A Wide-Area Prospective On Power System Protection: A State-of-Art

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***Abstract*— As the increase in demand for electricity is not been supplied by adequate increase in electrical power generation, the pressure on the electric grids is tremendously growing. so, reliability and integrity is becoming more difficult, sometimes, which may leads to large blackout. In addition, the grid experiences sudden changes due to the inability of the relays to adjust to the prevailing network conditions on the occurrence of a disturbance. This can be reduced by continuous monitoring of system transmission capacity margins and increasing stress on the system. The invention of measuring device, called Phasor Measuring Unit (PMU), that measures the phasor data across the system and communicates to dispatch center through a communication channel, made it possible to redesign network protection schemes to make them more adaptive and thus improve the security of the system. This paper presents the applications of the PMU data in making the relays more adaptive and in the monitoring of grids behavior under disturbances.**

Keywords*— *phasor measuring unit(PMU), wide area monitoring system(WAMS), supervise zone of protection, adaptive out-of-step relaying.

I. INTRODUCTION

Just before the blackout in India in July 2012, system was weakened by several scheduled outages of transmission lines connecting Western region (WR) with Northern region (NR) boundary, two important parts of the Northern Eastern Western (NEW) Grid. That time, Bina-Gwalior-Agra line was the only main 400KV AC inter-tie line connecting these two boundaries. As, many of the NR utilities drew excessive power from the grid, there was an over loading on this inter-tie link, which eventually got tripped by zone-3 of distance relay. This was happened just because of load encroachment seen by zone-3 distance relay. But, however, no fault was observed there. Since the inter-regional tie was weakened already , tripping of 400 KV inter-tie line has stimulated the NR system to completely isolate from the WR which was the originator of the succeeding blackout [1].This case is just one of many examples where mal-operation of protection schemes, whether by design flaw or poor maintenance or simple mistakes, have played a part in large events on the grid. And as our society and others depends so heavily on this critical energy infrastructure, large events on the grid reflect directly to large events in our economies. This paper gives an introduction to wide area measurement system (WAMS) followed by some investigations to several protection schemes which aim to increase the reliability and security of the operation of the electric grid by providing wide area measured data. This includes a supervisory zone for back-up protection, an adaptive loss-of-field relaying protection. These ideas became possible by the advent of wide data measurement strategy. As this measurement policy provides system wide data, it can be applied to scenarios in power system protection before issuing block or trip signal. This document also discusses the recent developments in power system protection and wide area measurements. This report is actually presented as described below. section II analyze the need of wide area measuring (WAM) system, its behavior under abnormal operating conditions. section III gives an insight into the principle of measuring phasor quantities using phasor measurement units. Section IV provides the applications of phasor measuring units exclusively in improving power system protection. Section V concludes with suggestions with certain constraints regarding the direction in which all these applications of this particular policy will come forth.

II. SIGNIFICANCE OF WIDE AREA MEASUREMENTS

A. Wide Area Measurement System

A wide area measurement systems can be referred as a monitoring device that collects parametric data from the grid with more coarseness and in synchronized real time, and then utilize that information for safe operation, improved learning and grid reliability as shown in fig 1. This advanced measurement technology provides a great informational means and operational structure that help in analyzing and monitoring of the complex behavior exhibited by big power systems. The measurements taken from various parts of system will not be fully integrated unless the measurements are measured at an exactly same instant. The most and an important requirement of WAMS is that the measurements must be synchronized. These measurements are precisely time synchronized against the satellite based global positioning system (GPS). Then these measurements are combined to form integrated and high resolution views of power system operating conditions. The primary and also first data source for this particular system is the phasor measurement unit (PMU) that produces extreme quality measurements of bus angles as well as frequencies in addition to more traditional

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quantities. A high sampling level, usually, 30 or more samples for every second, is especially significant for measuring strategy dynamics and is an additional essential requirement of WAMS technology [2]. In their existing form, WAMS might be used like a stand-alone structure which supplements the grid's traditional Supervisory Control And Data Acquisition (SCADA) strategy. Like a complementary strategy, WAMS is particularly developed in order to improve the operator's real-time watch of the method in the format of situational awareness together with information utilized between systems to guarantee secure as well as dependable electrical grid function.

A significant contribution involving WAMS technologies was proven during the course of failure of Western Electricity Coordinating Council (WECC), the Western power system on August 10, 1996. During this particular blackout, WECC system had been separated into four asynchronous islands alongside heavy loss of load. The outcomes of this particular separation, when compared with the dynamic data being supplied by WAMS inspired too many strategic approaches like remedial action schemes (RAS) by the power utilities. The information reinforced that power grid functioning in WECC considerably depends upon the current strategy models as well as that these models were insufficient in predicting system responses. One particular and biggest advantages recognized was that the data covered precursors of the impending electrical grid failure, that if had been precisely studied, could have permitted cautionary actions which could have either removed or greatly minimized the impact of the disturbance [3]. The cascading failure of 1996 was one of the largest driving factors for additional WAMS improvement as well as enhancement [2].

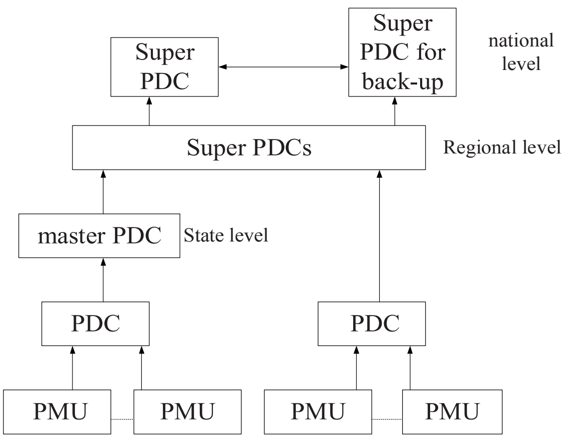

Fig 1: WAM structure

III. PHASOR MEASURING UNIT

The phasor measurement unit (PMU) is a power system measuring device. It has the capability of measuring the synchronized voltage and current Phasor. Synchronicity among Phasor Measurement Units (PMUs) is achieved by same-time sampling of voltage and current waveforms using a common synchronizing signal from the global positioning satellite (GPS). The ability to calculate synchronized phasors makes the PMU one of the most important measuring devices in the future of power system monitoring and control.

Phasor measuring unit (PMU) uses the GPS transmission to synchronize the sampling clocks so that the calculated phasors would have a common reference. The first pmu was developed in Virginia Tech laboratory. PMUs provide instantaneous of the state of entire power system by using GPS time pulse as a input to sampling clock. The GPS provides pulses at an accuracy of 1μs, which corresponds to 0.018 degrees for a 50Hz system. The GPS signal with 1pps is used a PLL to create the sampling pulses, which in turn used for sampling analog signals[4].Figure 2 shows the functional representation of phasor measurement unit.

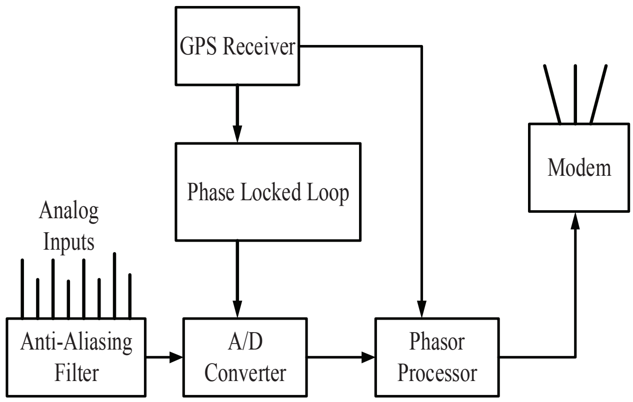

Fig 2: Functional block diagram of PMU

B. *Phasor Measurement Technique*

Let a pure sinusoidal waveform can be represented by a unique complex number.

This is known as a phasor. Consider a sinusoidal signal

$$x(t)= X_m \, Cos(wt+Ø) \qquad (1)$$

The phasor representation of this signal can be represented as

$$x(t)= \frac{Xm}{\sqrt{2}} e^{j\Phi} = \frac{Xm}{\sqrt{2}} (\cos Ø + j \sin Ø) \qquad (2)$$

The sinusoidal signal and its phasor representation are shown in fig 3. Most commonly the phasor representation of an input signal is determined from the samples taken from the waveform, and by applying the Discrete Fourier Transform (DFT) to calculate the phasor.

C. *Discrete Fourier Transform*

Since sampled data is used to represent the input signal, it is essential that Anti-aliasing filters must be applied to the signal before data samples are taken. Antialiasing filter is an analog device that limits the bandwidth of the pass band to less thanor equal to half the data sampling frequency (according to Nyquist criterion). A digital filter removes unwanted frequency components that may create problems for a particular application. The phasor estimator calculates the phasor representation of the input signal.

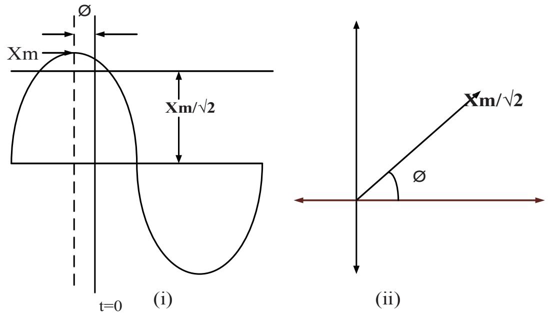

Fig 3:Phasor representation of sinusoidal signal
(i) Sinusoidal signal
(ii)Phasor representation

If x_k (k=1,2,3…N-1) are the N samples of the input signal taken over one period, then the phasor representation is given by

$$\mathrm{x} = \frac{\sqrt{2}}{\mathrm{N}} \sum_{k=0}^{N-1} x_k e^{-jk2\Pi/N} \qquad (3)$$

It is to be noted that for real input signals, the components of the signal at a frequency '*w*' appear in the DFT at '±*w*'. They are complex conjugates to each other. They can be combined, giving a factor of 2 in front of the summation sign in (3). Thus the peak value of the fundamental frequency is obtained and then converted it to rms value by dividing by 2 . The DFT calculation eliminates the harmonics of the input signal.

IV. APPLICATIONS OF WIDE-AREA DATA IN POWER SYSTEM MONITORING AND PROTECTION

A.WAM Based Fault Location:

Location of fault can be done based either upon phasor measurements or travelling wave concept. But surely it would be possible to estimate location of fault from each end, if wide area measurements are used [5]. According to [6,7] , the fault is determined based on fault detection index. This index is comprised of two complex phasors and angle difference between them. The pictorial representation for the wide area based fault detection and location method is shown in fig 4. From fig.4, relay collects data from its local PMU, and based on the data collects it sends command signal to its circuit breaker. Communications channel enables the data transfer between the adjacent relaying units. It is well known that the application of series compensator improves transient stability, increases power transfer capability. But because of its uncertainty by means of the variations in series compensation voltage during fault the protection has become a most difficult job and, an important subject of investigating relay for the relay vendors and protection experts.

Articles[8,9] presented well about series compensation impact on line protection. Protection scheme with fixed and controllable series capacitors in combination with metal oxide varistor (MOV), is suggested in [10]. WAM system based fault location algorithm is suggested in [11]. Conventional technique in calculating voltage drop across the series compensation device was done by considering device model.

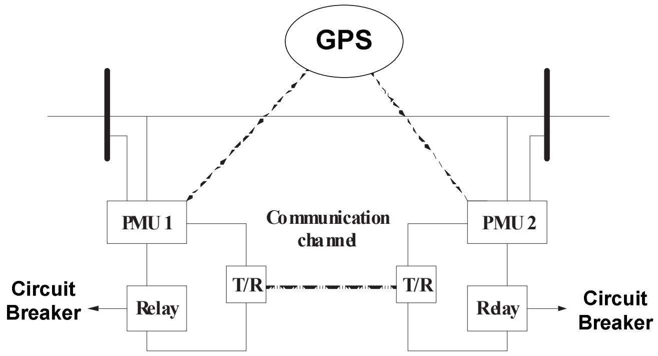

Fig 4: Wide area protection structure

This algorithm needs exclusively synchronous measurement data measured from both ends of the line, to calculate location of fault in a line integrated with thyristor controlled series compensator (TCSC).

B. Supervisory Control of Back-Up Zone Protection:

The back-up zone usually removes more number of system elements than required by the operation of the primary zone of protection. It is particularly true in case of long lines or zone-3 relays that serve as backup protection for the lines going away from substations with considerable in-feed. This is very dangerous during the course of wide area disturbances and could lead to cascading failures as it is seen recently during India blackouts [12]. Due to similar major disturbances in the past during zone-3 relay operations, back-up protection such as zone-3 was scrutinized and eventually was removed in many situations. But back-up zone-3 protection is still required in certain scenarios. A solution may be to monitor other relays in the vicinity to supervise zone-3 [13]. It means that if the protection zone-3 of a distance relay sees impedance characteristics within its protection boundary but an appropriate combination of zone-1 relays is not able to see a fault, this zone-3 should be blocked.

Distance relays are usually designed on the basis of fixed impedance setting this setting is called reach. Traditionally distance relays measures the impedance between the relay and the location of the fault, which indicates whether a fault lies within reach or not. Then the relay will either overreaches or under reaches based on the operating conditions and the location of the fault in the system However, the shortcoming in using distance relays is that their settings have to be reset for every change in the network structure[14].

In case of long transmission lines the back-up protection relay reach can be significantly large and the apparent impedance seen by this relays approaches the relay protective boundary while the loading of the line increases as demonstrated in Figure 5. In figure, for simplicity and easy of understanding, circular mho characteristics are considered. It is more beneficial to use quadrilateral characteristics than circular, as the quadrilateral characteristic provides high level of freedom in reach settings and more immunity to load encroachment. This can help in solving many of the protection problems that the protection engineers facing now a days. Impedance characteristics may enter tripping zone of the relay under very heavy loads and lead to tripping. This condition where impedance characteristic observed by distance relay enters the relay protective zone due to the power shift in the transmission lines is referred to as load encroachment.

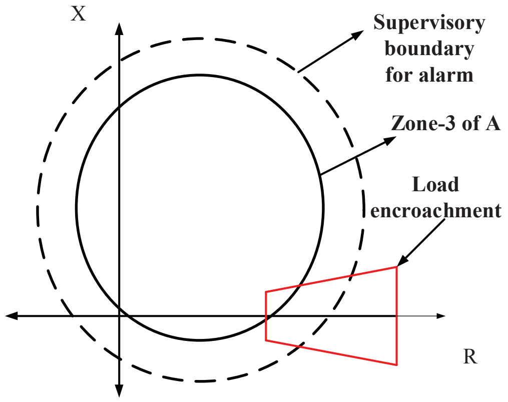

Fig 5: Load encroachment effect on zone-3 Characteristics

WAMS data provides an additional prospective for system protection if there is a need to take preventive actions truly. Multiple views of the system allow relays to differentiate between trip and block. In this case demonstrated in Figure 6, relay A can identify a violation of load-ability limit with respect to a system fault i.e. whether a zone-3 pickup is appropriate using information from PMUs at neighboring buses B and C.

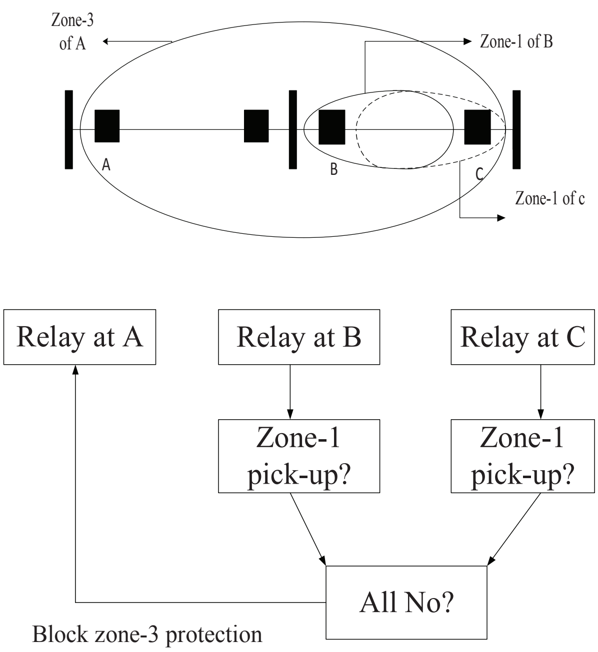

Fig 6: Supervision of zone-3 protection

C. Adaptive Out-of-step Relaying:

Out-of-step relay calculates the rotor angle difference of two machine equivalent systems, and utilizes it along with breaker status data to determine swing stability. Once an out-of-step condition is detected, then the selective tripping order will be issued for clearly unstable condition. The selective tripping must ensures a reasonable match between load and generation within each island after the system is being divided into islands. When a transient occurs, most of the transmission line relays see apparent impedance in R-X plane. From the fig 7, the distance relay at bus A, from fig 6, may see impedance trajectory Z-Z or Y for two types of system swings of different severity.

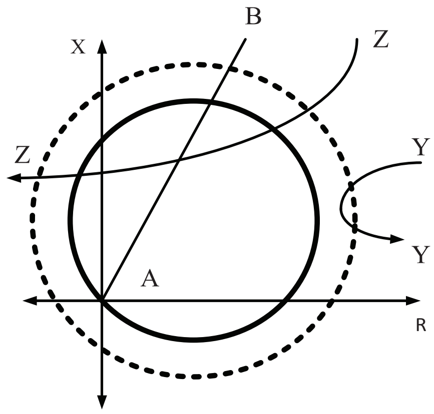

Fig 7: Impedance trajectory during transients.

The trajectory Y corresponds to stable swing, while the trajectory Z-Z corresponds to unstable swing. It is then clear that in any case, the impedance trajectory may enters one of the trip zone of the relay as shown above. Traditional out-of-step relays have been known to mis-operate when the prevailing system conditions have not been foreseen during the design. But the PMU based adaptive out-of-step relay recognizes changes in the power system, and adapts the settings accordingly.

The adaptive out-of-step relay installed at the interface between the two systems predicts power angle characteristics of post-clearing system during an outage of important transmission line case, calculates successive relative angle measurements to estimate the phase shift in mechanical power (P_m) during loss of generation case[15]. Along with the above applications, PMU technology also applied in system validation, accurate postmortem analysis.

D. Coherent Group Detection:

Coherent group is a certain group of generators in which all generators swing together after an occurrence of disturbance.
On the occurrence of disturbance, the rotor angles difference of any two generators, which is constant before the occurrence of disturbance, will be drifted and makes this group of generators to swing away from the rest of the system [16]. Once the disturbance is cleared, this group will swings back to synchronism with the remaining part of the system. While analyzing transient stability, this group of generators can be referred as a single equivalent generator, which removes high frequency and inter-generator modes from the new equivalent power system.

If, after occurrence of fault, coherent units have same velocity and acceleration then their phase angle differences will be constant, and it is given by

$$\delta_x(t) - \delta_y(t) = const = \delta^0_{xy} \quad (4)$$

$$\frac{d}{dt}\delta x = \frac{d}{dt}\delta y \text{ and}$$
$$\frac{d^2}{dt^2}\delta x = \frac{d^2}{dt^2}\delta y \quad (5)$$

Wide area information obtained from PMUs located nearby generators or group of generators is used to calculate frequency and rate of change of frequency which means the variations in angular frequency. Then from the equations (4),(5) and the calculated data from synchronized measurements, it could be very easy to identify the group of generators so called coherent group.

E. Intelligent islanding:

Once coherent groups were found then the next step is either to adapt out-of-step relay if the rate of change of frequency is stable, or to separate coherent group from the rest of the system intelligently if rate of change of frequency is unstable. Intelligent islanding is the process of separating an unstably swinging group from the stable system intelligently. Here intelligent means nullifying generation-load mismatch in each new area by proper shedding of loads prior to separation process. This intelligence will come by estimating phasor difference between two areas or by observing the differential frequency in the same two areas [17].

This estimation of phasor difference or differential frequency in two islands could be effective if there is a dedicated PMU which computes phasor with respect to synchronous frame of reference, on each node of inter-tie line connecting two areas .

F. Adaptive Loss-Of-Field Relaying:

When the field of alternator (termed as synchronous generator) lost then synchronous machine draws reactive power from an infinite bus connected to it. This may damages rotor because of heavy loading experienced, due to excess reactive power, by the machine. This in turn causes the reduction of voltage at the terminals of synchronous generator experiencing loss-of-field. Again this condition immediately causes severe voltage collapse in the rest of the system connecting to it. Hence, the LOF condition should be identified as fast as possible. During LOF, the final impedance locus should fall into fourth quadrant of the R-X diagram. So, any relay the exhibits its operating characteristics in the fourth quadrant is appropriate for this application.

The LOF relay settings include Thevenin reactance(X_t) of power system at generator terminals and synchronous reactance(X_d) of the machine. As any configuration change in the system near to alternator terminals changes $X_{t,}$ the relay should be trained to adapt to these variations and to estimate new setting for a unit or group of units. From the fig 8, the deep inner circle represents LOF characteristics of a traditional relay. When the network configuration changes, new LOF setting group corresponding to the new network configuration will be measured from wide area knowledge and then the relay will adapts itself to the new condition[18,19]. The middle circle is the adaptive characteristic obtained by the relay from the wide area data available at the terminal of the generator.

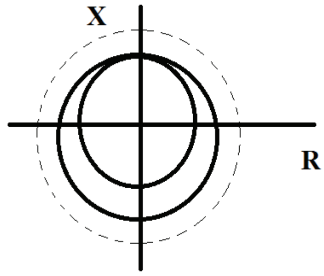

Fig 8: Adaptive LOF relay

The outer circle is for the supervision of relaying during opening of field, shorting of field, voltage regulator failure. This characteristic was drawn by estimating impedance locus at the generator terminals for different contingency made at nodes nearby generator terminals.

Along with the above applications, wide-area measurements could help in the following applications[20] also

- Generation-load mismatch detection
- Identification of generator trip locations
- And many more applications in the sense of power system monitoring and controlling.

V. CONCLUSION

Since the system operators gaining experience to deal with real-time PMU data, it would be a best choice to include PMU data in system state estimation and wide area protection procedures in a power grid energy management system. By choosing sufficient number of PMUs, it could be easier to perform linear state estimation system monitoring and controlling, and also it could be possible to track dynamic phenomena. Ultimately, this will improve protection and control functions.

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