Disturbance Analysis Tool based on Synchrophasor Data

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***Abstract*— Indian grid is among the largest synchronous grid in the world. With rapid growth in demand and generation and increased complexity in transmission network, the grid operation is becoming challenging day by day. With increased complexity, power system dynamic state visualization has a major role in grid operation. This has been achieved with the introduction of Synchrophasor Measurement Units also known as Phasor Measurement Units (PMUs). With the help of PMU, the grid dynamics now can be monitored at sub-second level at control centre. With the help of the sub-second data and phasor information, the power system fault can be easily diagnosed in real time which will help the operator in reducing the after effects and restoration time. This paper is focused on the development of Disturbance Analysis (DA) tool for analyzing faults in the grid using synchrophasor data and its localization at control centre. This will help operator in immediately accessing the fault and taking corrective measures. Various case studies analyzed using the developed DA Tool are discussed in the paper. This tool has eased the process of analysis and reduced the time for detailed analysis of grid event which has increased the operator confidence level during restoration. This tool has laid the path forward for the development of analysis tools as per the user conveyance to monitor the grid.**

***Index Terms*— Disturbance analysis, Event classification, Fault classification, Phasor measurement unit, Power system fault.**

I. Introduction

PHASOR Measurement Units (PMUs) have increased the power system operator visualization of the electrical grid. With the help of such devices in field, the control centers are able to visualize and analyze any power system phenomenon in real time at sub second level in time synchronized fashion. Various power system phenomena like low frequency oscillation, power system faults, power swings etc. can be easily detected with the technological advancement in the field of Wide Area Monitoring, Protection and Control (WAMPAC) [1]. Power system operators are now able to observe the dynamic change in the electrical grid in real time. The synchrophasor data is received at control center at a rate of 25 phasors per second which is of lesser use to operator until the data is analysed, processed and visualized to provide situational awareness.

Developing a tool which can analyse the vast data for detecting various power system disturbances like faults, generation /load loss will help operator in assessing the situation in real time. This paper is focused on the development of one such tool named as Disturbance Analysis (DA) tool. The tool is designed as an offline tool which can take input data from any number of PMUs in a fixed comma separated value (.csv) format. The input handling in COMTRADE format as per IEEE Std C37.111-2013 [2] is also taken care.

The Paper is organized as follows. Section II introduces the basic framework and knowledge base on power system disturbance analysis using synchrophasor data which was used for the development of the DA tool. Section III explains the algorithms and flowchart for the fault detection, localization and their characterization. While in section IV, the various case studies analyzed using the developed DA tool is discussed. Section V discusses the future challenges in area of development of a full-fledged tool and section VI concludes the paper.

II. Power System Disturbance Analysis with Synchrophasor Data

Power system experiences disturbance continuously which may be broadly classified as generation/load variations and event disturbance. Event disturbances can be sudden generation/load loss, switching of equipment's state and power system faults. Such disturbances result in abnormal change in the system parameters like voltage, current, frequency, impedance etc. Detecting an event and classifying it into normal and abnormal system behavior is a complicated task. At present analysis of system event is either done online using existing SCADA system or it is done offline with data collected by Disturbance Recorder (DR) and Event Logger (EL).

Reference [3] describes the use of various statistical methods to identify the possibility of an event. Such event detection methods will provide the information about the range of data on which a detailed analysis needs to be performed. PMU based fault detection and locations techniques have been discussed in reference [4, 5]. These techniques provide accurate information regarding faults but require PMU's to be located on both ends of transmission line.

The operational experiences of Power System Operation Corporation (POSOCO) provide an insight into the faults/events characteristic as observed from the Synchrophasor data [6, 7]. Various application developments have been discussed in the reference [8, 9]. Based on the experience of Indian grid operators and industry practice the following decision rules are used while analyzing the PMU data manually.

A. *Use of Frequency and Rate of Change of Frequency (ROCOF)*

During power system disturbance such as faults, the net electrical power is not balanced against the net mechanical input power which reflects as frequency change as shown in Fig 1. The change in frequency is governed by the swing equation [10]. The ROCOF can be used to differentiate between normal and disturbed operating conditions. Further ROCOF is also a good indicator of closeness of disturbance from the measurement point. In Fig 2, it can be observed that for a fault close to substation H, highest ROCOF is measured by the PMU located at substation H.

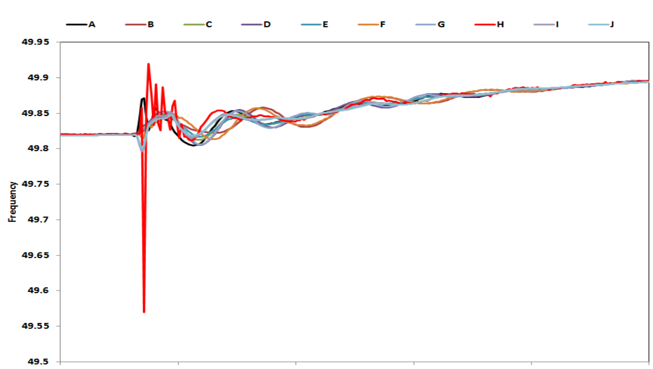

Fig. 1. Frequency change during a fault near to Sub-station H. Maximum variation in frequency observed at near o the fault location

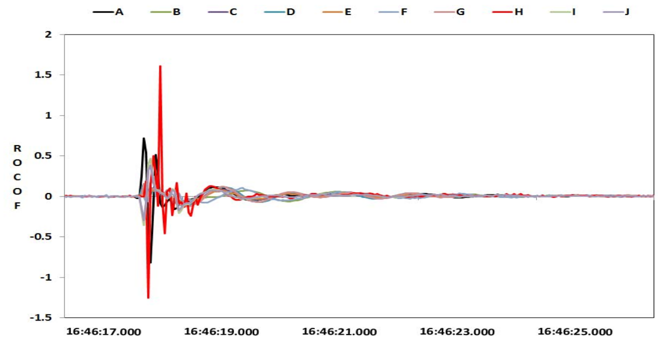

Fig. 2. ROCOF variation during the fault near to Substation H.The Rate of change of frequency also has maximum peak in the PMU located nearest to the fault location.

B. *Use of Voltage Angle Deviation*

With time synchronized nature of PMU data, the voltage angle between two PMU's can be computed with good accuracy and can be used for detecting disturbance. Reference [2,8] discusses the use of change in angular difference for detecting disturbance. In Reference [2] various statistical methods are described. Fig 3 shows the variation of voltage angle during a fault.

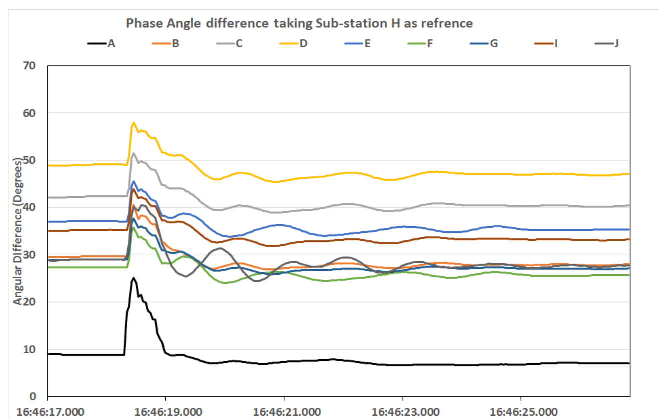

Fig. 3. Voltage angle difference between rest of the sub-stations taking sub-station H as refrence.

C. *Use of Voltage Dip Criteria*

During Faults, a sharp dip in voltage can be observed which can be used to identify the occurrence of a fault. Depending on the phases in which high voltage dip is observed, faults classification is performed. The voltage profile during fault is shown in Fig 4.

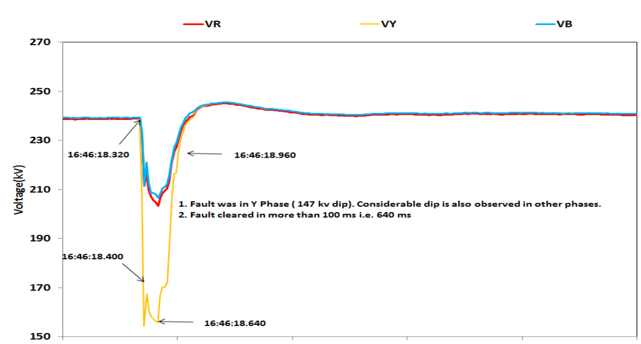

Fig. 4. Substation H bus voltage data

It can be observed from Fig 1 and Fig 2 that during a fault near to sub-station H, the variation in the frequency and ROCOF are maximum at nearest event location and gradually decreases with electrical distance [7]. While from Fig 4 it can be observed that at station H the bus voltage has dipped in the faulty phase compared to other phase voltage. Also depending on Synchrophasor reporting rate, fault clearing time can be calculated which is very useful to verify the protection operation.

These methods have given appreciable results for the manual event detection but they consume lot of operator time. Event analysis tools to detect and classify events are the need of an hour and research is in progress throughout the globe in this area. Automation in terms of developing simple analysis tools are required to minimize the effort put in manual tasks. Following any event, it is the responsibility of the operator to restore the system at the earliest. The valuable piece of information regarding an event, its classification and location can serve a great assistance to the operator.

III. DA TOOL MODELLING AND ALGORITHM FOR EVENT ANALYSIS

DA tool was developed keeping in view of the objectives of detection, characterization and localization of an event. The program control flow of developed DA tool is shown in Fig 5. The offline version of the tool can accept the data in a fixed comma separated value format and is compatible with the IEEE Std C37.111-2013 [2]. The tool also has the capability to analyze the Disturbance Recorder (DR) files in COMTRADE format; however, the discussion in this paper is limited to the PMU data.

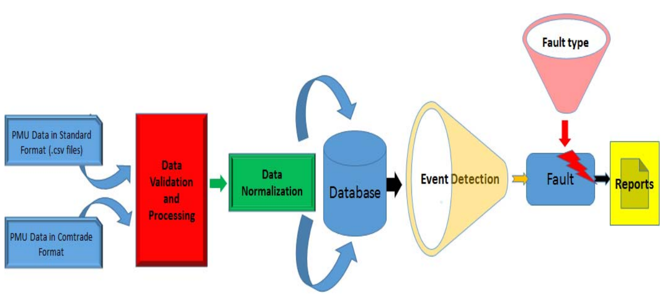

Fig. 5. Program control flow for the DA tool.

Depending on the PMU configuration, the following data sets can be available for each PMU.

1. 1 CT -1 PT
2. 2 CT -1 PT
3. 2 CT- 2 PT

Where, CT refers to three single phase current data; PT refers to three single phase voltage data. The number represents number of feeders/buses from which the data is available. In addition to this, frequency and df/dt data are also available.

The data from the PMU file is first validated and pre-processed before applying the decision rule. The analysis is performed in following sequential steps:

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

A. *Event detection algorithm*

In order to efficiently handle the vast PMU data, analysis is performed based on window algorithms. The window size and movement is user configurable. The objective of event detection is to extract the window information in which there is a possibility of an event. These windows are then used for more detailed analysis using the event classification and localization algorithms.

The analysis consists of three windows (prior, target and posterior) each of length "W" and are separated by certain number of samples defined as detection range "t" [3]. The windowing technique divides the detection range into three ranges of equal duration, a target detection range (t1), a prior detection range (ending t2 seconds before the target range) and a posterior range (beginning t3 seconds after the target range), as shown in Fig 6. The event detection algorithm analyzes these windows for decision rules to confirm the occurrence of event in the target window. The prior and posterior windows are only used to assist the target range.

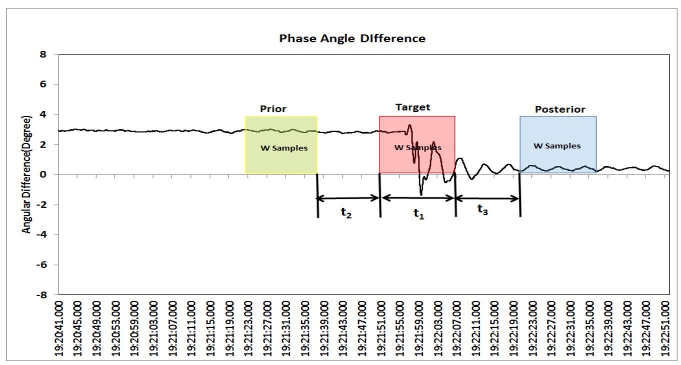

Fig. 6. Window selection for event detection analysis.

Based on literature and operators experience, a single common factor/parameter will not suffice event detection for different system conditions. Various decision rules have been tested and the following rules are found optimum.

1. Variance ratio of ROCOF
2. Threshold check of ROCOF
3. Mean of voltage angle difference
4. Variance of voltage angle difference
5. Voltage magnitude threshold

With "N" PMU data fed to the tool, there exist ${}_{N}C_{2}$ combination of voltage difference. Analyzing all the combinations will be inefficient as most of the PMU pairs may not be in region of disturbance. To simplify this, first reference PMU is fixed which is then used to compute the voltage angle difference with all other PMU's. This limits the number of voltage angle difference pairs to N-1.

The reference PMU is the PMU closest to the disturbance and can be found by using the ROCOF data. As already discussed [7], the ROCOF is found to be highest for the PMU which is closest to the fault. This can be detected using the variance of ROCOF. The PMU file which has the highest variance of ROCOF for the given window duration is considered as the reference PMU for that window. The reference PMU gets updated for every window, which allows the tool to detect events occurring in any location with high accuracy.

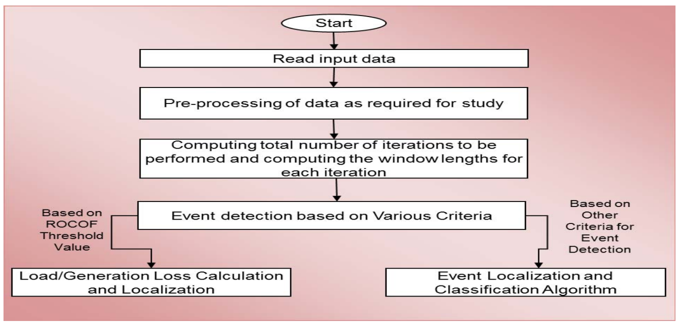

Fig. 7. Event Analysis Flow chart .

The flowchart of event analysis algorithm is shown in Fig 7. It can be observed that for load/generation loss and fault detection, separate algorithms are followed and these two processes are independent of each other.

B. *Event classification algorithm*

Event classification algorithm is applied on those windows where a probability of event has been established. In the initial stage, only fault classification has been developed and can be extended to other types of disturbances.

The classification of an event as a fault is based on the principle of calculating the rate of change of voltage (dv/dt). If the rate of change of voltage exceeds the set threshold, the event is declared to be a fault. From Fig 4 it can be observed that if the fault is on a single phase, voltage dip is observed on the non-faulted phases as well. Hence only dv/dt cannot be used to specify the faulted phase.

In order to detect the faulted phase, a new rule called "dv/dt ratio" is used and is defined as:

P = max (|phase A dv/dt|, |phase B dv/dt|, |phase C dv/dt|)

Ratio A = |phase A dv/dt| / P

Ratio B = |phase B dv/dt| / P

Ratio C = |phase C dv/dt| / P

This ratio is computed for all the three phases when dv/dt exceeds the set threshold in at least one phase. If the ratio exceeds a set threshold, it is declared that the corresponding phase is involved in the fault.

This algorithm can be used to detect 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). After detecting the type of fault, additional parameters like fault initiation time, fault removal time, recovery from fault time and auto reclose status can also be found.

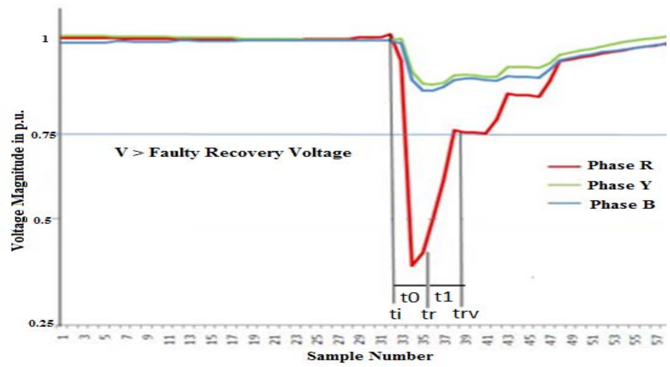

Fig. 8. Fault clearing time.

The accuracy of the various timings related to fault depends on the reporting rate of the PMU which is generally 40ms (can be increased depending on communication bandwidth). The occurrence of any fault is accompanied by the phenomenon of high dv/dt and hence the previous sample from the sample at which high negative dv/dt is detected (more than threshold dv/dt for fault detection) is considered as fault initiation time (t_i) as shown in Fig 8. During the fault period due to action of AVR, a slight change in voltage can be observed and on clearance of fault, dv/dt is again high (more than threshold dv/dt Fault Recover) and hence the previous sample from the sample at which high positive dv/dt is detected is considered as fault removal time (t_r). On removal of fault the voltage tries to recover and the instant at which the voltage is greater than or equal to ">V Fault Recover" is considered as recovery time (t_{rv}). as shown in Fig 8. The fault clearing time and recovery from fault time is calculated as follows:

$$\text{Fault clearing time} = t_r - t_i$$

$$\text{Recovery from fault time} = t_{rv} - t_r$$

The net fault time observed from the synchrophasor data will be the summation of fault clearing and recovery from fault time.

For detection of successful and unsuccessful auto re-closer operation following an SLG fault, the same algorithm for detection of fault is used. In case a second SLG fault is detected on the same phase within auto reclose time from the occurrence of first SLG fault, and then the auto re-closer operation was unsuccessful. Else, the auto reclose action is termed as successful/no auto reclose.

C. *Event localization algorithm*

After the detection and classification of the event has been done, the final step is to localize the event. As PMU may not be present in every substation, it is not possible to detect the exact location of fault. Therefore, the information regarding the localization of fault to an area between two PMU's is done.

For localizing the area in which the fault has occurred, the delta difference data and negative sequence currents is used. The set of PMU within which the delta difference was highest during the event period is the region within which there might have been a fault. The reference PMU which was derived earlier is considered as closest to fault. It is observed that for unsymmetrical faults, the negative sequence currents in the feeders from these two PMU's can be measured and PMU having the highest negative sequence current contribution at the instant of fault can provide the possible direction in which the fault might have occurred. The flow chart for event localization is shown in Fig 9.

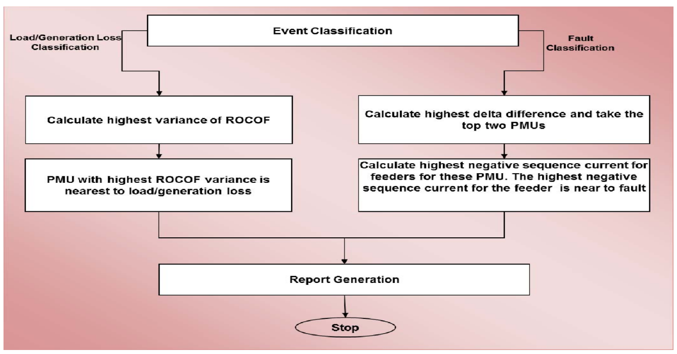

Fig. 9. Event Localization Flow chart .

After all these details and analysis, the results are consolidated in the report format for the use by the opeartor and analyst. The user window of the DA tool developed is shown in the Fig 10.

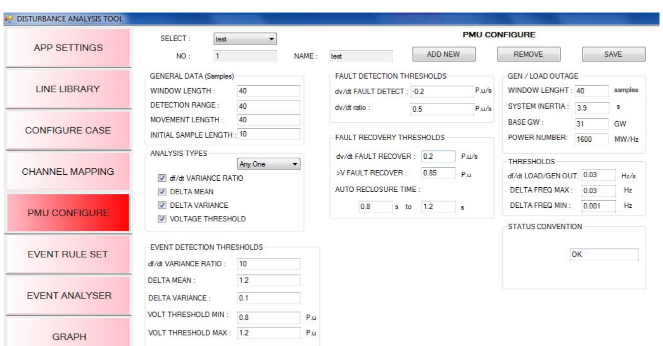

Fig. 10. Snapshot of developed DA Tool .

In the next section case studies have been described based on synchrophasor data analysis using DA tool.

IV. CASE STUDY

The DA tool has been developed keeping in view of the changed scenario of the power system. All the parameters/threshold values are user configurable and as observed it is rule based. The user configured rule set can also be used for event detection. This has made it easier for the operator to use as per his experience. The tool was initially tuned to detect various events and classify and localize the events. Here two case studies analyzed using DA tool are discussed.

A. Single phase to Ground Fault

R phase to ground fault occurred on 400 kV Itarsi Bhopal circuit 2 on 26^{th} February 2014 and A/R did not occurred on the circuit. The phase voltage magnitude as observed from the Itarsi PMU is shown in Fig 11.

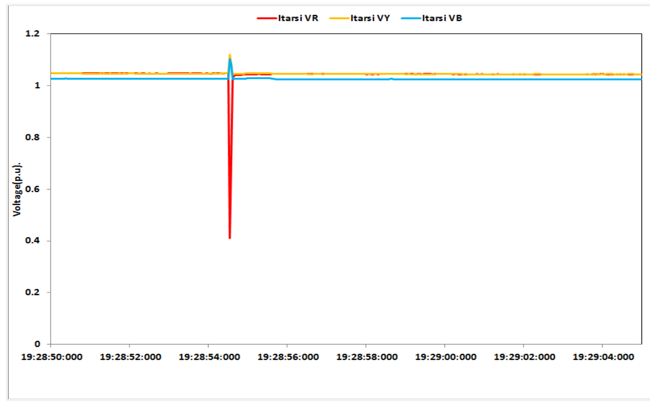

Fig. 11. Bus Voltage of 400 kV Itarsi during R Phase to earth fault on Itarsi – Bhopal Circuit 1.

The data from Bhadrawati, CGPL, Itarsi, Jabalpur, Korba and Raipur PMU's is fed to the DA Tool. The output of DA tool is shown in Fig 12. The analysis correctly predicted the fault location, fault type, A/R activity and fault related timings.

FILE INFORMATION

DESCRIPTION	VALUE
File Names	Bhadrawati,CGPL,Itarsi,Jabalpur,Korba,Raipur
Group Start Time	26 February 2014 19:28:50:0
Group End Time	26 February 2014 19:29:04:960
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
2	26 February 2014 19:28:53:200	26 February 2014 19:28:54:800	R-G Fault	Itarsi-Raipur	Itarsi/Feeder 1	Successful/No Auto Reclosure	OK

LOSS OF LOAD SUMMARY :
No

FAULT TIME DETAILS :

EVENT ID	FAULT INITIALIZATION TIME	FAULT REMOVAL TIME	FAULT CLEARING DURATION (sec)	FAULT RECOVERY DURATION (sec)
2	26 February 2014 19:28:54.480	26 February 2014 19:28:54.520	0.04	0.08

Fig. 12. DA tool analysis for R phase to earth fault on 400 kV Itarsi Bhopal circuit 1 .

B. Phase to Phase Fault

Second case is for phase to phase fault on the Dehgam Gandhar circuit 2 on 8^{th} January 2014 as shown in Fig 13. The data from CGPL, Dehgam, Itarsi, and Mundra PMU's is fed to the DA Tool. The output of DA tool is shown in Fig 14. The analysis correctly predicted the fault location, fault type, A/R activity and fault related timings. This is a special case where fault occurred in the feeder for which PMU data was available (CT of feeder 1 and feeder 2 and PT of Bus 1 are the analog input to the PMU installed at Dehgam) [3]. The result correctly predicts the feeder in the direction of which there is a probability of fault.

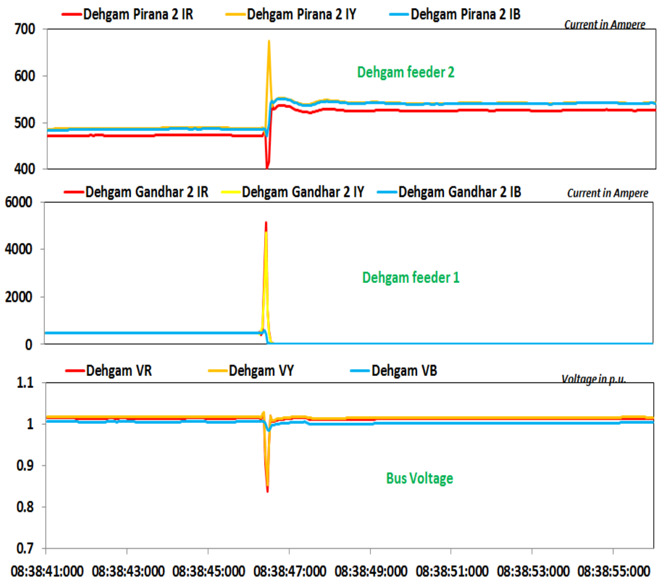

Fig. 13. Bus Voltage of 400 kV Dehgam and Line current of Dehgam Gandhar 2 and Dehgam Pirana 2 during R-Y fault Dehgam gandhar 2 circuit.

FILE INFORMATION

DESCRIPTION	VALUE
File Names	CGPL,Degham,Itarsi,Mundra
Group Start Time	08 January 2014 08:38:41:0
Group End Time	08 January 2014 08:38:55:960
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	08 January 2014 08:38:45:800	08 January 2014 08:38:47:400	R-Y Fault	Degham-CGPL	Degham/Feeder 1	NA	OK

LOSS OF LOAD SUMMARY :
No

FAULT TIME DETAILS :

EVENT ID	FAULT INITIALIZATION TIME	FAULT REMOVAL TIME	FAULT CLEARING DURATION (sec)	FAULT RECOVERY DURATION (sec)
1	08 January 2014 08:38:46.360	08 January 2014 08:38:46.440	0.08	0.04

Fig. 14. DA tool analysis for R-Y fault on 400 kV Dehgam Gandhar circuit 2.

V. Challenges Faced and Further Development

As observed from the previous sections, DA tool provides a good amount of information to operator and analyst after analyzing various PMUs data for event. Yet a lot of challenges are still existing which are as follows:

1. Online implementation of DA tool.
2. Standardization of PMU input format and naming convention.
3. Improving data handling and storage requirements for optimum utilization of resources.
4. Unreliable data in PMU data stream can trigger the various algorithms which can give false indication about the event. Handling such situation optimally is a challenge.
5. To classify event occurring due to high impedance or fault far from PMU location.
6. To classify loss of load/generation related events and to predict the quantum of power loss.
7. Improving the algorithm for verification of auto re-closure operation.
8. Opening of transmission line due to over voltage operation or maintenance condition.
9. HVDC tripping or HVDC charging.
10. Use of Digital status from the PMUs for improving fault analysis.
11. Correlating Disturbance recorder and Synchrophasor analysis from the DA Tool.

These are few of the major challenges authors are working on in order to develop a better solution which will further enrich the real time operator.

VI. Conclusion

This paper has discussed the disturbance analysis tool development in India which is capable of analyzing synchrophasor data for event detection. This is one of the first tools which have been developed to detect the event, characterize it and finally localize the affected area. This tool 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 tool so as to make it more robust, optimum computational time and processor usage.

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