the SPS designed to control the line loading operated due to undamped oscillation. In this case the damping ratio prior to SPS operation was -3 %, which increased to 8 % resulting in stable system.

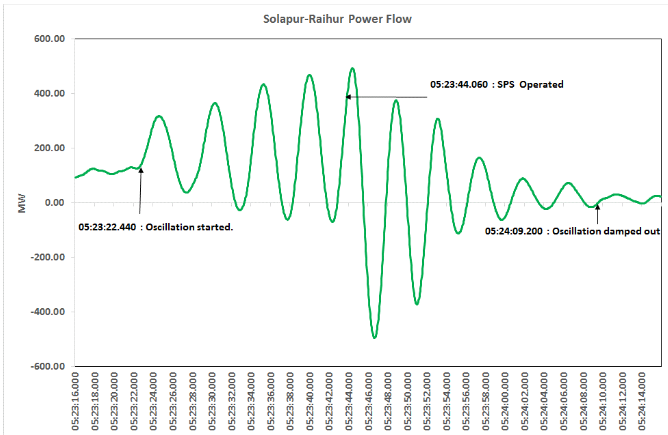

Fig. 6. Undamped oscillation observed in the AC tie line on 6th May 2014 due to hunting of a generator in Southern grid .

Thus, it can be observed that, SPS has operated and reduced the load /generation automatically to improve the system damping torque. The Design of the SPS scheme was further improved with the analysis of synchrophasor data, which provided the feedback that power flow on tie line is high during first swing, and gets reduced after 5 seconds i.e. one cycle of inter-area oscillation 0.2 Hz. In view of the same, SPS designed was improved by introducing a delay of 2.5 seconds in SPS, which has improved its selectivity.

It was also observed during the real time operation that any generation tripping in southern grid will be observed as increased power flow on the 765 kV Solapur-Raichur tie line. The power flow on this line oscillates with 0.2 Hz and is felt across the grid with good positive damping. Figure 7 shows the tripping of 600 MW generating unit in southern grid. It can be seen that the tie line flow has oscillated with 0.2 Hz and come to a stable limit after few seconds due to positive damping in the grid

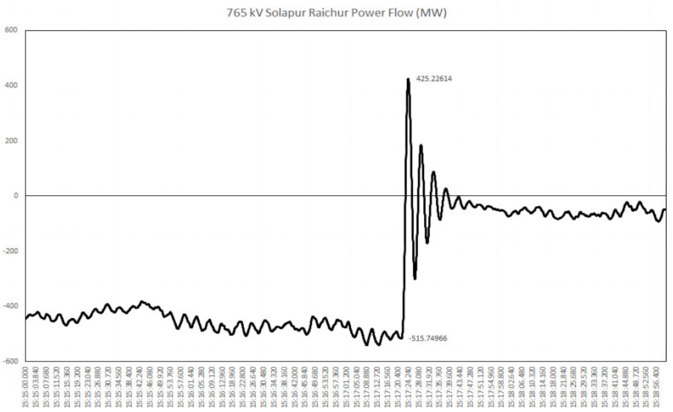

Fig. 7. Oscillation during Unit tripping in Southern grid.

Therefore, in this section it was learnt that the synchronization of large grids has resulted in inter-area oscillation of 0.2 Hz, which was not observed in either of the NEW and SR grid prior to synchronization. Further, its damping was positive except the two cases described in this section.

Based on the above experience of synchronization and inter-area oscillation, it can be inferred that:

1. PSS tuning of all the generators in the Indian grid is very much desired to further improve the damping of Inter-area oscillation.
2. Power oscillation damper (POD) of HVDC and TCSC tuning for the inter area oscillation.
3. Ramping of load has to be properly coordinated so that no large load changeover is observed at a time. This will help in controlling the power flow on the tie line.
4. Further strengthening of tie lines between NEW and SR grid is required to improve the stability. The second tie line has also come into service during June 2014 which has further improved the damping of the inter area oscillation.
5. Modal validation of the generators for having better models for simulation of small signal stability issues.
6. Secondary frequency control for the Indian grid is also required to further control the line loading on the tie lines.

Overall synchrophasor played a major role in the monitoring and control of the Indian grid after synchonization.

CONCLUSION

This paper has illustrated the role played by the synchrophasor measurement in synchronization of large grid. The importance of synchrophasor measurements usage has been shown at control centre for smooth synchronization of large grid. It can be observed that how PMUs have helped for better visualization of system dynamics. The operator console developed for synchronization is unique as it is a replica of synchroscope used in fields. It has provided the operator with a better monitoring tool and helped in smooth synchronization and resynchronization whenever there is a requirement. This has enhanced the operator confidence level during synchronization of two large grids in real time. In addition, it can be observed how PMUs data helped in the analysis of various SPS operations and in further modification of the SPS scheme for better selectivity. Further, this paper emphasizes the further actions required for the better operation of the synchronous Indian Grid. Overall, paper has deliberated a use case of how synchrophasor measurement can be used in a large grid for real time monitoring and operation.

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