PMU Data Based Post Disturbance Analysis for a Large Grid Using Wavelets and Lyapunov Exponent

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***Abstract*—SCADA systems that are used nowadays for the monitoring purpose of power system are becoming inefficient for dealing with many specific problems happening in the grid. The post disturbance analysis cannot be efficiently done using the SCADA. The introduction of PMU technology provides a greater perspective about the grid monitoring and post event analysis. The disturbances that have affected the power system can be thoroughly studied and analyzed using the high reporting rate of the PMU. This helps in modifying the existing power system to a more stable system. The classification of the faults based on the signature patterns associated with each disturbance can be done with the help of PMU data. Signal processing techniques like wavelet transforms are used for this signature identification and classification. The scope of post disturbance analysis can be increased by using Lyapunov Exponent based transient stability studies for visualizing the stability variations during an event.**

***Keywords*- Supervisory Control and Data Acquisition System (SCADA), Phasor Measurement Unit (PMU), Phasor Data Concentrator (PDC), Wavelet Packet Transform (WPT), Fault Monitoring, Pattern Recognition, Lyapunov Exponent(LE)**

I. INTRODUCTION

The use of Phasor Measurement Unit (PMU) for monitoring and control of power system has been increasing over the years. The present SCADA based technology cannot be used for the dynamic visualization of fast events occurring in the power system. The PMU technology based offline and online analysis has caused a paradigm shift in the power system operations.

The need for post event analysis in large power grids is very important as far as power system operations are concerned. Many incipient problems can be diagnosed in the root itself. The probable result of not doing these analysis will have catastrophic effects on the power system [1].

Various research works in the area of PMU based disturbance analysis and location have been reported in the literature. The transmission line impedance based fault location in large power system is presented in [2]. The fault detection based on PMU signal analysis using Fast Fourier transform (FFT)and equivalent phasor angles is presented in [3].

Preliminary works for identifying singularities in the power system have been done using the Discrete Fourier Transform (DFT) and Short Time Fourier Transforms (STFT) techniques. The multi-resolution Discrete Wavelet Transform (DWT)technique has better results compared to the above two methods. The various wavelet based feature analysis techniques reduces the issues present in the STFT and are more reliable and accurate in identifying the nature of a non stationary signal [4], [5].

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The efficient data archival reduction methods can be implemented using a variable length sliding window algorithm. During the occurrence of the event inconsequential information can be reduced as well as minimum loss of information can be assured [6].

The Wavelet Packet Transformation (WPT) offers a finer decomposition in the high frequency components also. A suitable criterion can be chosen for decomposition and the coefficients can be obtained for desired levels of decomposition . Many statistical features can be computed using these coefficients and the unique feature for the disturbances can be extracted out of these [7].

The high resolution PMU data can be used to provide reliable, timely information about the system's stability. The Lyapunov Exponent (LE) serves as a certificate of stability where the positive (negative) value of the LE implies exponential divergence (convergence) of nearby system trajectories, hence, unstable (stable) rotor angle dynamics [8].

Transient stability status of a power system after being subjected to a severe disturbance with precision and speed so that the overall grid is secure. Implementation of an emergency control scheme against transient instabilities based on early prediction should be established for the system stability [9].

This paper proposes a new system for analyzing the PMU data and monitoring power system faults with minimum operator skill so that the post event information can be identified and handled effectively in the Load Dispatch Centers. Wavelet based signal processing methods with the intelligence of the fuzzy based classifiers to extract all the features in the PMU data is proposed. Then the system can be trained to classify the fault based on the knowledge already built in to the expert system through extensive training.

The structure of this paper is as follows. Section II provides the introduction to PMU, various PMU applications and the introduction on the proposed system. Section III explains techniques used for the analysis of the PMU signal. In Section IV, the feature extraction and classification algorithms are discussed. The algorithm validation using IEEE standard 14 bus system is explained in section V. Section VI comments on the simulation results obtained and output of the final expert system developed.

II. PHASOR MEASUREMENT UNIT(PMU)

Universal time synchronized data at a very high reporting rate can be obtained using the PMU technology. Time synchronized wide area data is required to have an accurate view of a large power grid. PMU produces the synchronized estimates of voltage phasors, current phasors and sequence component phasors, frequency and rate of change of frequency (ROCOF) from voltage and current measurements. Apart from these many analog and digital values are also estimated. These PMU report to the Phasor Data Concentrator (PDC) which act as a node in the power system.The PDCs will be situated in the Regional Load Despatch Centers (RLDCs) where the various event data are stored.

A. PMU Application

PMU has many applications as categorized in Fig. 1. These applications can be used to a high extend in power systems. The offline application of post disturbance analysis is used for studying the signature patterns of the disturbances that has been recorded. Synchrophasor technology enables fast and accurate reconstruction of the sequence of events that are of importance. The high reporting rate of PMU enables wide area monitoring of changes in voltage, frequency and occurrence of other oscillations.

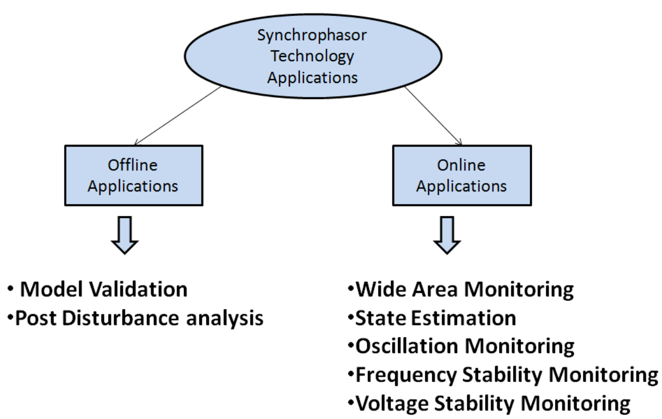

Fig. 1. Applications of PMU

B. Proposed System

This paper focuses on building a system to identify various disturbances in the power grid. The system will be able to classify the different disturbances and faults that occur in the grid. The Transient stability in each case can be visualized by the change of LE waveform pattern. The system can also find out the approximate origin of the disturbance.

The developed algorithm were validated using 14 bus standard IEEE bus models simulated in MATLAB Simulink. Later on the real PMU data for various events are obtained from the Southern Regional Load Despatch Center, India (SRLDC) and the system was validated.

Transient stability analysis were carried out using the load angle information obtained from the PMU data. A new analysis methodology using the Lyapunov Exponent was proposed to analyse the transient stability condition. This serves as a good technique at the time of postmortem analysis of the event using the PMU data. The variation of the Largest Lyapunov Exponent (LLE) will be negative in the case of transiently stable systems. The LLE values of some of the PMUs will be positive in the case of transiently unstable system.

III. ANALYSIS USING WAVELET BASED TECHNIQUES

Time- frequency localization is an important feature of wavelets. The high frequency signals can be expressed with good time localization and the low frequency signals can be expressed with good frequency localization.

Wavelet can be assumed to be a band pass filter. By using high pass and low pass filtering methods, the signals can be decomposed into several frequencies. Taking the convolution between the function and the scaling function, the condition when the expression is tending to zero can be analyzed. It shows that using Wavelet transforms sharp impulse type of transients also can also be detected

$$lim_{a\to 0}\phi_a\left(t\right) = (1/a)\phi\left(t/a\right) = \delta\left(t\right) \tag{1}$$

By shifting and dilation of the mother wavelet $\psi(t)$, every signal can be represented as a linear combination. The representation of mother wavelet in the two-scale difference equation is [5],

$$\psi\left(t\right) = \sum_{k} d_k \hat{\phi}\left(2t-k\right) \tag{2}$$

Here d_k's are the decomposition coefficients. So, the normalized Continuous Wavelet Transform (CWT) can be represented as,

$$(W_\psi f)(b,a) = \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{a}}\psi(\frac{t-b}{a})\,dt \tag{3}$$

here, a and b are the scaling (dilation) and translation (time shift) constants [4].

The Discrete Wavelet Transform (DWT) is given by,

$$(W_\psi f)[m,n] = \sum_{k} f[k]\frac{1}{\sqrt{a_0^m}}\psi(\frac{n-k_0^m}{a_0^m}) \tag{4}$$

where, $f[k]$ is the sampled waveform, $a = a_0^m$ and $b = ka_0^m$ are the discretised parameters of scaling and translation respectively [4]. DWT is very suited to multi-resolution analysis of finite length discrete signals.

The DWT offers decomposition only in the low pass filter region.Taking into consideration the decomposition in the high pass filter region, Wavelet Packet Transform (WPT) is preferred for this application [6].

WPT offers information in both low frequency and high frequency regions of this signal. This wide range of frequency information can be utilized efficiently for the PMU signal analysis. For a signal f the Wavelet packet coefficients can be computed as,

$$w_{a,n,b} = f < a, n, b >= \int f(t) W_{a,b}^{n}(t)\, dt \qquad (5)$$

here, n is an oscillation parameter.

For all the disturbance that is being analyzed, each one will have a particular signature associated with it. The Wavelet having the highest correlation with the disturbance signals should be taken as the mother wavelet. The energy correlation comparison of different wavelet families are shown in Fig. 2.

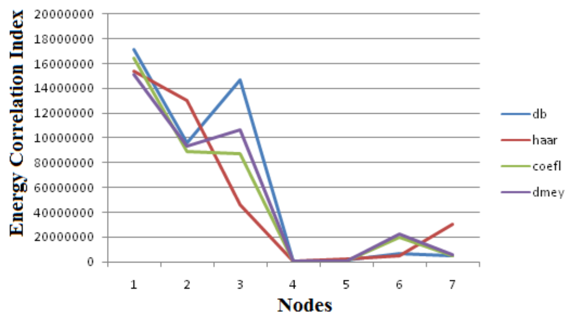

Fig. 2. Energy correlation comparison of different wavelet families

The Daubechies wavelet was used as the mother wavelet for the wavelet packet transform. Major faults and disturbance signals were analyzed in detail, the Daubechies family of wavelets were found to be the best suited one among the Wavelet families and Daubechies 8 (db8) was taken as the mother wavelet by analyzing the condition of vanishing moments.

Each coefficients that are obtained after decomposition using WPT can be expressed as

$$w_{a,n,b} = f < a, n, b >= \int f(t) W_{a,b}^{n}(t)\, dt \qquad (6)$$

Direct assessment from these individual coefficients will be tedious and not an efficient way of extracting signal information. So, some features lying inside the WPT coefficients are extracted for analysis.

IV. Feature Extraction and Classification

The PMU sends many measured parameters. It is very important to choose the best parameter that can represent a fault. Most of the time, it may not be just a single parameter alone which will be used for identifying a disturbance. Observing the nature of the parameter variation with disturbance, it can be seen that the voltage phasors, frequency and the sequence components are some of the crucial parameters which reflects the nature of disturbances.

The event data of various disturbances that have occurred is decomposed using WPT. Shanon entropy criterion upto 3rd level is used for this decomposition. The decomposition tree of a typical SLG fault that have reported is shown in Fig. 3.

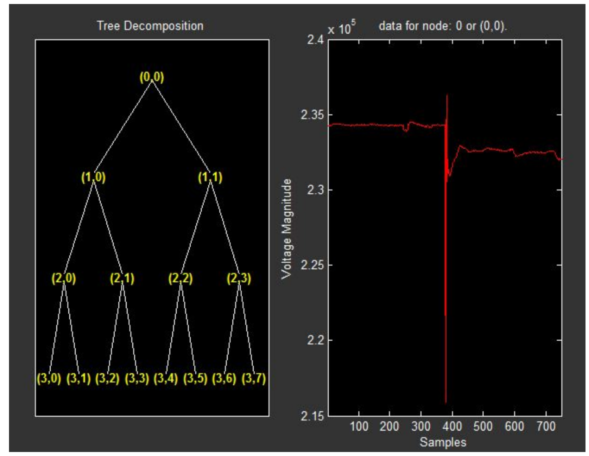

Fig. 3. Wavelet Packet Tree decomposition of the SLG fault data

Using these decomposition coefficients obtained, statistical features like Mean (μ), Standard Deviation (σ), Energy (ED) and Entropy (ENT) of the signal can be calculated. The algorithm for the feature extraction using WPT coefficients is shown in Fig. 4.

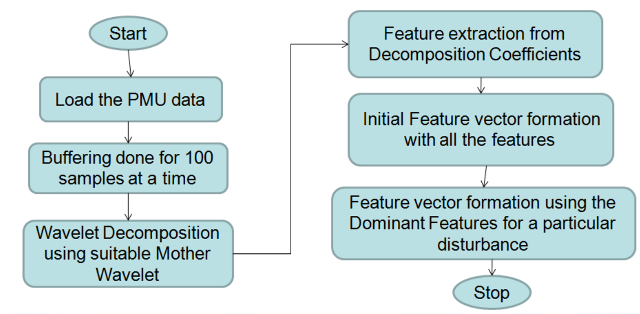

Fig. 4. Algorithm for Feature Extraction

Many sets of event signatures are analyzed and the extracted features are stored in a feature vector that will have the dominant features of the most affected PMU. Feature vector corresponding to each particular event will be stored and will be used at the time of classification. The feature vector reflects on the signature of the actual PMU disturbance.

The event data that needs to be analyzed is passed into the system which contains all the feature vectors. The same process of feature extraction is carried out and the obtained feature matrix of the event is compared with the stored feature vectors. The classification of this is made using the fuzzy nearest neighbor algorithm which works on the closeness to the measured value expressed in terms of Euclidean distances. The feature vector matrix is trained with many number of disturbance cases, the correlation between these with the unknown data can be used to execute this algorithm. Fuzzy nearest neighbor algorithm searches the k training samples that are adjacent to the unknown sample given for the classification process [7].

Apart from the classification of the signals the location of the origin of the disturbance and the magnitude of the loss suffered by the grid were also predicted along with the classifier algorithm. The location of the most affected PMU indicates the approximate origin of the disturbance. The frequency number of the grid was obtained from the load despatch center and the power loss or load loss was approximately calculated based on frequency variation in the grid. This will be very useful for the operators to have an idea about the unit generator that has tripped. The algorithm for the same is given in Fig. 5.

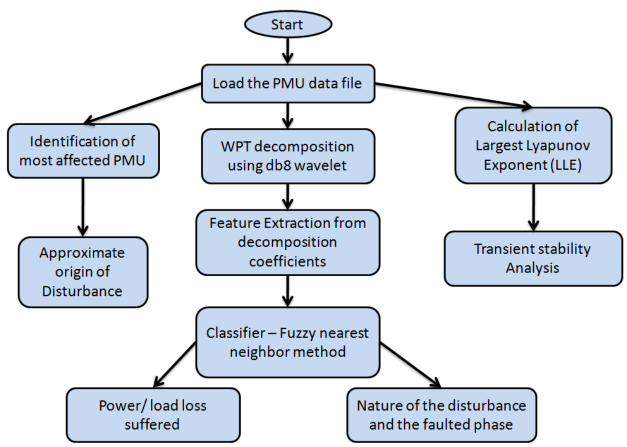

Fig. 5. Algorithm for Feature Classification

V. Validation with IEEE 14 Bus System

Many of the disturbances happening in the power system is very rare, hence not all the events can be checked in the algorithm using the actual data. In order to validate the algorithm for all the cases happening in the power system simulated models of IEEE 14 Bus system is considered. All the disturbances are tested in this system at different positions and the results where verified using the GUI developed in MATLAB.

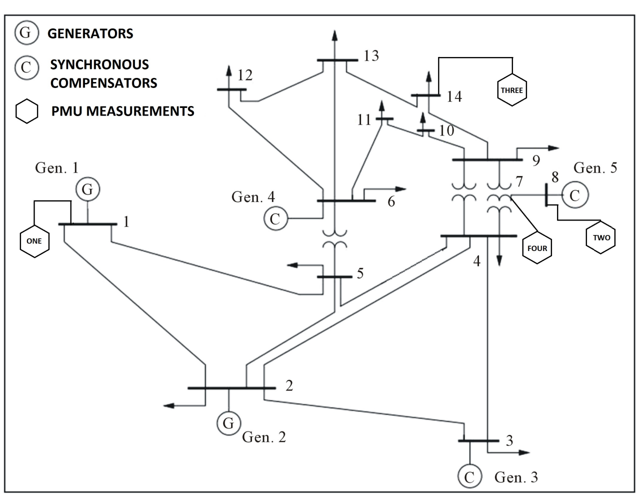

Fig. 6. Standard IEEE 14 Bus system

Fig. 6 shows the single line diagram. The 14 Bus System consists of 14 buses (nodes), 5 generators, 11 loads, 16 lines, 5 transformers and one shunt.

Different types of faults were simulated at different parts of the system and measurements similar to the PMU measurements were taken from four different parts of the grid named one, two, three and four. The measured values are stored in csv format files. These files were tested using the developed program. The program was able to classify the type of disturbance simulated. A 3 phase fault was given near bus 7 and bus 9. The results obtained using the developed system is shown in Fig. 7 and results are very much satisfactory.

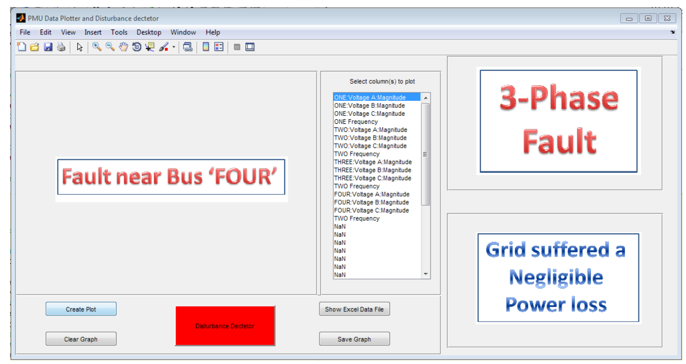

Fig. 7. GUI output for simulated fault condition

VI. Results and Discussion

The Algorithm gave accurate results for all the events simulated. Actual PMU event data obtained from load despatch center was analysed using the developed algorithm. The results obtained during the analysis of transient stability, feature extraction and classification has been discussed.

Lyapunov exponent characterizes the rate of separation of infinitesimally close trajectories. It is common to refer to the largest one as the Largest Lyapunov exponent (LLE), because it determines a notion of predictability for a dynamical system. A positive LLE is taken as the indication that the system is chaotic. The positive or negative value of LLE implies exponential divergence or convergence of nearby system trajectories. System stability can be predicted based on the variation of LE.

The LLE at time $\lambda_i^R(k\Delta t)$ is given by,

$$\frac{1}{Nk\Delta t}\sum_{m=1}^{N}\frac{log|\theta_i^R((k+m)\Delta t)-\theta_i^R((k+m-1)\Delta t)|}{\theta_i^R(m\Delta t)-\theta_i^R((m-1)\Delta t|} \tag{7}$$

Here, θ_i^R is the relative angles calculated from the PMU data, n is the number of generators, Δt is the sampling period and N specifies the initial conditions [8].

The load angle data directly obtained from the PMU cannot be used for the transient stability analysis. The relative load angle is calculated from load angle variation keeping a PMU as reference. The relative load angle variations of a SLG fault in the grid is shown in Fig. 8.

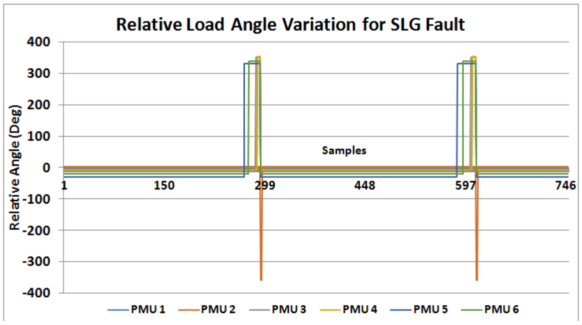

Fig. 8. Relative load angle variation from the grid

The Largest Lyapunov Exponent(LLE) values are calculated based on these relative angle measurements. The graph obtained in Fig. 9 shows that the system is stable as no LLE value positive.

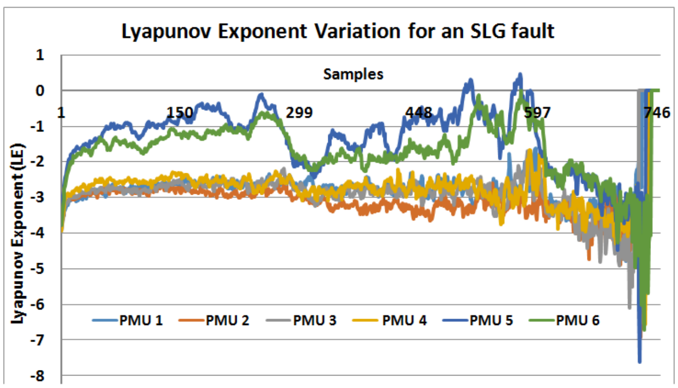

Fig. 9. LE variation for the disturbance occurred

The relative load angle variations of a generator tripping in the grid is shown in Fig. 10.

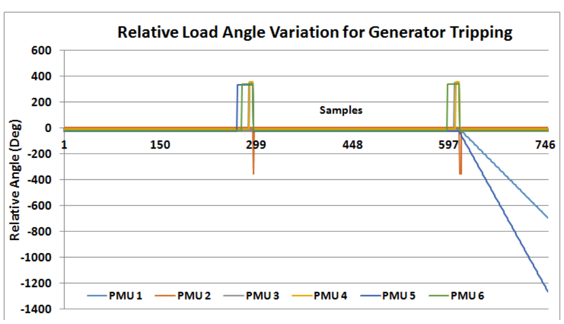

Fig. 10. Relative load angle variation from the grid

The LLE values are calculated based on these relative angle measurements. The graph obtained in Fig. 11 shows that the system is unstable as two of the LLE values are positive.

The features like the energy entropy standard deviation and mean were calculated from the decomposition coefficients. The characteristics of the features for different disturbances showed distinct differences. The faulted phases could also be easily identified in all cases. The node energy variation for an

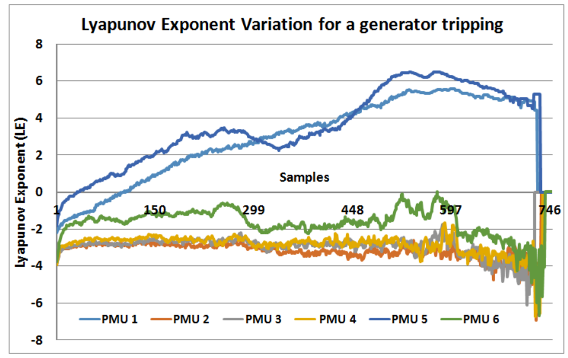

Fig. 11. LE variation for the disturbance occurred

actual Single line to ground fault (SLG) is shown in Fig. 12. Energy 1,2 and 3 corresponds to the energy of the R,Y and B phases respectively.

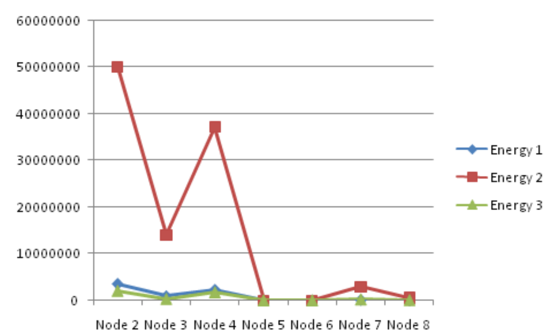

Fig. 12. Node Energy feature of the SLG fault data

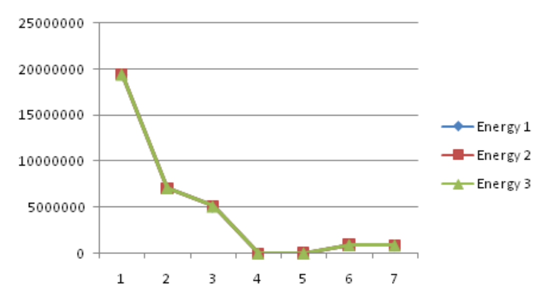

Fig. 13. Node Energy feature of the generator tripping data

If only the voltage phasor data of PMU is analyzed, the unsymmetrical faults can be easily identified and localized but for disturbances like generator tripping, 3 phase faults, load throw off and special protection scheme action , the features of disturbance are in the similar fashion. In Fig. 13, The energy feature of the generator tripping condition is very similar to a 3-phase fault occurring as shown in Fig. 14.

Other PMU data such as the sequence components and the frequency can be used to extract the feature in such cases. These features are taken for the formation of the feature vector

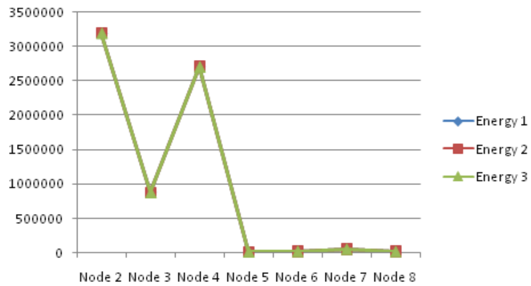

Fig. 14. Node Energy feature of the 3-phase fault data

matrix. Other dominant features can be identified and can be used for higher accuracy. The reliability of the results can be improved by analyzing more number of PMU fault data occurred at different points and at different network conditions.

A. Analysis Tool Developed

Incorporating the Transient stability, fault classification and localization, a disturbance detection tool has been developed in MATLAB. The 'Disturbance Detection' button in the GUI shows all the corresponding analysis of the event data fed into the system. The system accepts the comma separated value (.csv) data of events stored in the historian of load despatch centers.

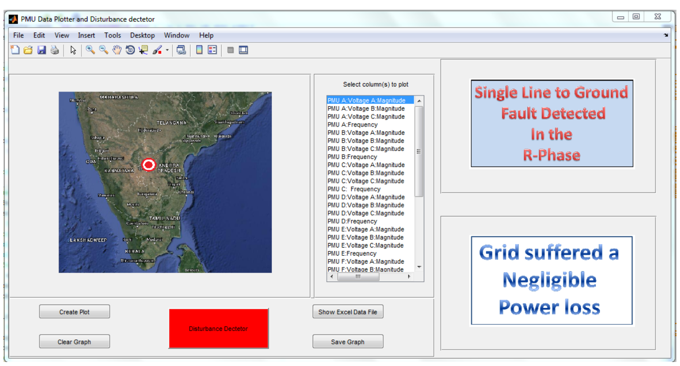

Fig. 15. GUI output for an actual SLG fault suffered

The output of the GUI in the real cases of an SLG fault and Generator tripping condition are shown in Fig. 15 and Fig. 16 respectively. The approximate location of the fault, the nature of the fault, the phase in which the fault occurs and the power loss suffered are indicated in the GUI output. The frequency number of the Indian grid is 6000, the power loss suffered below 200 MW are considered to be negligible considering the total connected load.

VII. Conclusion

A novel feature based offline system for disturbance detection and classification including transient stability analysis have been developed. The algorithms were executed and validated using the PMU based measurements that have a noticeable advantage over the present SCADA technology.

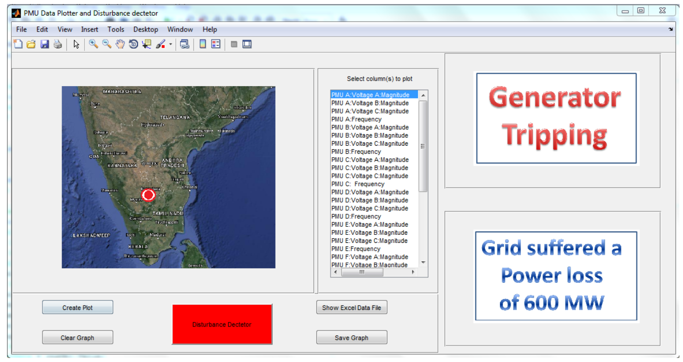

Fig. 16. GUI output for an actual generator tripping suffered

The dynamic visualization of high frequency events that have occurred in the grid can be analyzed and the root cause can be found out. The operators in the despatch centers can use this to analyze and study the overall system condition with very less manual expertise. The likely result of not doing these analysis may result in a fault in the grid or a significant machine damage. The use of Lyapunov Exponent for the transient stability analysis proves an effective methodology for accurate identification for the stability of the system. The developed system hence provides a total solution in the area of post event analysis in power system.

VIII. Acknowledgment

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