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PHASOR MEASUREMENT AS A NEW APPLICATION OF DISTURBANCE RECORDERS

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ABSTRACT

Phasor Measurement (PM) has proven to be the vital source of data necessary for many applications in Power System Real Time Wide Area Monitoring, Control and Protection (RT WA MCP). Several Utilities already use Phasor Measurement Units (PMU) as a separate device to collect system-wide data required for disturbance analysis, security monitoring and emergency control.

This paper examines the capability of the microprocessor based Disturbance Recorders (DR) to include the PM function. Both technical and economical adequacies of these recorders to perform the PM function are discussed. Some additional technical requirements to be considered by the DR manufacturers are explained to make the phasor measurement's technical specification of their disturbance recorders satisfy the requirements of these applications.

The paper illustrates also how the phasor data obtained from DR's that installed at different locations in a Power System (PS), is used to display the voltage phasors (amplitude and angle) beside the system frequency variations during different real operating PS states.

Keywords: *Phasor Measurement, Disturbance Recorders, Real Time Wide Area Monitoring Control and Protection, Phasor Data Accuracy, Phasor Display*

1. INTRODUCTION

In the last few years, there are some international changes and facts contributing to threat the power system operation. Among these changes and facts are:

- The deregulation of electricity industry
- Competition markets
- Gradual growth of consumption
- Restricted expansion
- Environmental constraints
- Aging of equipments
- High reliability requirements
- Increased energy trading due to international interconnection
- The tremendous cost of blackouts or brownouts

The assurance of power system stability and reliability under these threatening conditions has resulted in the need for new concepts and techniques for power system monitoring, control and protection. These concepts and techniques use the real time phasor measurement data as an essential tool for power system real time wide-area monitoring, control and protection applications.

Lessons learned from the analysis of large systems' blackouts indicate the importance of the operator awareness of power system states. The measurement of voltage phasors at different busbars in the power system, and displaying them to the system operators is a big contribution to the operator awareness of the power system status. The phasors data captured during power system disturbances could be useful in post-nortem analysis and in both off-line and on-line power system studies. They also could be used for better state estimation functions, and model validation.

Since the early 80's, when the microprocessor based disturbance recorders were introduced, and as the price of the computer memory continued to decrease, these recorders became less expensive and found wide applications within power systems.

New functions continued to be added to these recorders. Nowadays, beside fault recording function, they include dynamic system monitoring functions, power quality monitoring features ...etc. These recorders sense and digitally record data occurred prior to, during and after disturbances or any system changes detected by their triggering functions. They have also the capability to create virtual channels which can help the PS disturbance analysis, and also allow programmable triggering of the recorder.

The state-of-the-art of these disturbance recorders permits the data captured by them to be used to evaluate the power system status in its different states of operation, i.e normal, alert, emergency, extremis and restoration states. These devices provide useful data for the analysis of power system disturbances including transients, dynamics, power quality…etc.

The microprocessor based disturbance recorders are permanently connected to, and scattered within the power system. Adding the function of phasor measurements to them will make easy attaining phasor data all over the system. This will also reduce cost as it saves installation of new phasor measurement devices. Extra saving is expected knowing that many of these devices are connected to local and wide area computer networks, and also are equipped with Global Positioning System (GPS) time synchronization.

This paper introduces and examines the phasor measurements as a new application of the disturbance recorders. The technical and economical adequacies of the disturbance recorders to provide the phasor measurement requirements for real time wide-area monitoring, control and protection is discussed. The paper also illustrates, using actual recorded cases, how the voltage phasors at different substations in a real power system during different operating states can be presented to the system operator.

2. THE IMPORTANCE OF PHASOR MEASUREMENTS

The analysis of the large systems blackouts during the last years have pointed out the need for the function of real-time wide area monitoring, control and protection. Phasor Measurement is considered as the backbone of the applications assigned for this function. In fact, the voltage phase difference within the electrical network grows as the system weakens. Early recognition of the widening phase difference may allow remedial actions to be taken which help the restoration of the system stability before a catastrophic incident occurs.

The RT WA MCP applications include several functions such as:

- Real Time phasor displaying
- On-line studies
- Power system state estimation
- Power system stability monitoring
- Real time control

- Adaptive relaying applications
- Post-nortem analysis
- Fault location
- Off-line studies
- System planning
- Modal validation

By using known measured phasor values between two nodes of a system, as opposed to values generated using theoretical studies, it is possible to determine the true phase relationship and accurately calculate steady state limits at which the system will remain stable. At the same time, it is also possible to verify the models used in the analysis software (S/W) programs.

It worth mention that the North American Reliability Council (NERC) cited in their documents the following objectives for Disturbance Monitoring System [1]:

- Determining the performance of system components.
- Analysis of the nature and cause of a disturbance.
- Identifying equipment misoperations.
- Identifying causes of oscillations.
- Analysis and correction of protection systems and control deficiencies.
- Reducing the risk of recurring misoperations.
- Gathering of modeling data to verify the relevant characteristics of the models and parameters used in simulation programs.

Some of the above mentioned objectives can be fulfilled by waveform recording of analogue values (voltages and currents) for short time, but others need long time RMS values recording. Besides that, recording of status input is necessary for complete analysis.

3. GENERIC REQUIREMENTS FOR PHASOR MEASUREMENTS

Figure 1 shows the primary Hardware elements of a synchronized phasor measurement system.

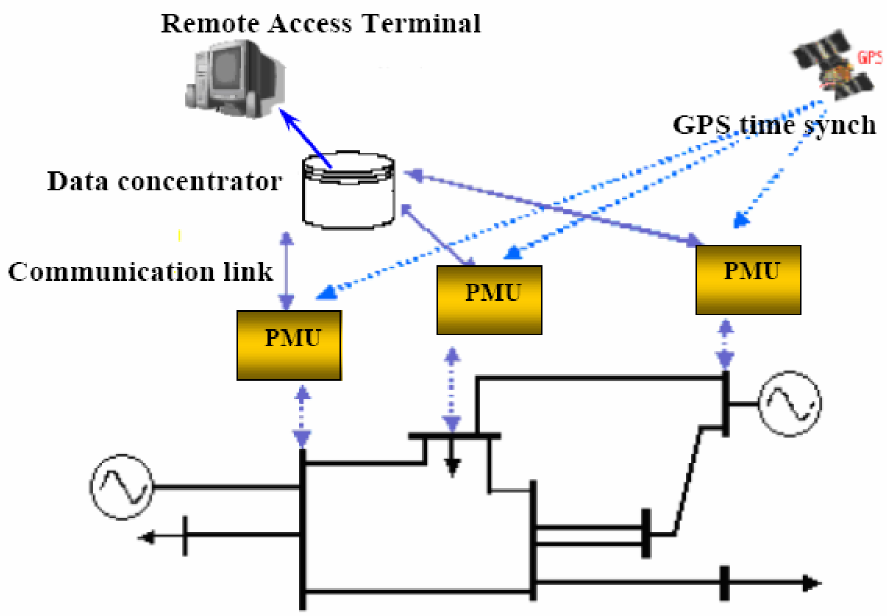

Fig. 1: Phasor Measurement System

The Consortium for Electric Reliability Technology Solutions (CERTS) has highlighted the following phasor data requirements for RT WA MCP applications [2]:

Event Triggering is recommended if continuous recording is not available
Triggers are necessary such as:

- Over/under frequency
- Major facility tripping
- Severe voltage disturbance
- Sudden power flow changes on critical facilities, and
- Manual triggering

Minimum Recording Time for typical unstable event lasts for 1-60 seconds or longer, so:

- The minimum recording time of 30 sec for recorders with sigle event recording capability is required, but
- 5 minuets for triggered events is preferred

Pre-disturbance Recording Time for a minimum of 10 sec is essential, and 60 sec is preferred

Wide Area Monitoring Systems (WAMS): Instability events involving wide-spread area include oscillations and control interactions between utilities. So, multiple PMU's at PS key locations are required.

Time Synchronization: The use of Global Positioning System (GPS) time synchronization is mandatory for time correlation to provide meaningful data.

Data Retrieval: Central archive system for data retrieval is preferred to have data from all recorders following regional disturbance systematically.

4. REALIZATION OF PHASOR MEASUREMENTS

Implementation of phasor measurement function can be achieved using different Intelligent Electronic Devices (IED's) such as:

1. Separate Phasor Measurement Units (PMU's)
2. Protective Relays
3. Disturbance Recorders
4. Fault Locators
5. Remote Terminal Units (RTU's)

Among these devices, for PM implementation, we will examine the Disturbance Recorders as a candidate.
In the following section, we will discuss the generic requirements for RT WA MCP mentioned in section 3 above, and illustrate how the disturbance recorders are capable to meet these requirements from both technical and economical points of view.

4.1 DR Technical Adequacy

Continuous recording
Although the traditional function of the disturbance recorders was waveform recording for voltages and currents within the protection operating times, the use of microprocessor based technology made easy the recording of slow system incidents which last for long times. Digital Monitoring Recorders include beside Digital Fault Recording (DFR) function, slow scan recording features, which can be either triggered or continuous.

While the sampling rate for DFR is more than 100 samples per cycle which is necessary for wave form recording, the slow scan quantities are calculated on cycle-per-cycle basis and

continue for longer time periods of up to 10 min. for triggered slow scan, or which may expand to several days or a month for continuous slow scan.
Moreover, due to the continuous decrease of the industrial computer memory price, the number of values (traces or channels) which can be recorded continuously may reach 32 quantities for a time period of days or even a month.

Event triggering

Disturbance recorders have a variety of triggering possibilities such as: threshold, rate of change, window, and oscillations. Moreover, S/W triggers are available using combined analog calculated quantities, or even a criterion of mixed analog and digital (binary) quantities. In fact, this type of triggering is very suitable for detecting and recording all possible power swings either stable or unstable. Digital input status channels can also trigger the device when facilities change their status. Manual triggering is also available. Disturbance recorders with all these means of triggering can record any type of power system disturbances: transients, dynamic, status change or even power quality problems.

Minimum recording time

In reference [2], it is recommended to have at least 5 minutes recording time for triggered events. Nowadays, disturbance recorders may have 10 minutes recording time for these events which is more than enough to capture the prolonged PS incidents.

Pre-disturbance recording

The pre-disturbance recording period for slow scan triggered events, in modern DR's, may reach 5 minutes period compared with only 1 minute required in [2].

Data retrieval

Disturbance recorders installation, as shown in Fig.2, has central master station to collect disturbance data from all recorders after a regional disturbance and can archive them.

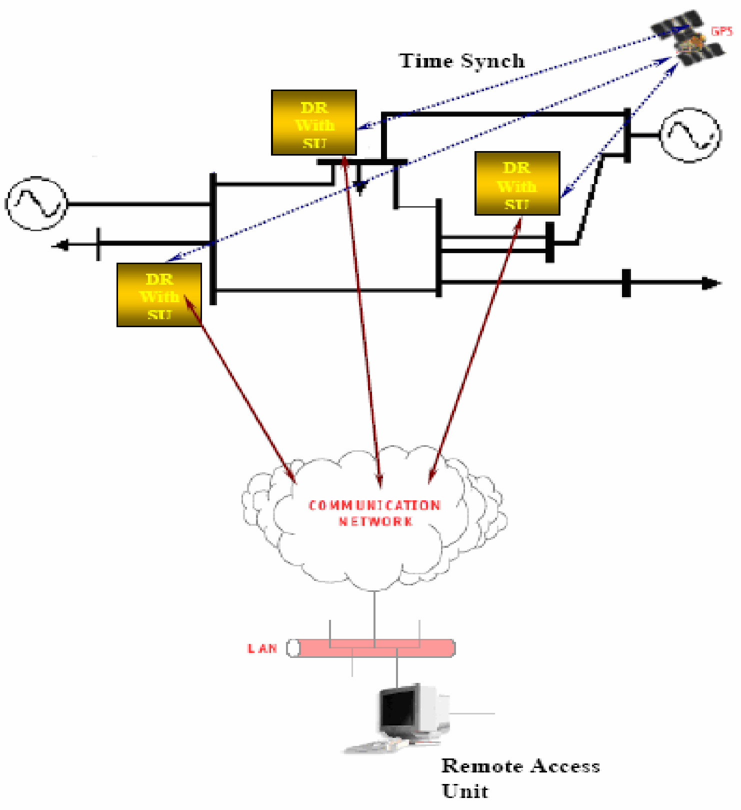

Fig. 2: Disturbance Recording System

4.2 DR Economical Adequacy

The master station existing in typical disturbance recorder installations (Fig.2) is connected to all recorders at different locations via a Wide Area Network (WAN) to collect the GPS synchronized data for further analysis purposes.

Wide area monitoring
Most transmission substations selected for synchrophasor data collection are already equipped with digital fault recorders. Utilizing the existing digital fault recorders (DFR) offers several economical advantages to the utility:

- Less expensive DFR upgrade than purchasing new PMU equipment
- Less expensive installation since the existing field wiring and PT/CT circuits are used

Time synchronization
Majority of existing DR installations, especially at the important locations are equipped with GPS time synchronization. So, no additional cost for GPS is required.

Although protective relays are capable of using these synchronizing signals, and providing phasors of voltages and currents, which can be used in several monitoring, protection and control functions in a power system, protective relays could not be burdened with the PM requirements such as triggering functions, minimum recording time, pre-disturbance recording duration, slow scan records,…..etc. Also, other devices such as RTU's or Fault Locators need these functions to be added to them. The addition of such functions to these devises means a drastic change in their architecture, which needs development and extra cost.

5. ADDITIONAL REQUIREMENTS

Disturbance Recorder's manufacturers have to take into consideration the following phasor measurement requirements for the different applications of real time wide area monitoring control and protection.

Sources of Errors in Phasor Measurements
Synchronized phasor measurements applications such as state estimation and out-of-step relaying require phasor estimation errors on the order of tenth of a degree [3]. Typical sources of these errors [4] include GPS transmitters and receivers, instrument transformers, and phasor estimation devices. The errors from these devices can be divided into two categories:

- Time synchronization errors, which are determined by GPS transmitters, GPS receivers, and phasor estimation devices.
- Data acquisition errors, which are determined by instrument transformers and phasor measurements devices.

These errors and typical corresponding values that must be considered in these applications are:

Error Source	Time Error	For 60 Hz	For 50Hz
Time synchronization,	±1 μs	$\pm 0.0216^o$	$\pm 0.018^o$
Instrument transformers,	±14 μs	$\pm 0.3^o$	$\pm 0.252^o$
Phasor estimation devices	±5 μs	$\pm 0.1^o$	$\pm 0.09^o$

PT, CT accuracy
Instrument transformers are the main contributors to synchronized phasor measurement error, as shown above. For phasor measurement, the phase value is very important. For predicting stability or control of oscillations, accuracies of plus or minus one tenth of a degree should be

adequate. In some cases, accuracies of plus or minus one degree must be fulfilled [2, 3]. In the near future, a remarkable improvement is expected by using the optoelectronic instrument transformers.

Accuracy for frequency measurements
Frequency data should be collected every 0.1 sec with a resolution of ± 0.001Hz with accuracy better than one milliHertz [2].

Simultaneous samples
Simultaneous sampling of all input variables is commonly used, but sequential sampling could also be used with software correction for sample delays. This will contribute to the accuracy of measurements

Time delay for Real time Wide area Monitoring Control and Protection
It is often the case that the degree to which synchrophasors can be made useful to any particular group within an electric utility organization depends on how far and how fast synchrophasor data can be moved from a variety of different locations to where the information can be processed, displayed, and analyzed [5]. It should be noticed that a total time required for a total adaptive process is about 185 ms with 5 ms left for sensor processing time [2]. This time is estimated for a complete Digital Fiber Optic Network, and has to be considered for PM function.

Phasor Displaying
In the phase-angle oriented system, the synchronizing signal (or 'zero reference phasor') is asynchronous with the power system frequency. Therefore any power system voltage phasor is nearly rotating with respect to this reference, sometimes clockwise, sometimes counter clockwise. This means that the "absolute angle" of a voltage phasor with respect to the reference phasor is not bounded. Solution of this problem creates S/W design challenge [3]. This phasor rotation has to be handled in a way that makes phasors appear fixed in steady state condition.

Low frequency oscillations
Beside the information of voltage, current, phase angle, active and reactive power….etc, low frequency oscillation of a 3% or 5% damping, should be allowed to the dispatcher [2]. It should be noted that during frequency oscillations, the frequency is deviated from its nominal value. This fact also adds another challenge in the calculation of the magnitude and phase quantities during oscillations.

Communication subsystem
Communication links used by WAMS include both wire (telephone lines, fiber-optics, power lines) and wire-less (microwave, satellites) options. Delays associate with the link act as a crucial indicator to the amount of time-lag that takes place before action is initiated. The delays are an important aspect for on-line data transmission to the control room, and should be incorporated into any power system design, as excess delays could destroy any control procedures adopted to stabilize the power grid. Direct digital systems like fiber and microwave links are much faster than analog systems with modems. Dial-up and internet connections are not currently reliable enough for continuous, real time systems [6].

Synchrophasor Data format
There are two worldwide versions of standards for synchrophasor streaming data protocol for data output, and they can be used simultaneously. They are IEEE Standard for Synchrophasors for Power Systems, IEEE Std 1344-1995, December 1995, and IEEE PC37.118. Both protocols can be implemented on TCP/IP Sockets [7, 8].

6. EXAMPLES OF PHASOR PRESENTATION USING DATA FROM DISTURBANCE RECORDERS

Figure 3 shows the calculated frequency traces during an actual power system incident for three apart stations (K, H, and T). The DR's located in these stations have GPS time synchronization. This figure shows a 600 seconds period of slow scan record.

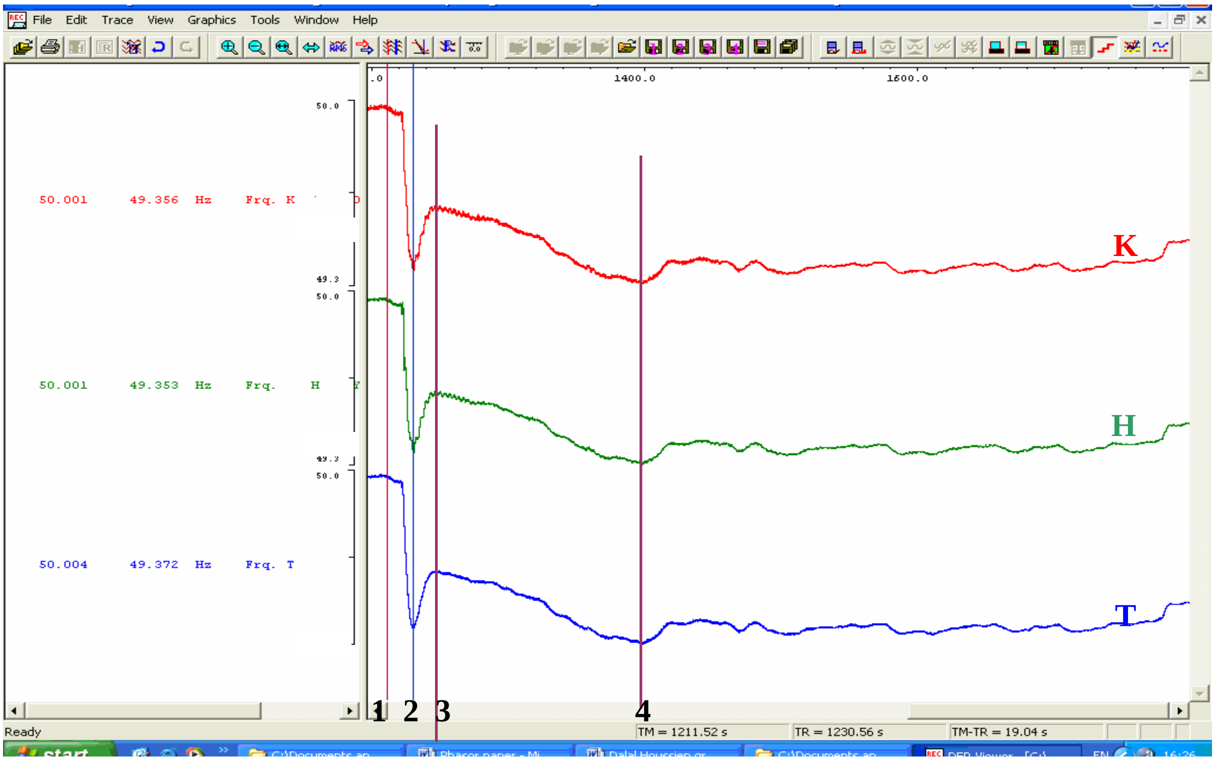

Fig. 3: Frequency variation during actual system real incident at three locations

The phasor data calculated by the DR for the same shown time interval for the three stations have been exported to program designed using MATLAB software. Figure 4 shows the block diagram of this program where the data of the actual record, selected from Master Station archive, is exported to a file that imported in the Matlab workspace, and plotted via a designed subprogram. This program is responsible for the presentation of the voltage synchronized phasors as shown in the next figures 5 and 6 which are corresponding to the time instances 1, 2, 3, and 4 marked on Figure 3.

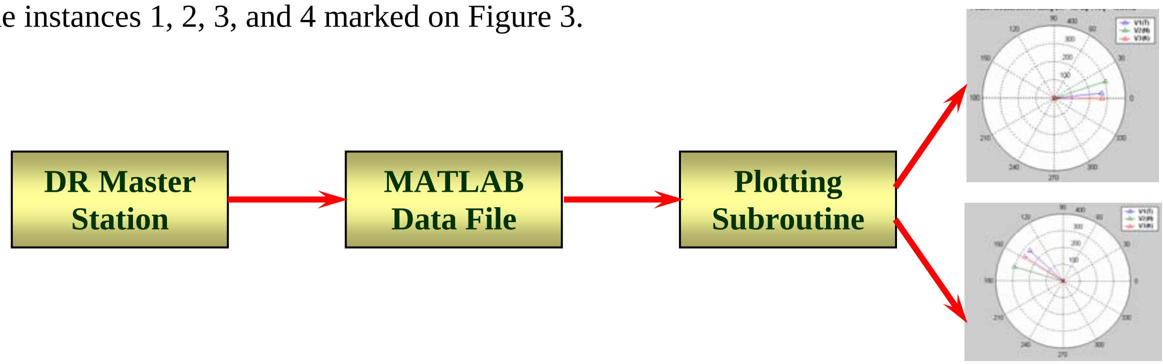

Fig. 4: Block Diagram of the Program for Phasor Presentation

The four cursers in Fig. 3 represent four instants starting short time before the incident, i.e normal operation (1), and three other instants within the selected disturbance period. Figure 5 shows the phasors at the three stations during normal operation (instant 1) with and without rotation (Fig. 5 a&b) respectively.

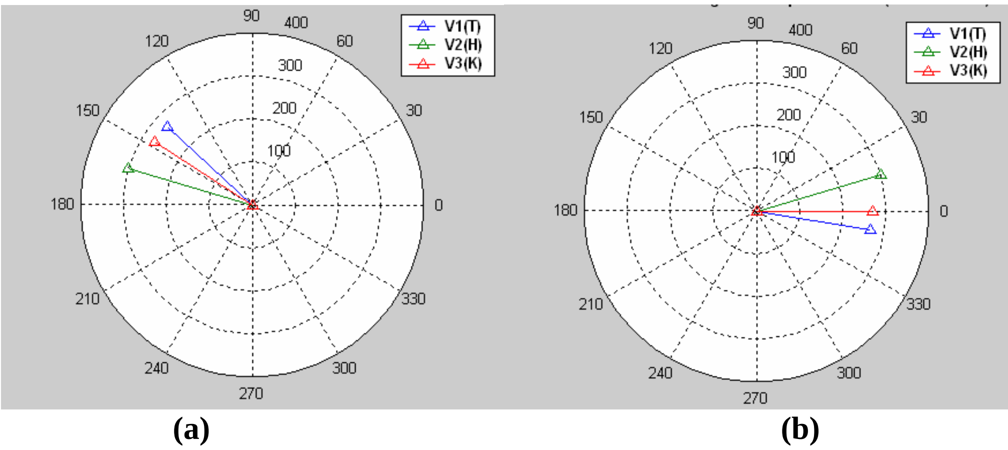

Fig.5: Voltage Phasors before the incident (at instant 1 of Fig. 3)
(a) With phasor rotation
(b) Without phasor rotation

Figure 6 shows the voltage phasors during the incident. Three different instances were chosen to illustrate the variation of the phasors during the selected period of the record. It is clear that the variation of the angle between each station and the reference one represents the state of the power system. The appearance of this powerful data to the control center can lead to fast and quick remedial actions that rescue the power system from further consequences.

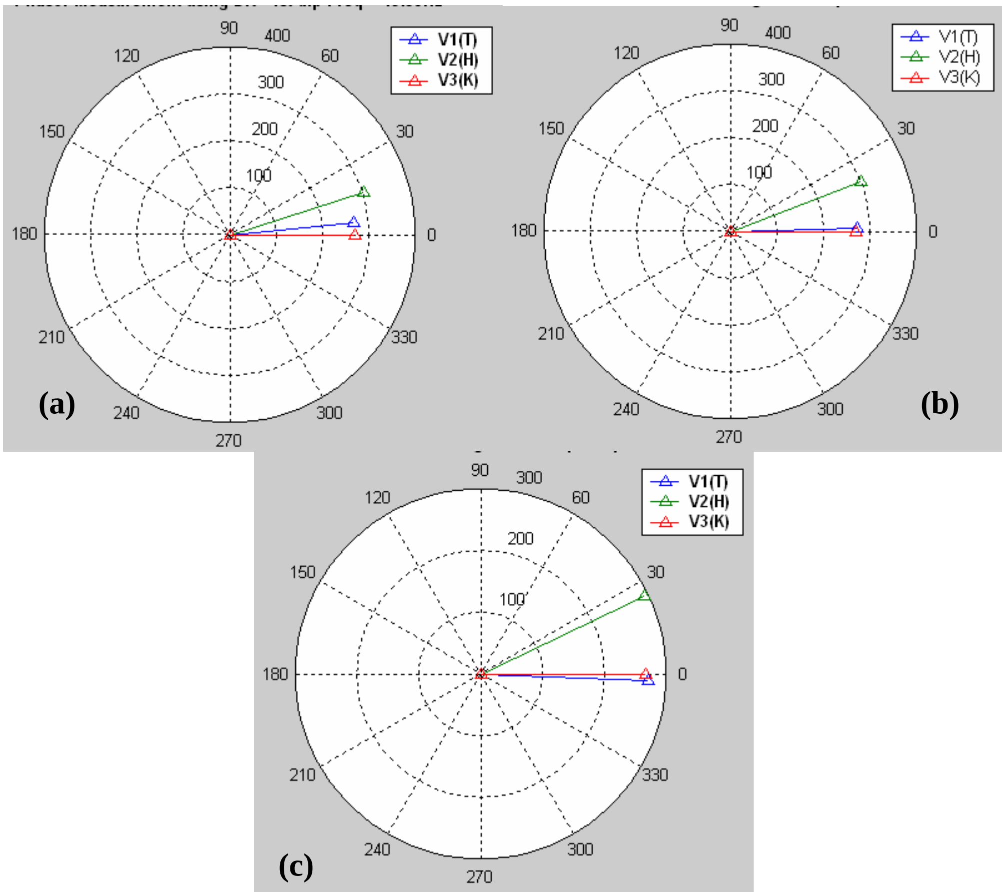

Fig. 6: Voltage phasors during the incident
(a) at instant 2 of fig. 3
(b) at instant 3 of fig. 3
(c) at instant 4 of fig. 3

7. CONCLUSIONS AND RECOMMENDATIONS

There are some devices which are candidates to perform the phasor measurement function. These devices are: special separate PMU, Protective Relays, Disturbance Recorders, Fault Locators or RTU's. This paper introduces, after examining their technical and economical adequacies, the Disturbance Recorders to perform the phasor measurement functions. DR proved to be technically adequate for PM, and economically feasible for providing this function.

However, disturbance recorders manufacturers have to study carefully the requirements of the phasor measurement as a primary tool for providing data to the real time wide area monitoring, control and protection so that they upgrade their disturbance recorders to suit best these requirements.

This paper also illustrates how the phasors data provided by a disturbance recorder can be used to present the voltage phasors during an actual system disturbance to the system operators.

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9. BIOGRAPHY

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