Automated Fault Analysis Using Synchrophasor Measurements

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SUMMARY

Synchrophasor data has led to paradigm shift in the Indian Power system operation. This new measurement availability at control centres has provided a dynamic insight into the various power system phenomena that were not observed earlier from the conventional SCADA system. Indian Power system has also adopted this technology in year 2010 and now more than 60 PMUs has been installed across the grid for better observability and decision making in real-time operation. This technology has played a very pivotal role in synchronization of Southern grid of with rest of the Indian Grid in recent past. In addition, the synchrophasor data is being extensively utilized by the system operator in analysing any event after its occurrence in real time for faster restoration. This has accelerated the analysis process yet this requires human intelligence and considerable time. Keeping in view of the fast analysis in near real time with synchrophasor data, Disturbance analysis (DA) tool has been developed which has the capability to analyse the synchrophasor data from various Phasor measurement Units (PMUs) and Disturbance Recorder (DRs) and give result to operator in least possible time. The application is as of now working very well in offline mode and further research work is underway towards its online application. This paper is focused on the fault analysis tool development with detailed outlook on its modelling and challenges faced during the development.

KEYWORDS

Disturbance analysis, Indian Grid, Phasor measurement unit, Power system fault.
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1. Introduction

Phasor measurement units (PMUs) are devices that can send the time synchronized phasor information from the field to the control center and enable operator to look into the power system dynamics with higher number of data. Synchrophasor data is the fundamental frequency component computed over a fixed moving window [1]. These devices provide phasor information at defined reporting rate, which varies between 25-100 samples/second for 50 Hz system and 30-120 samples/second for 60 Hz system. With such fast data rate, getting useful information for real time operator is one of the most researched topics across the globe. Various research and development is going on this field to make maximum use of PMUs. Among these developments, most important is the diagnostic of power system events followed by their characterization and localization.

This paper is focused on the development of an event analysis tool developed by POSOCO in consultation with PRDC. The tool is able to detection various event from synhcrophasor data and find out the type of event and its other characteristic. At the last, it locates the area based on the information near to which the event has occurred.

2. Event Analysis using Sycnhrophasor Data

Power system events are characterized by the abnormal changes in the power system parameters i.e. in voltage, current, power, frequency etc. For characterizing such events, there is a need to classify events based on time scale required for observation. Based on the observability of the events, it was found that, these could be classified in second and millisecond second range. Events that are occurring in milliseconds are the various power system faults. While the generation/load loss events can be categorized in the later category due to their observability time frame.

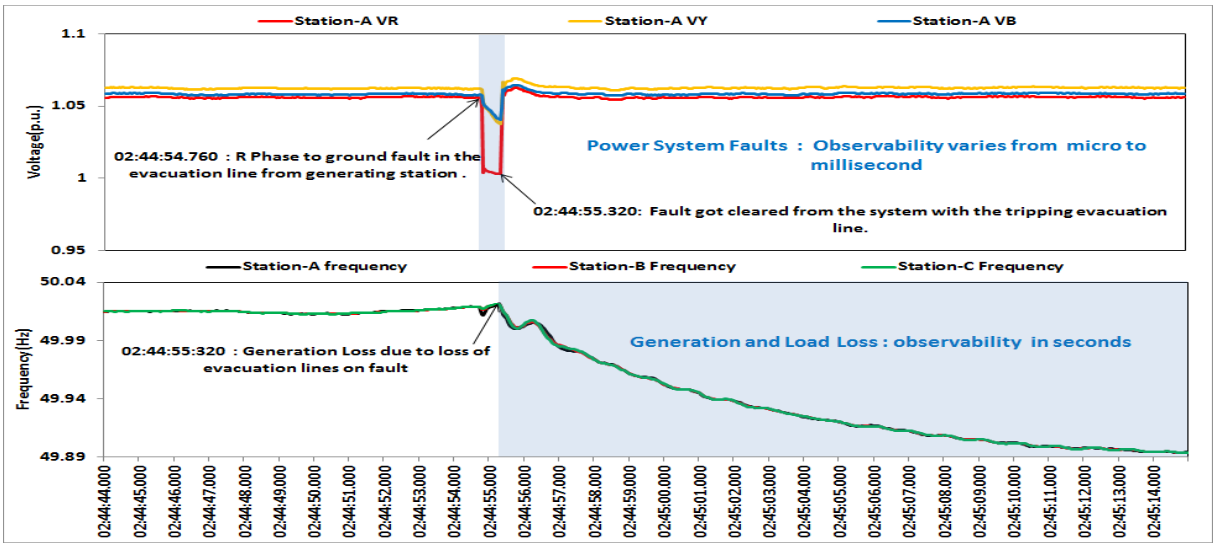

Figure 1 : Voltage and frequncy observed from Synchrophasor data during the fault followed by generation tripping near Station A.

It can be observed from figure 1 that, the fault observability in the system is limited to millisecond depending on the fault clearance by the protection system. While the generation or load loss can be characterized by the frequency drop, which can be observed over a period of few seconds.

With the introduction of synchrophasor in Indian power system, operator have utilized it extensively in real as well as offline for understanding of power system dynamics like fault, oscillation, islanding etc. [1-2]. This has given a proper insight into characterizing different phenomenon for development of application for detecting these phenomena in real time for helping operator in providing situational awareness. In this paper, the focus is on the identification and use of various signatures of power system event as discussed above based on synchrophasor data for the development of automated tool for their detection. This tool is developed keeping in view the limited numbers of PMUs present in the system and better utilization of the available set of data.

First step for any power system event analysis is its detection. It is observed that the Frequency change and Rate of change of frequency (ROCOF) during event is more than a set threshold value compared to normal state of power system. Closer the synchrophasor unit is located to the event, more will the frequency change and ROCOF value observed from that synchrophasor unit [3]. Apart from that, other parameters like angular difference, instantaneous voltage variation can also be used for detection of such events [4]. These detection techniques can be automatized and used for event detection in real time for the benefit of power system operator.

Now the detection of event need to be followed its characterization for increasing the situational awareness. As discussed above, the tool is devised to detect the two types of event which can be observed completely with synchrophasor data i.e. power system fault and load/generation loss. Any power system fault can be classified as symmetrical or unsymmetrical fault. Unsymmetrical faults are lien to ground (LG), line-to-line (LL), and line to line to ground (LLG). While symmetrical fault can be either three phase fault which may or may not involve ground [5].

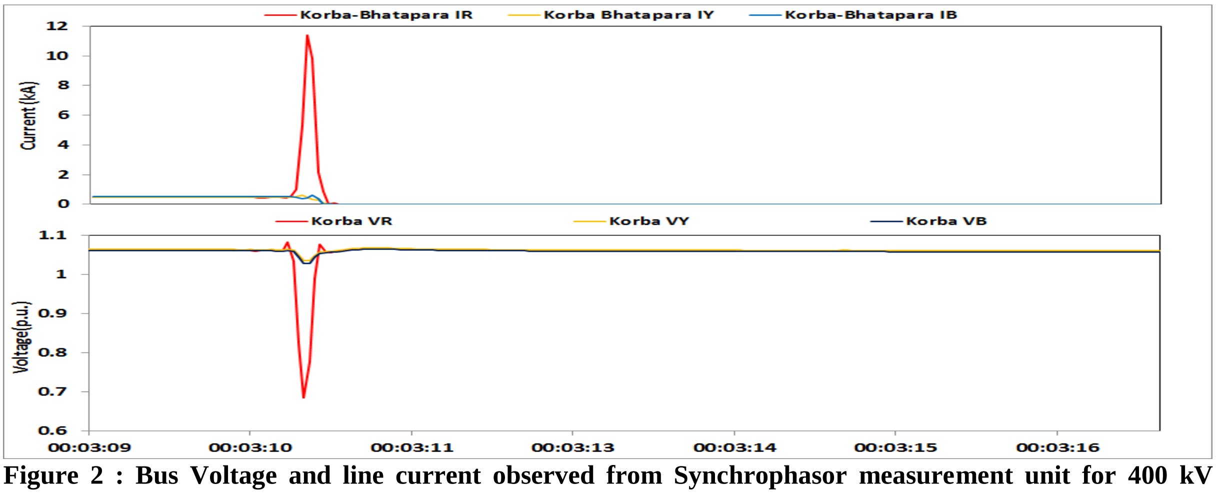

Figure 2 : Bus Voltage and line current observed from Synchrophasor measurement unit for 400 kV Korba Bhatapara circuit during R phase to earth fault on the line from Korba end.

These faults are characterized with the voltage and current imbalance in the power system and it is reflected in the measured value from PMU. The voltage of the faulty phase will dip for the bus where the fault is located either on the lines from that bus or bus itself. While the current in faulty phase will increase. For example, R phase to earth fault on a 400 kV Korba-Bhatapara circuit as measured by the PMU installed at Korba end is shown in figure 2. It can be observed that Bus voltage of R phase of the Korba has dip due to the fault while the current in faulty phase of the line has increased while feeding the fault.

While in case of load/generation loss, the frequency will increase/decrease accordingly and a large ROCOF will be observed during the period. This change in frequency and ROCOF can be used for calculating the approximate loss of load/generation in the system. With these signatures of the synchrophasor measurements during power system events, the next section explains how the Disturbance analysis tool was developed for the use of event analysis.

3. Disturbance Analysis tool and its development

Disturbance Analysis (DA) tool was developed keeping in view of the four objectives, which are detection, characterization, localization of any event and extent of load/generation loss. The program control flow of developed DA tool is shown in figure 3. It can take synchrophasor data in two input which are comma separated (.csv) and standard comtrade format file as per C37.118.1™-2011 [6]. This has resulted in standardization of the tool and can be used by any other utility.

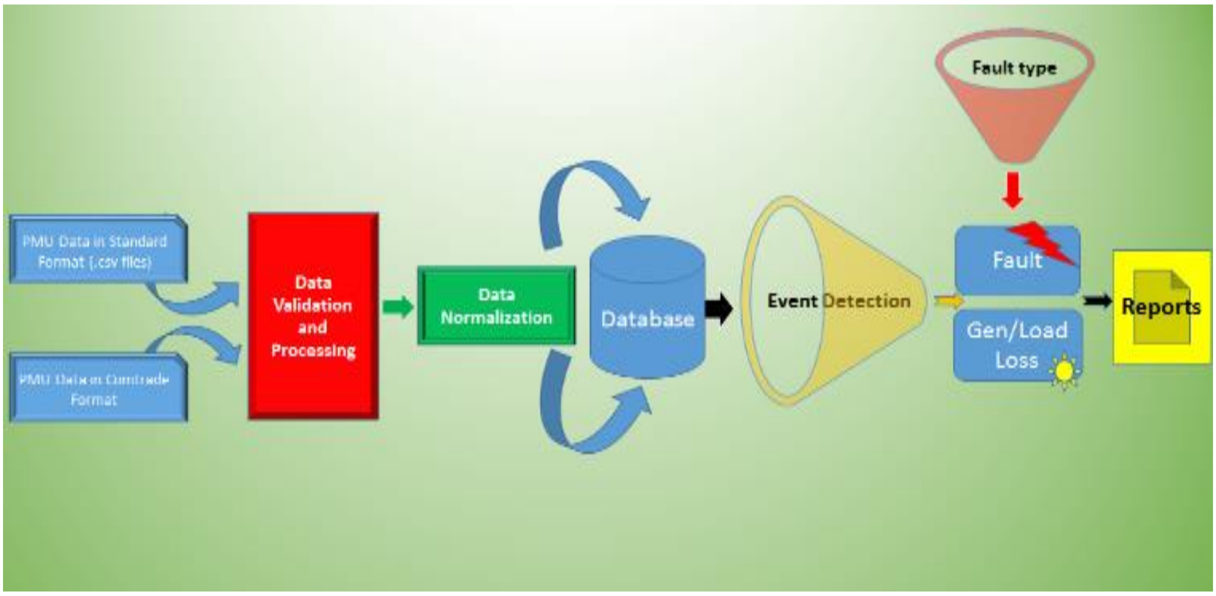

Figure 3 : Program control flow for the DA tool.

The steps involved in the development can be broadly categorised as data validation and it's processing to filter out bad data based on status tag from the PMU. This is followed with the data normalization, which involves angle unwrapping and per unit conversion for utilization of the data for event detection. Event detection as can be seen is done for two separate event i.e. faults and loss of load/generation. In the end, the user is given a report for understanding the event and taking decision.

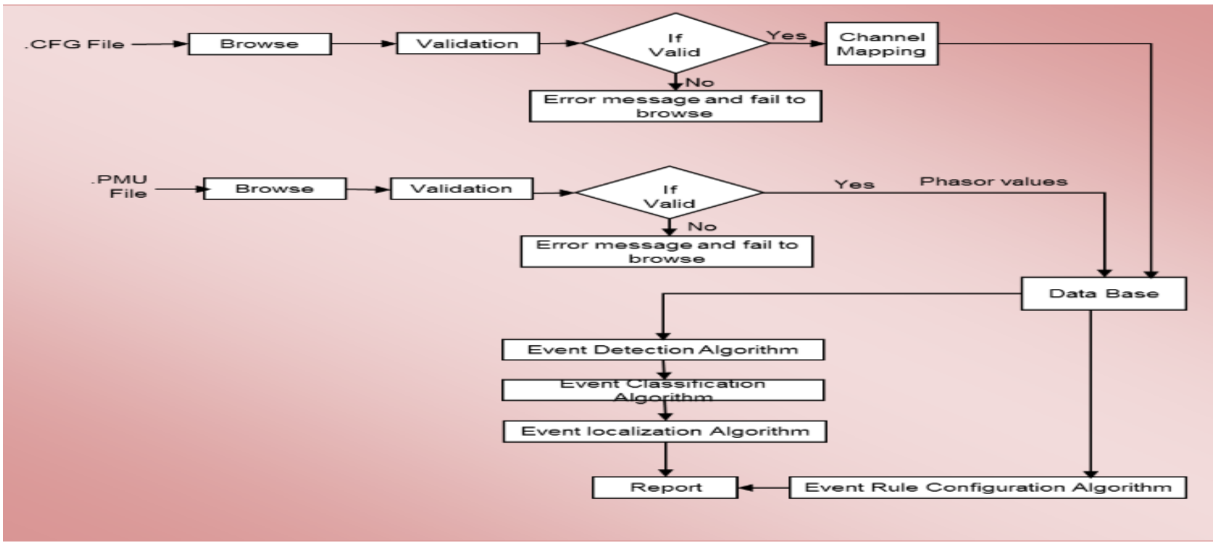

Figure 4 : Algorithm of DA-Tool .

The basic algorithm of DA tool is shown in figure 4. It can be inferred that the first step after fetching the data is to validate it. The validation of data is done for checking and isolating any bad data from the given set based on the data tag associated. After completion of validation and processing of the data, they are stored in the database for analysis. The analysis consists of mainly three algorithms, which are:

1. Event detection algorithm
2. Event classification algorithm
3. Event localization algorithm

As based on literature and operators experience, a single common factor/parameter will not suffice the event detection for different system conditions with the help of synchrophasor data. Therefore, in order to detect the events, various parameter were checked for event analysis and out of these following four have been found to be most effective in detecting almost all the major events in the given data set:

1. ROCOF variance ratio
2. Phase angle difference mean
3. Phase angle difference variance
4. Voltage magnitude threshold

The event detection is done using the moving window analysis of the data using the above techniques so that the whole data can be analysed in accelerated way [4]. After the event detection, the selected window having events is being analysed for various types of faults and load/generation loss. During faults, the frequency prior to fault and after fault will remain almost same. While during

Load/generation loss, it will be different based on the quantum of load loss and system inertia. Based on the rise/fall in the detection range, load/generation loss is classified for the PMU where ROCOF is maximum. The calculation of the load/generation loss is calculated based on simplified equation 1 and 2 as shown below.

$$\Delta P_{ele} = (2H/f_0)*(df/dt) \quad (1)$$

$$P_{act} = (\Delta P_{ele} + (\Delta\ f_{final} * \text{Power Number}) \quad (2)$$

Various faults can be classified based on the dip observed in voltage phase along with the zero sequence voltage presence from the synchrophasor data [7]. The dv/dt ratio of phase voltages and zero sequence voltage for the set of PMUs whose delta difference is high in the selected event window is calculated and compared against a set threshold values. This result in classification of the event in single phase to ground (SLG), phase to phase (LL), phase to phase to ground(LLG), three phase to ground(LLLG) and three phase faults(LLL). Various other characteristic like fault clearing time, fault recovery time, Successful/unsuccessful/no auto-reclosure can also be calculated based on the synchrophasor data whose process has been detailed in the [2]. .

After the detection and classification of the event has been done, the final step is to localize the event. The load/generation loss can be narrowed down to nearest PMU using the maximum variance of ROCOF. While for localizing the area in which the fault has occurred, the delta difference data and negative sequence currents are being used. The set of PMUs within which the delta difference is highest during the event period is the region within which there might have been a fault. Further, if the fault is unsymmetrical, the negative sequence currents in the feeders from these the first two PMU's can be measured and PMU having the highest negative sequence current contribution at the instant of fault is considered closer to the fault. .

Based on above, the different algorithms were combined and the tool has been developed to analyse the data. The algorithm developed has been explained in the parallel paper [4] and is not being explained in details in this paper. The aim of this paper is to describe the basic ideology, algorithm, concept behind the development of the process and provide good details to operator for the event. This can be best explained with the help of case studies, which is described in details in next section.

4. Case Study Analysed with Disturbance Analysis Tool

The tool developed is based on the user experience of analysing synchrophasor data , its validation for various practical cases and coming out with a set of rules for characterization and localization combining the theoretical and practical power system information in unison. This requires proper tuning of the tool, which is based on various values that are required to be set to detect event and its categorisation and localization. The various threshold, which is tested for Indian power system for event detection based on synchrophasor data are as following:

1. ROCOF Variance ratio : 5
2. Delta(δ) mean :1
3. Delta Variance : 0.01
4. Voltage Max. Threshold: 1.2 p.u.
5. Voltage Min. threshold: 0.85 p.u.
6. dv/dt threshold: -0.1 p.u/sec

These values were calculated after analysing a series of sample case studies before implementing the tool in control centre. After this various cases has been analysed out which three cases are explained in this section as a proof of concept.

The first case discussed is of single phase to earth fault on the 400 kV Navsari-Vapi circuit one in the grid. In this case, the PMU is not located on the line/bus where the fault has occurred. The Voltage of nearby bus Mundra is shown in figure 5. During this tripping, it was observed that line tripped immediately and operators were not aware that whether the line attempted the auto-reclosure or not. This information is very important while deciding whether to attempt the charging of the line or not. In addition, the fault clearance time and other details need to be known to verify that weather the line tripped within the 100 millisecond or not. This helps in verifying the protection related information related to the line in the real time, which helps in taking the corrective action as soon as possible.

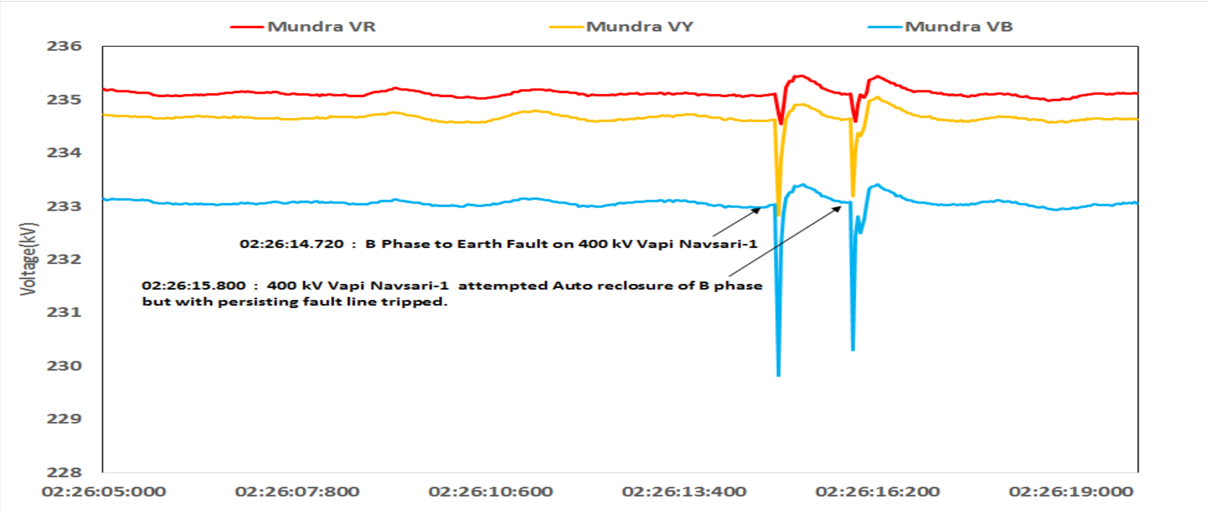

Figure 5 : B Phase to Earth fault on 400 kV Nasari –Vapi 1 as observed from the Synchrophasor at Mundra .

To analyse the event, seven PMUs data were taken to analyse with the developed algorithms. The result of the detailed analysis is shown in figure 6. It can be inferred from the analysis that the nearest PMU where event is located is Mundra and Sugen which is correct as the fault location near to these two 400 kV sub-stations. The fault is classified as B phase to ground fault with unsuccessful A/R which can be observed to be correct from figure 5. The fault clearing time is 40 ms while the fault recovery time is not detected as the threshold has been set high. It can be observed that the event was detected by ROCOF variance and Delta variance and other methods were not able to detect as PMUs were located far from the event site. This signifies the importance of using various methods when PMUs are sparsely located in the grid.

FILE INFORMATION

DESCRIPTION	VALUE
File Names	CGPL,ITARSI,JABALPUR,MUNDRA,SUGEN,BHADRAWATI, RAIPUR
Group Start Time	12 March 2014 02:26:05:0
Group End Time	12 March 2014 02:26:19:960
Duration (mm:ss:ms)	0:14:960
Sampling Interval (ms)	40
Sampling Frequency (Hz)	25

SUMMARY REPORT

EVENT ID	START TIME	END TIME	FAULT TYPE (by dv/dt Algo)	FAULT LOCALIZATION (First Close -Second Close)	FAULT LOCALIZATION(PMU/Feeder Name)	AUTO RECLOSURE	PMU FILE CHECK
2	12 March 2014 02:26:14:600	12 March 2014 02:26:16:200	B-G Fault	MUNDRA-SUGEN	MUNDRA/FEEDER 2	Unsuccessful Auto Reclosure	OK

LOSS OF LOAD SUMMARY : NO

DETAILED REPORT

EVENT ID	FAULT INITIALIZATION TIME	FAULT REMOVAL TIME	FAULT CLEARING DURATION (sec)	FAULT RECOVERY DURATION (sec)
2	12 March 2014 02:26:14.720	12 March 2014 02:26:14.760	0.04	Fault recovery time is undetected

EVENT ID	EVENT DETECTION METHOD	DF/DT VAR RATIO PMU 1	DF/DT VAR RATIO PMU 2	MIN DELTA DIFF MEAN A (deg)	MIN DELTA DIFF MEAN B (deg)	MIN DELTA VARIANCE
2	df/dt Threshold , df/dt variance ratio , delta variance	853.67854	NA	NA	NA	0.11948

Figure 6 : Analysis for B phase to earth fault on 400 kV Navsari Vapi 1 from the DA Tool.

The above case shows how the developed rule set based technique is able to detect fault event when PMUs are located at a distant from source of event. To check the accuracy of the tool, the second case is of single phase to earth fault on a 400 kV transmission line where current of the transmission line and bus voltage of one of the end is available from the PMU.

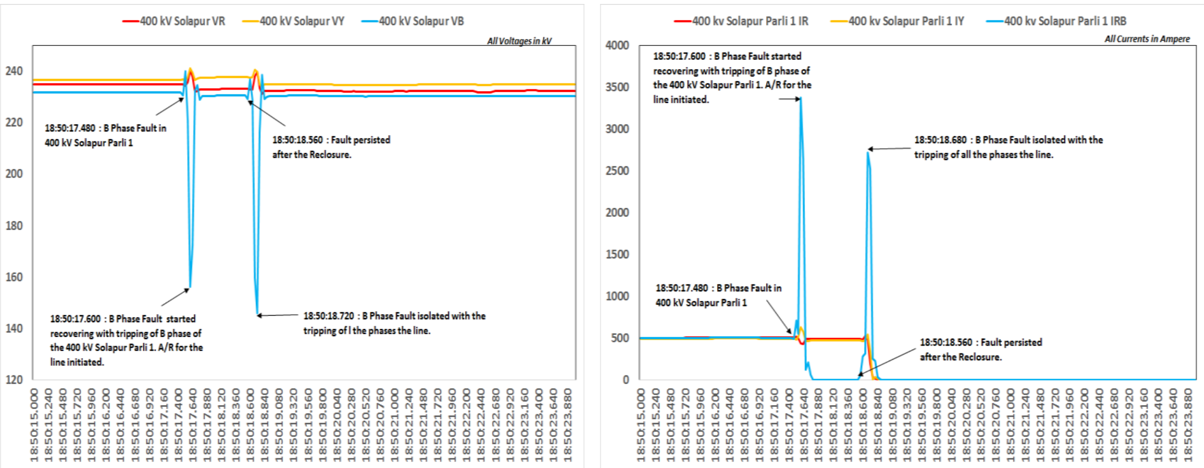

Figure 7 : Voltage plot of 400 kV Solapur bus and Current plot of Solapur-Parli 1 feeder during single phase to ground fault on the circuit observed from Solapur PMU.

Figure 7 shows the voltage of 400 kV Solapur Bus and current of 400 kV Solapur Parli 1 indicating the fault and unsuccessful auto reclosure attempt due to persisting nature of fault. To analyse the event 4 PMUs data were given as input to the DA tool. The report generated by DA tool is shown in figure 8. It can be inferred that nearby PMU are Solapur followed by Raipur and the fault is B phase to earth fault with unsuccessful Auto-reclosure, which can be verified from figure 7. The fault clearing time is

80 ms while the fault recovery is also 80 ms that means that total fault time is 160 ms and it can be seen that protection has operated correctly. The last but important thing is the localization of Solapur feeder 2, which is the same feeder on which the fault has occurred. Further, it can be seen that all the methods has detected the fault.

FILE INFORMATION

DESCRIPTION	VALUE
File Names	BHADRAWATI, SOLAPUR,RAIPUR,ITARSI
Group Start Time	09 March 2014 18:50:12:0
Group End Time	09 March 2014 18:50:26:960
Duration (mm:ss:ms)	0:14:960
Sampling Interval (ms)	40
Sampling Frequency (Hz)	25

SUMMARY REPORT

EVENT ID	START TIME	END TIME	FAULT TYPE (by dv/dt Algo)	FAULT LOCALIZATION (First Close -Second Close)	FAULT LOCALIZATION(PMU/Feeder Name)	AUTO RECLOSURE	PMU FILE CHECK
1	09 March 2014 18:50:16:760	09 March 2014 18:50:18:400	B-G Fault	SOLAPUR-RAIPUR	SOLAPUR/FEEDER2	Unsuccessful Auto Reclosure	OK

LOSS OF LOAD SUMMARY : NO

DETAILED REPORT

EVENT ID	FAULT INITIALIZATION TIME	FAULT REMOVAL TIME	FAULT CLEARING DURATION (sec)	FAULT RECOVERY DURATION (sec)
1	09 March 2014 18:50:17.520	09 March 2014 18:50:17.600	0.08	0.08
2	09 March 2014 18:50:18.760	Fault removal time is undetected	Fault removal time is undetected	Fault removal time is undetected

EVENT ID	EVENT DETECTION METHOD	DF/DT VAR RATIO PMU 1	DF/DT VAR RATIO PMU 2	MIN DELTA DIFF MEAN A (deg)	MIN DELTA DIFF MEAN B (deg)	MIN DELTA VARIANCE
1	df/dt Threshold , df/dt variance ratio , delta mean , delta variance , voltage threshold	24739.95008	9.85308	NA	2.38533	0.22538
2	delta variance , voltage threshold	NA	NA	NA	NA	0.47446

Figure 8: Analysis for B phase to earth fault on 400 kV Solapur Parli 1 from the tool.

These two cases have illustrated how effectively the tool is able to analyse the fault using the synchrophasor data from various PMUs. The third case is of generation loss of 3750 MW power plant followed by ROCOF (df/dt) based load shedding which will give a proof of concept for the load/generation loss events. On 12th march 2014, 3800 MW generation was lost from the Indian grid due to islanding of CGPL ultra mega power plant with the loss of all the evacuation lines from the CGPL complex. Figure 9 shows the frequency observed at various locations in the grid. The islanding of 3750 MW generation from the grid resulted in sharp decrease in the frequency in the grid which has resulted in activation at ROCOF based load shedding of the quantum 960 MW in the control areas which are near to the event . So net generation loss during the event was of order 2800 MW.

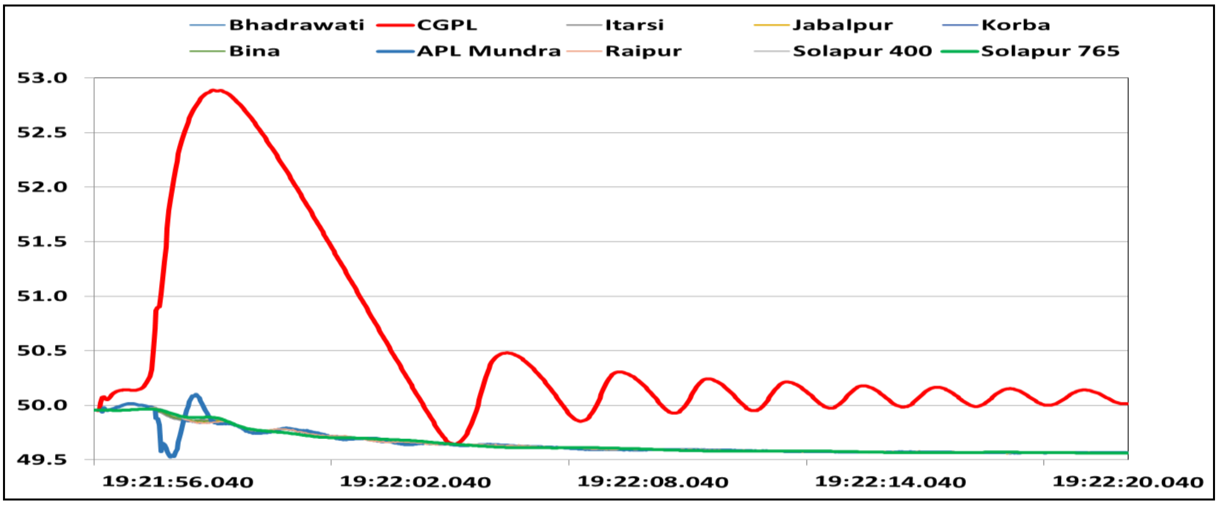

Figure 9: Frequency during the islanding of CGPL generation from the rest of the Grid .

During the event the power swing has resulted in voltage drop in all the three phases in the near by location to the event. The event was analysed from the DA tool and the reort is shown in figure 10.

FILE INFORMATION

DESCRIPTION	VALUE
File Names	Itarsi,Jabalpur,Kalwa,Mundra,Sugen
Group Start Time	12 March 2014 19:21:48:0
Group End Time	12 March 2014 19:22:02:960
Duration (mm:ss:ms)	0:14:960
Sampling Interval (ms)	40
Sampling Frequency (Hz)	25

FAULT SUMMARY :

EVENT ID	START TIME	END TIME	FAULT TYPE (by dv/dt Algo)	FAULT LOCALIZATION (First Close -Second Close)	FAULT LOCALIZATION (PMU/Feeder Name)	AUTO RECLOSURE	PMU FILE CHECK
1	12 March 2014 19:21:56:0	12 March 2014 19:21:57:600	RYB-G Fault	Mundra-Jabalpur	NA	NA	OK

LOSS OF LOAD SUMMARY :

EVENT ID	START TIME	END TIME	TYPE OF LOSS	QUANTUM LOSS (MW)	LOCALIZATION	PRE-DISTURBANCE FREQ(Hz)	POST DISTURBANCE FREQ(Hz)	SETTLING FREQ(Hz)	PMU FILE CHECK
1	12 March 2014 19:21:56:0	12 March 2014 19:21:57:600	Loss of Generation	-3014.56348	Mundra	49.956	49.688	49.688	OK

Figure 10: DA tool analysis for CGPL UMPP generation Loss.

Here it can be observed that loss of generation calculated from the tool is 3014 MW, which is close to 2800 MW. In addition, the three-phase fault is detected at Mundra, which is due to the severe power swing observed at CGPL, Mundra and nearby areas during the event resulting in severe voltage drop during the power swing. This case illustrate that how this tool can help operator in estimating the generation/load loss during an event.

The case studies discussed in this section have illustrated the usefulness of the developed tool from system operation perspective. Still a lot of further development is yet to be achieved in the near future. The next section is on the various challenges and limitation, which need to be focused in further development of the tool.

5. Limitation and Future Development

As observed from the previous section, the tool is effective in providing a good amount of information to operator and analyst after analysing various PMUs data for event. Yet many challenges still exist which need to be debriefed in the future development. Out of these, few have been listed out here, which are as follows:

1. **Big Data Handling:** There is a need for improving data handling and storage requirements for optimum utilization of resources. As in future, the number of synchrophasor will be large in number and operator need tools that can analyse that huge sum of data to provide the analysis.
2. **Real time implementation :** As the tool is now used offline and there is a need to use it in real time by automatizing it the real time streaming data from the PDC.
3. **Handling of the missing data:** Missing data in PMU data stream can trigger the various algorithms, which can give false indication about the event and so it need to be handled

carefully. Handling such situation optimally is a challenge and hence there is a need to introduce algorithm to crosschecking of synchrophasor data.

4. **Limitation of type of PMUs:** At present three types of PMUs have been included which can further increased to various type of PMUs available in the market.
5. **Other Events:** Various other event classification like opening or closing of lines based on the digital status from the synchrophasor data is still to be integrated in the algorithm.
6. **Disturbance recorder files and Synchrophasor data:** The is a need of correlating disturbance recorder and synchrophasor analysis from the DA Tool to give a good result for post disturbance analysis, which will save a lot of time.

The ongoing research in the area of handling of big data and other developments is going on in the synchrophasor fraternity will help in meeting the mentioned challenges in future.

Conclusion

Although PMUs have become increasingly widespread throughout Indian power system, the buses monitored by PMUs still constitute a very small percentage of the total number of system buses of the grid. The paper has detailed about the research work carried out for developing tool to utilize the data from limited number of PMUs to analyse the event and various other characteristics. This paper has discussed the Disturbance analysis tool development that is capable of analysing synchrophasor data for event detection along with load and generation loss during the event. This is one of its kind that has been deployed to detect the event, characterize its type and localize the affected area using the synchrophasor data implemented in control centre. This tool in future when implemented online will make the job of operator easier during power system fault to locate the affected region. Further research is being carried out for various improvements in the algorithm to make it more robust, optimum computational time and processor usage. The related work is continued and it will be reported in near future.

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