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Integration of PMU, SCADA, AMI to Accomplish Expanded Functional Capabilities for Smart Grid

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Abstract-Technologies of synchrophasors - PMUs – control systems – SCADA and smart meter systems – AMI are core enabling technologies for SMART GRID. The integration of these advanced sensor technologies to accomplish expanded functional capabilities of SMART GRID are discussed and presented.

lntlex Terms-Advanced sensor, integration, smart meters, smart grid, synchrophasor systems.

I. INTRODUCTION

ELECTRIC energy is a transitional form of energy with characteristic features. It can be transported along narrow corridors in bulk quantities at practically the speed of light. These narrow corridors are the transmission lines, the distribution network, etc. Parallel channels are used to form the energy delivery infrastructure. It operates very reliably using alternating currents at a power frequency of 50 Hz or 60 Hz. This allows the use of transformers to change the operating voltages to various levels. In the USA the Ultra High Voltage (UHV) levels (500 KV -1000 KV) are used at the transmission line to deliver the electric energy from the widely geographically dispersed generation centers to the load centers and also to reduce the line conductor losses. At the distribution levels, the medium voltages ranging between 4.0 KV to 34.5 KV are used for the main circuits serving large number of distribution transformers, which subsequently step down the voltages to the service level at the customers' premises. The medium voltage circuit can be very complex with a large number of network configurations and interconnections.

Another unique feature of the electric energy is that it can easily be split into minute or bulk quantities and conversion of electric energy into other forms of energy is a well known technology. Heating elements convert electric energy into thermal energy. Electric motors convert the electric power into useful mechanical power, etc. The 50 Hzl60 Hz energy delivery infrastructure uses 3-phases and voltage transformations use three phase or single phase transformers. Van• Vbn and Yen are the line to neutral voltage base phasors and the line to line voltages are linear combinations of the base phasors. Also for any phasor at the substation bus there is a corresponding phasor at the network served by the substation.

Advanced technologies in the area of digital electronics, communication technologies, data base management systems, GPS systems, etc. can generate new applications to optimize the electric energy delivery system operation. The syncho-phasor system uses the satellite communication technology to link the phasor measurement units (PMU) to monitor and collect data at the various locations of the transmission voltage network. The advanced metering infrastructure (AMI) provides communications between major communication nodes at the distribution network to the remote intelligent metering devices at the customer premises. SCADA is used to monitor and collect data at the link between transmission and distribution. By time synchronizing the monitoring and data gathering at the whole network, a wealth of new applications and control strategies can be designed for optimizing and improving the reliability of the generation and energy delivery to the customers. All the monitored and collected data provide a comprehensive insight and understanding of the state of the generation, the delivery system and at the consumer premises and can be correlated as a function of time and circuit locations.

II. THE SYNCHRO-PHASOR TECHNOLOGY FOR SUPPORT OF TRANSMISSION AND GENERATION OPERATION

The Smart Grid concept is the fundamental need to increase the reliability and efficiency of the electric energy generation and delivery system. The integration of phasor measurement units (PMUs) and other advanced sensors into comprehensive wide-area monitoring networks will enhance the situational awareness of the grid and enable system operators to react to system disturbances and anomalies more accurately and expeditiously. The data collected by these systems can be used to develop advanced operating procedures/algorithms and ultimately allow some level of automatic advanced control of the grid. The data from these systems could also be utilized to make the grid self healing by avoiding or mitigating power outages, power quality problems, and service disruptions.

The conventional technology used by grid operators for monitoring the grid is the Supervisory Control and Data Acquisition (SCADA) system. These data are then used by the State Estimation (SE) application to determine and display the state of the power system. Synchro-phasors are precise grid

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measurements taken by PMUs at high speed, typically 30 times per second, compared to one every 4 seconds using conventional technology. Each measurement is time-stamped according to a common time reference. Time-stamping allows synchro-phasors from different utilities to be synchronized and combined, providing a precise and comprehensive view of a regional interconnection. Synchro-phasor data enable the determination of grid stress and can be used to trigger corrective actions to maintain reliability.

Synchro-phasor technology, because of instantaneous, high-resolution and more-detailed measurements, PMU data are well suited as input to activate local or centralized automated controls. Such use of synchro-phasor technology for wide-area monitoring and control will facilitate the evolution of the existing grid into a smarter transmission grid.

The massive data from PMUs has brought challenges to store, analyze and transmit results without causing a bottleneck in the available information processing infrastructure. In addition to the amount of data, the dimensionality of synchro-phasor data is bound to increase with more PMUs to support a wide-area monitoring. In order to enable real time surveillance of the grid, high-speed synchro-phasor data has to be processed before a new set of data arrives for processing. A method of dimensionality reduction of synchro-phasor measurements such as voltage, current, frequency etc. utilizing principal component analysis (PCA) can extract correlations between measurements summarizing trends in PMU data without the loss of vital information where trends are more important than exact data [10]. Transmission, storage and computation of data become less expensive after dimensionality reduction of the synchro-phasor data.

To illustrate an online dimension reduction via a PCA approach assume at time t, synchro-phasor data arrives as a n dimensional vector xt = [xt,1, xt,2, xt,3, ... xt,n]. The synchro-phasor vector is comprised of electrical parameters such as frequency, voltage, current etc. There may be some

operating condition. However, the correlation gets changed

correlation between these parameters in a steady state

during disturbances and evolves to a new correlation when the system evolves to a new operating condition. In the PCA method of dimensional reduction, correlation of electrical features will be tracked using principal component analysis [10]. It does not require buffering of past measurements, which can be discarded as soon as new set of synchro-phasor data arrives [10].

III. THE INTEGRATION OF AMI AND SCADA TO SUPPORT SMART GRID APPLICATIONS

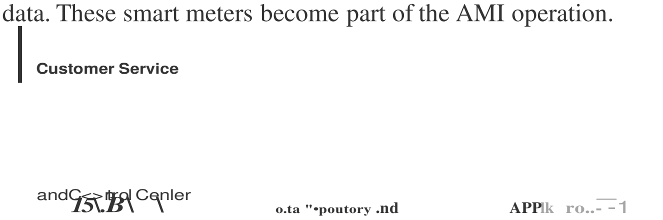
AMI implies a two-way communication system that can reach every customer to bring back metering data reliably and accurately in a timely fashion. The delay due to data transfers, signal propagation reliability, baud rate, long messages, processing at the transmitter, receiver and nodes should be minimized. Rerouting due to node problems is needed.

Smart Meters can generate information for designing algorithms for new applications. When added-value applications are equally important as the meter reading function to the prospective user of the AMI system, it is important to ask the right questions which should be answered properly to every party's satisfaction. *"Can a system that is designed for automatic meter reading, be economically expanded to implement future added-value capabilities without requiring a major overhaul, large increase in capital expenditures andfuture added utilization costs".*

An AMI system has a *Central Net Server computer* to handle all communications to the remote intelligent devices, maintains the data-base of communication paths and nodes, transponder addresses to access the transponders is also linked through gateways to other remote devices and other parties' service computers, such as the Customer Billing, the Demand Response Dispatch, the Service and Maintenance computers.

A schematic diagram of the AMI infrastructure linking all the parts into an operational network including a link to the substation SCADA is shown in Fig. 1 SCADA controls and monitors the network connected to the substation bus. It monitors the energy flow on each phase of the feeders of the substation bus and also alerts the AMI system when an unusual condition arises at the distribution network [8]. Detection of a fault current on a phase of a feeder can help the AMI system trigger a polling operation to determine the extent of an outage [2, 4, 6, 7].

Ifthe SCADA system also collects interval metering data in synchronism with the smart meters on each phase of all the feeders at the substation bus, then new applications can be generated to support Smart Grid functions. For utilities without SCADA at some of their substations, smart meters can be used on each phase at the substation to monitor and collect data. These smart meters become part of the AMI operation.



Downloading communication addresses, instructions and real time to remote devices, sensors and nodes should be easy, remotely verifiable and easy to update.

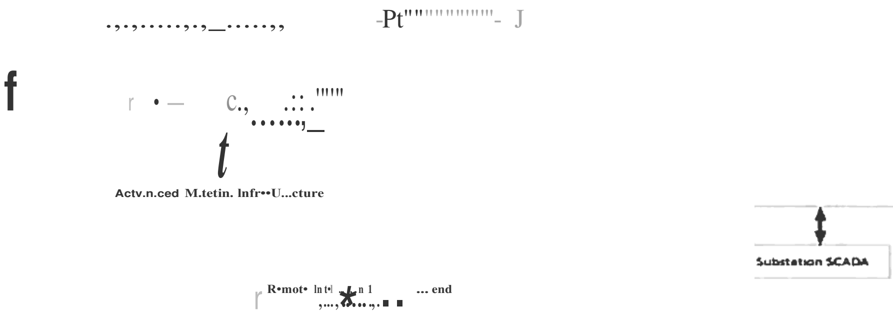


Fig. I AMI system infrastructure

The distribution substation data provide an insight of the energy state of the distribution network to support energy flow control at the transmission lines and the generation dispatch center. The smart meters dispersed throughout the distribution network provide a microscopic view of the load behavior, local problems and events.

Data from various locations of the electric grid are useful when they are cross-correlated with time and physical locations. Energy metering interval data from smart meters when time synchronized can be used to determine the coincident demand of the total system. If the phase, feeder number and the substation bus information are also tagged to the data, implementation of load control, load balancing and other functions is made possible. Voltage data can be used to improve the voltage profile on the feeder through optimal scheduling of capacitor banks switching and voltage regulator control. Smart Grid applications also require information about the physical locations of the transponders at the distribution network and sometimes also their geographical locations [1, 3].

The name "transponder" is used in this paper to denote all remote devices such as energy metering, intelligent monitoring and control devices, alarm and switching devices. Hence data monitored and collected by each transponder has to have the time stamp the data is taken and the associated distribution circuit information. Suppose the physical data that is measured is defined by the letter Q. Then Q can be defined as follows.

$$Q\{t, s, f, \langle l \rangle, lx, g)$$

Where t : the time s : substation name
f: feeder number :feeder phase
lx : feeder segment number g : geographical location

The information tied to a data point are needed for designing many of the utility functions. The data collected from the Smart Meters, such as KWHr, KVAHr, Voltage, etc. when time stamped, synchronously in time and spatially correlated to the circuit maps, will generate applications that will benefit the electric utility and greatly enhanced its operational capability [3].

Some utilities also have information systems called AM/FM (Area Map and Facilities Management). An Outage Management System, coupled with an AM/FM system can improve maintenance and repair services by reducing the time for line patrol to quickly identifying which protective device has operated. It also determines the de-energized communication nodes. Communication Network Monitoring and Control, Outage Management are the functions to maintain service continuity.

With such a large number of transponders to retrieve data from, data flow control, control actions, etc. are very important issues. This implies that one has to be able to determine ahead of time which transponders belongs to a group that are accessible through the same communication path by a single group command. The Smart Grid functions that are now considered by many electric utilities can be grouped into several main categories. A possible method of grouping them is as follows.

- Customer Services and Demand Management
- Improvement of Service Reliability and Assets Management.
- Supporting Function

IV. CUSTOMER SERVICES AND DEMAND MANAGEMENT

If a meter reading at T_1 is P_1• at T_2 it is P_2, then $(P_2 - P_1)$ is the energy consumed during the interval/1 = $(T_2 - T_1)$. The smaller the interval/1 is chosen, the more accurate one can characterize the load behavior. For load survey and demand metering *11* is typically 15 minutes. For other applications *11* is typically 30 or 60 minutes [6, 7].

Deregulation of the utility industry allows retail sales of the electric energy by different companies to customers. One metering service is the pre-payment method. The customer deposits an amount of money to buy an amount of KWHrs. The customer is alerted before funds run out and is given a grace period before a total power disconnect is done. Disconnecting a customer may not be allowed without alerting him and disconnecting the power implies that a service disconnect switch is installed at the customer's premises.

Load management uses scheduled turning on and off of groups of cyclic loads to reduce coincident peak demand. Such loads are central air conditioners, water heaters and electric heating systems and they normally operate in random cyclic fashion. To implement a control strategy, a population of similar appliances, such as air conditioners is divided into groups. Group 1 is turned on for $11T_1$ minutes and turned off for $11T_2$ minutes. The second group uses the same on-off cycle but starts a bit later than group 1. The same time shift is applied to the other consecutive groups. After repeating this process several times, the air conditioners start to follow the load control algorithm. This technique, when properly applied reduces the peak demand and also improve the system load factor.

Time-of-Use (TOU) rate is another form of load control which involves customer active participation. Different rates apply during peak, shoulder and base load periods. Candidates for TOU rates are based on their energy usage profile .. Continued time synchronized interval reading of the electric meters will determine how effective TOU is to reduce total system peak demand.

A load factor improvement is illustrated in Fig. 2. In case I, a source supplies two identical loads through a circuit with a resistance R.

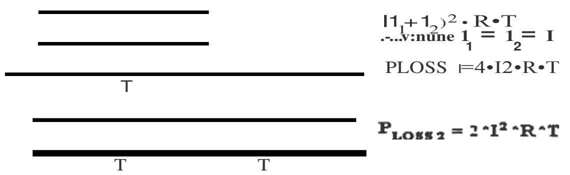


Fig. 2 Load factor improvement.

The load duration is T and the loss in the conductor is $P_{wss\,1} = 4I^2RT$. The source handles double the load current for the duration of time T. In the second case, the second load comes after the first one. The conductor loss $P_{wss\,2} = 2I^2RT$ is cut by 50%. The source carries one peak demand only. Load shifting improves the load factor, reduces the losses in the network and the peak demand supplied by generation. The voltage drop in the line is also reduced. This method can be applied to all phases of the feeders served by the substation bus. Continuous time synchronized interval meter reading provides an immediate assessment how effective the strategy is.

Brown out disconnects power to groups of customers by feeder or by substations for a period of time on a rotational basis when the system spinning reserve is low. It continues to do so until total demand drops to a safe margin of the spinning reserve. This method has some pitfalls too. For example, if all central air conditioners are off for quite some time, temperatures in the buildings will rise. Upon power restoration, all central air conditioners turn on simultaneously causing *cold load pickup* inrush currents causing a feeder circuit breaker to trip. For systems under load management control, prior to disconnecting power to the feeder, all large cyclic loads are disconnected using a control command. Upon power restoration all cyclic loads are restored in a scheduled step by step fashion to avoid large inrush currents.

Interval load monitoring by SCADA RTU of the loads on a feeders in synchronism with the Smart Meters, allows circuit losses to be extracted as a function of time [6, 7, 8]. If P_{phase} is the total incremental load on a feeder phase obtained by SCADA RTU for an interval T at time T, and ($P_{L1} + P_{L2} + .. + P_{LN}$) is the sum of all the loads on the same feeder phase as monitored by the Smart Meters at the same interval, then the circuit loss on the feeder phase is :

$$\Delta P_{loss} = \Delta P_{phase} - (\Delta P_{L1} + \Delta P_{L2} + .. + \Delta P_{LN}) \quad (1)$$

Loads causing the largest circuit loss for that period of time can be obtained from all the phases of the feeders. It also indicates how well the loads are distributed on the feeders. Transferring some loads to the other phases of the feeders may improve the load factor.

Monitoring the coincident demand of the loads of a distribution transformer helps to determine the time and duration of overloading. Avoiding overloading improves the voltage at the customer side and prolongs the life of the transformer.

A. Optimizing Service Reliability

One important function is the *Outage Management System.* The first step is to do *Outage mapping* to detect the extent of an outage. The next step is to isolate the faulty segment of the network and re-energize the healthy portions from a different source. Hence *fault isolation and system restoration* are part of Outage Management System [2, 4, 7, 8].

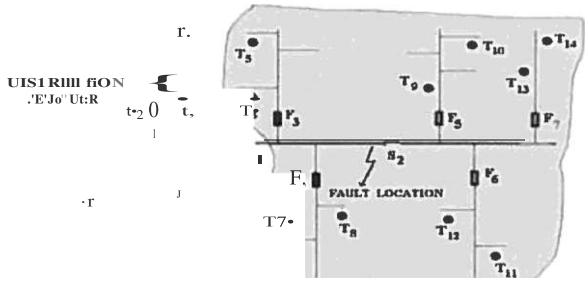


Fig. 3 Outage mapping diagram

Selective coordination of protective devices is used by utilities to isolate a fault from the source. Fig.3 shows an example of how selective coordination of protective devices operates to minimize the impact of a fault on a single phase of a feeder. A feeder has two circuit breakers S_1 and S_1 and 7 laterals protected by the fuses $F_1, F_2, .., F_7$. Two transponders are shown per lateral, indicated by T with the appropriate subscripts. A fault at a location in the figure opens breaker S_1 and $T_5 - T_{14}$ are all de-energized. All transponders at the de-energized circuit will be out of power. AMI is used to poll all transponders on the feeder where the fault is detected by the SCADA RTU. The results indicate that T_1, T_2, T_3 and T_4 are energized. By inference the fault is beyond breaker S_1 and is now open. By opening breaker S_2 restoration of power to the circuit beyond S_1 is by re-energizing the healthy portion from another source.

In general the magnitude of the fault current is much larger than the feeder load current. A differential technique as described in several publications [5] is used to extract burst transients from feeder currents. If F(t) describes the AC current and F(t-N*T) is the current at N*T before the time t where N is an integer and T is the period of the AC then the following value of the residue as a function of the time t is:

$$\delta(t) = F(t) - F(t - N*T) \quad (2)$$

0 for steady state conditions.

$\neq$ 0 for non- steady state conditions.

This technique is also rooted in the Fourier Transform method as shown in the IEEE Transaction papers [5] .The differential technique method is applied to one example for illustration. Fig.4 depicts a case of breaker operation followed by a loss of load. The darkened parts are the fault current peaks.

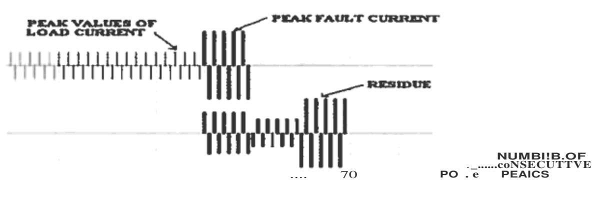


Fig.4 Five cycle breaker operation with load disconnect.

The Electro Magnetic Transient Program (EMTP) can be used to generate models for circuit breaker, re-closer or fuse operation due to faults in an electric utility distribution network. The digitized data from the models can be processed using the differential technique algorithm to generate signature patterns for reference to determine the types of faults. By comparing the different residue patterns, it is clear that by choosing larger values of (N*T) it will be easier to differentiate the various types of protective devices used. If the SCADA RTU recognizes a pattern such as shown in Fig.4, it triggers an alarm to the AMI system to poll only one or 2 transponders beyond the breaker S_1. Hence TJJ T_1, T_3 and T_4 are still energized and the other I 0 are out of power.

B. Detection of Unbalance and Assets Management

Bad load distribution on the phases causes unequal voltage drops on the different phases. Voltage unbalance on a feeder increases line losses and problems with motors. Unbalance is defined as the ratio of the negative sequence voltages to the positive sequence voltages. Ifthe absolute values of the line to line voltages are defined as a= I Vab I, b =I Vbc I and c = I Veal then the Voltage Unbalance Factor can be expressed by the following equation.

$$\left|\frac{V_2}{V_1}\right| = \sqrt{\frac{\frac{1+x^2+y^2}{6} - \sqrt{\frac{(1+x+y)(x+y-1)(1+y-x)(1+x-y)}{12}}}{\frac{1+x^2+y^2}{6} + \sqrt{\frac{(1+x+y)(x+y-1)(1+y-x)(1+x-y)}{12}}}}$$

In the expression above, the absolute value of lv.b I is assumed to be the largest in magnitude and x and y are set equal to x = (b/a) andy= (c/a). In Europe, the standards limit the unbalance to 2% at the medium voltage level. In the USA ANSI C84.1 Annex I and NEMA MGI, voltage unbalances in excess of I% requires a de-rating of motors.

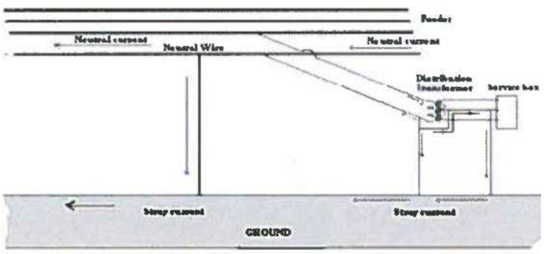


Fig. 5 Stray currents flow in the soil

Unbalanced loads also cause stray currents to flow in the soil as shown in Fig.5. This is due to grounding the neutral wire at the poles and at the step-down transformers. Step-voltages due to stray currents cause step voltage problems to animals and human beings.

C. Monitoring Power Quality

High impedance faults, increased voltages at the distribution transformers generate harmonics. Burst transient phenomena can impair the operation of electronic devices and digital devices. Revenue meters are affected by distorted voltages and currents. Monitoring power quality at strategic locations of the network helps to identify the cause and determine measures to maintain the quality of the power delivery. One method is to determine the total harmonic distortion {THD) of the service voltage for each interval T during several consecutive intervals *(N *LH)*. They are stored at the monitoring device for later retrieval. Where the variation of the THD is maximum it could be an indication where the source is that causes the harmonic distortion [5].

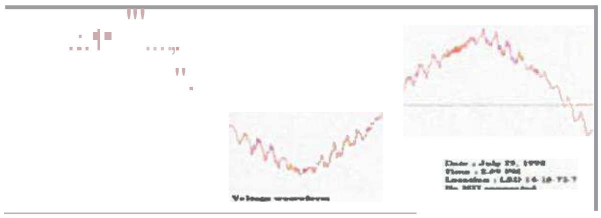


Fig.6 Voltage profile at a pulse width modulated motor drive.

Fig .6 shows the voltage distortion due to a pulse width modulated motor drive. What data to collect to locate the harmonic source and to decide that a power quality problem exists is still at a research stage.

High impedance faults generate sparks at the point of fault near the peak of the voltage. The current bursts are not large enough to cause a protective device to operate. Fig 7 shows histograms of a high impedance fault spectral data of the voltages at two different locations on the line. The spectral data of the voltages are analyzed for a number of consecutive time intervals AT and the magnitude of each harmonic is plotted on the same graph.

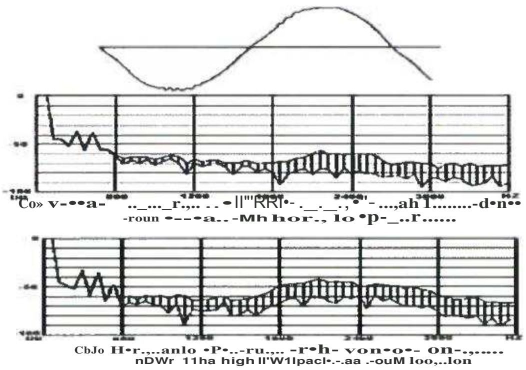


Fig.7 Histogram of voltage harmonic spectra due to a high impedance fault.

The spectral component strengths are larger in spread near the site where the fault is. Similar histograms are of voltages near arc furnaces. The large spectral spread in magnitudes as a function of time is from a site close to the furnace. Switching in and out of large electric motors cause voltage dips and transponders installed at some strategic locations can detect voltage dips using the differential technique algorithm.

V. DISTRIBUTED GENERATION AND ELECTRIC VEHICLES

Small distributed generators are directly connected to the service voltage side. The prime movers can be wind turbines, solar panels, etc. The concerns are about power quality, islanding and safety issues. Connection to the utility network can be direct AC coupling, or through power electronic ACIDC/AC assemblies. Wind turbines, photovoltaic cells for single homes ranging around 4.0 KW are coming down in price and can be coupled to the service voltage. A fault at the distribution circuit causes islanding conditions that affect metering and household equipment.

Electric vehicles battery chargers are connected to the service voltage circuit [9]. The price of electricity of US$0.10/kWh is equivalent to the price of gasoline at US$0.70 per gallon but electric utilities are not allowed to compete against oil companies. A new issue is the additional demand. Home battery charging systems for electric vehicles, are in the range of 3.3 KW and 6.6 KW. A 3.3 KW charger takes 8 hours to charge the batteries. If the batteries are charged when the owners get home from work, an increase in demand will occur during the evening hours for almost 8 hours. The non-cyclic load lasting the whole night per vehicle cannot use peak shifting control to reduce peak demand.

VI. CONCLUSIONS

The PMU technology when integrated with SCADA and Smart Meters can generate data for developing control algorithms of new applications. Advanced Smart Distribution Grid functions require knowledge of the of the smart meters locations at the electric network, such as the phase, feeder and distribution substation the data is obtained from. The time synchronization of all data monitoring is an essential requirement for determining the energy state of the network. The Maintenance and Repair department needs speedy locating, repairing and restoration of the networks. Knowing the topological locations of the protective devices and major nodes linked together by a communication system will dramatically enhance the system operation. Distributed generation and electric vehicles are new issues to be dealt with. The Smart Grid concept also has to be expanded to include the substation protection and monitoring as an integral part of the optimization process of the energy delivery system.

VII. REFERENCES

[I] W. M. Lin, M. T. Tsay and S. W. Wu, Application of Geographic Information System to Distribution Information Support, *IEEE Transactions on Power Systems, Febntary /996, Vol. II, No. I*

[2] Sioe T. Mak, Synergism Between Intelligent Devices and Communication Systems for Outage Mapping in Distribution Networks, *CIRED, 15'h International Conference on Electricity Distribution, Nice, France, 1-4 June, /999.*

[3] Sioe T. Mak, Knowledge Based Architecture Serving as a Rigid Framework for Smart Grid Applications, *ISGTIIEEE, Washington DC, January19-2/, 2010*

[4] Sioe T Mak, A Synergistic Approach to Using AMR and Intelligent Electronic Devices to Determine Outages in a Distribution Network, *Power System Conftrence 2006, March 14-17, Clemson University, Clemson, SC.*

[5] Sioe T. Mak, Application of a Differential Technique for Characterization of Waveform Distortions, *IEEEIPES Winter Meeting, Jan 2000, Singapore*

[6] Sioe T. Mak, Nader Farah, Strategic Use of Smart Meters Data and AMI Capability to Develop Advanced Smart Distribution Grid Applications, *CIRED 2I'h International Conference on Electricity Distribution, Frankjitrt. Germany, 6-9 June 20II.*

[7] Sioe T. Mak, Smart Meters Serving as Synchro-Sensors for Smart Distribution Grid Applications, *Panel Paper, IEEE/PES General Meeting, Detroit, Michigan, 24-28 July 2011.*

[8] Sioe T. Mak, Nader Farah, Synchronizing SCADA and Smart Meters Operation for Advanced Smart Distribution Grid Applications, *ISGTIIEEE Smart Grid Conference paper, Washington DC, January 16-/9, 2012*

[9] Larry Dickerman, Jessica Harrison, A New Car, a New *Grid IEEE Power & Energy, Vol. 8, No.2, March/Apri/20/0*

[10] Dahal N, King R.L., Madani V, Online Dimension Reduction of Synchrophasor Data, IEEE PES Transmission and Distribution Conference and Exposition, Orlando, FL, May 2012

VIII. BIOGRAPHY

Sioe T. Mak received his Diploma in Electrical Engineering from the University of Indonesia, the M. Sc. and Ph.D. in EE from the Illinois Institute of Technology, in Chicago. He was Senior Staff Scientist at the Distribution Control Systems, Inc., a subsidiary of ESCO Technologies Corp. He served at many IEEE Committees, published numerous papers in the area of EHV Pole Fires, High Voltage Insulation Contamination and Power Frequency Communication Technology. He is also involved with Communication Infrastructure Studies, Reliability and Life of Electric Equipment, Remote Metering and Distribution Automation and Power Quality. He holds US and world-wide patents in the area of PLC technology (TWACS), currently used in the USA by many electric utilities for AMI and Distribution Automation. He is also IEEE Life Fellow

Eddy So (M'74-SM'84-F'90) received the M.Sc. and D.Sc. degrees in Electrical Engineering from George Washington University, Washington, D.C., USA. In 1977, he joined the National Research Council of Canada, Ottawa, Ontario, Canada. In 1991-2004 he was the Director of the Electromagnetic and Temperature Standards Section in the Institute for National Measurement Standards, where he is currently a Principle Research Officer and Leader of the High Voltage Power and Energy Measurements Project. His research interest includes the development of measurement techniques and instrumentation for accurate measurements of active/reactive power and energy under difficult operating conditions. In 1979-1989 he was Adjunct Professor at the University of Ottawa and Carlton University. In 2002-2008, he was Chair of the Conference on Precision Electromagnetic Measurements (CPEM) Executive Committee. He is Past Chair of the IEEE Power Systems Instrumentation and Measurements Technical Committee, Power Engineering Society, Chair of its Subcommittee on Electricity Metering, Chair of its Working Group on Low-Power-Factor Power Measurements, and is also its Standards Coordinator. He is also a Registered Professional Engineer in the Province of Ontario. He is a Fellow ofiEEE.