STRATEGIC USE OF SMART METERS DATA AND AMI CAPABILITY TO DEVELOP ADVANCED SMART DISTRIBUTION GRID APPLICATIONS

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ABSTRACT
Advances in communication technology, data base management systems and smart meters open the door to deploy numerous new applications for optimizing the distribution network operation. This paper explores new advanced applications in the area of Demand Response, Assets Management and improved Customer Services.

INTRODUCTION
AMI (Advanced Metering Infrastructure), MDM (Metering Data-base Management), SMART GRID, GIS, ASSETS MANAGEMENT, DEMAND RESPONSE, etc. are fast becoming reality. Communication technology provides the ability to communicate to every single point at the distribution network to collect metering data in a timely fashion and also to communicate to other remote intelligent devices. They open the door to a multitude of new applications that were previously unheard of in the electric utility industry. This paper is intended to generate and describe new applications, their synergistic relationships with each other and the impact of green technologies on the total energy delivery infrastructure.

New generation of Smart Meters can generate other types of data besides energy consumption. Monitoring of Voltage, Current, THD (Total Harmonic Distortion), Status of Control Devices, etc. should also be considered as metering data. Until recently Retail Wheeling and Demand Response were initially the few functions which influenced the requirements that an AMI system has to meet. To name a few of those requirements,

1. Interval metering data for intervals of one hour, half-hour or 15 minutes are collected and stored at the meter for future retrieval.
2. The readings must be time stamped. Time keeping is performed by the meter’s internal clock. Standard time reference can be the NBS atomic clock in the USA and other countries can use the GPS time. The smart meter should have the capability to re-synchronize its clock, if a power outage causes the meter to become de-energized.
3. Multi registers data storage shall be available. These three items already provide capability for innovative rate designs and billing and also for implementing many different utility applications. The amount of information collected and stored for later retrieval can be enormous. As an example, a distribution network serving 1,000,000 customers whose meters are read every hour, generates 24,000,000 metering data points on a daily bases. Add time information and customer name to the metering data, the storage requirements go up by a factor of 3 or 4 times. If seasonal and weather impact on energy use is needed to develop predictor models, the need for more storage, data access, partitioning and organization, data security become very critical. Advances in computer and software technology have already reached a point where all storage requirements, accessibility, etc. mentioned above can be met and generically described by the Metering Data Base Management (MDM). MDM becomes a key to the success for implementing many of the utility functions. The MDM system becomes a clearing house and source for different interested parties. Mining the data leads to development of new applications that benefit the energy delivery infrastructure and improve service reliability and customer satisfaction. The collected data will become even more valuable if the metering data can be tagged with information about the meter location at the distribution network. An explosion of new applications is generated if the information can be cross-linked to a GIS system.

NEW METERING ISSUES
Deregulation in many countries has reorganized electric utilities from vertically integrated generation, transmission and distribution monopolies into a consortium of generating companies, transmission and distribution companies. Electric energy has become a commodity and can be marketed to customers through various retailers. Retail wheeling is gaining popularity and is intended to lower the price of electricity through competition in the open market.

Pre-paid metering is also slowly gaining popularity. The introduction of electric vehicles creates new issues. The price of energy for an electric vehicle should be allowed to compete against gasoline fueled cars. Electric utilities are not obligated to subsidize owners of electric vehicles. New possibilities imply the following:

- Customers are given the choice from which energy retailer to buy electric energy.
- Energy retailers are not necessarily competing electric utilities. Retailers can be financial institutions, appliance stores, credit card companies, billing companies, etc. Energy retailers can buy bulk amount of KWHr or its equivalent Carbon Credits for retail through the internet.
- Innovative rate designs
• Customer energy usage profiling for educating pre-paying customers.
• Sub-metering of EV chargers (public or at customer premises) and allow competition with the oil industry to sell energy for transportation.
• Monitoring anomalous use of electricity to detect possible unauthorized use of electricity.

DEMAND RESPONSE

Customer energy consumption profile coupled with time information enables utilities to determine coincident demand and implement demand response through direct load control or voluntary time of use rates. Stratification and categorizing the customer base by socio-economic level, small and medium size businesses, energy consumption levels, etc. also lead to innovative rate structures for demand reduction. Coincident peak demand throughout the whole distribution network is used as a measure to exercise demand response type control through partial demand shifting techniques. Interval reading of KWhr consumption is essentially integrating demand over a time interval and operates as a filter by eliminating minor excursions of demand with respect to its running average. Time interval data of all loads obtained over a period of ΔT minutes have to be synchronized and time stamped in order to determine the total system coincident demand. The synchronization is performed at smart meter by its internal real-time clock.

Another important issue is to determine which customers are candidates to participate with the demand response program. At one time the monthly electric bills were the initial indicators to determine the candidates. Tape recorded load data from selected customer residences were used to obtain the load profiles. For homes that looked similar to the ones monitored, Kalman filtering methods were used for estimating and categorizing load profile similarities of other customers with same size homes. The ability to obtain synchronized interval metering data and saving them into a data base eliminate the guess work to determine the participants for demand response. Contributors to the coincident peak demand can be extracted from the data base. Cyclic loads which are turned on and off during specific periods of the day and randomly distributed throughout the distribution network are the main culprit of causing demand to peak. Load Management strategies were developed to curtail peak demand by using load shifting techniques of groups of customers to reduce peak demand and eliminated the need for peaking unit generation plants. Two-way systems also have the advantage to monitor the health of each load control switch and identify those units that require replacement. The cost of reliability is hence reduced. If during load control, the time synchronized interval meter reading is also operational, then an immediate assessment of the effectiveness of the load control strategy becomes available.

New private companies using advanced sensor technologies are now providing demand response services to the networks. Some have over 5,000 MW of capacity under Demand Response contract. Some regional independent system operators also allow demand response to be bid into their system.

The ability to extract the cyclic load information from the customer load usage profile provides an additional benefit to the utility. If an outage lasts long enough to affect the activities of cyclic type loads such as air conditioners and space- heaters, during power restoration all the units turn on simultaneously causing massive inrush currents. The “cold load pickup” current can cause substation breakers to open. By extracting the cyclic load data from each customer’s load profile, utilities can develop cold load pick-up predictor curves. They are functions of day of the week and seasons. Actions to avoid the adverse effects of cold- load pick up currents are to randomly delay turning on the load control switches which automatically open when a loss of voltage is sensed.

Load restoration for the sound part of a feeder after a fault by transferring it to another source can still pose a problem. The additional load to the other source can exceed its capacity causing undesirable overload conditions. If load profiles of all the phases of the feeders are known, it is possible to design plans for load transfers between feeder segments which will not cause overloading conditions or massive imbalance conditions on the feeders. Intelligent planning for locating the transfer switches, connecting lines between feeder segments to adjacent feeders, etc. will be much more simplified.

DISTRIBUTION ASSETS MANAGEMENT

A unique property of three phase systems is that for any voltage phasor at the distribution substation bus, there is a corresponding voltage phasor at parts of the network served by the substation. It is slightly phase shifted with respect to the substation bus voltage phasor. The magnitude depends on the circuit voltage drop and the intervening transformer winding ratio. Without any intervening power conditioning devices, one can make this phasor connection all the way from remote customer end to generation. Any current drawn at the service voltage side also has its corresponding phasor at the generation side. A massive cumulative imbalance of load or peak demand at the distribution side will reflect as massive imbalance or peak demand at the generation side. Interval load data collected by the smart meters should be tagged with circuit information. This circuit information can be defined in terms of electric network coordinates (s, b, p, f) where

\[ s : \text{ medium voltage substation number} \]
\[ b : \text{ substation bus number} \]
\[ p : \text{ bus phase (phase AN, BN, CN, AB, BC, CA)} \]
\[ f : \text{ feeder number} \]

The demand shifting technique applied to circuit loads
improves the circuit load factor. An intuitive understanding can be developed as shown in fig. 1. In the first case a source supplies two identical coincident loads through a conductor with resistance R and duration T. Calculations show that the loss in the conductor is \( P_{\text{loss}} = 4I^2RT \). The source has to handle the double load for the duration of time T. In the second case, the second load comes in at the end of the first one. The loss in the conductor is \( 2I^2RT \).

The conductor loss is cut by 50% and the source only handle one lower demand only. Hence demand shifting methods improve the load factor, which reduces the losses in the supply network, but also reduces the peak demand requirement for the generation. Here is a case where demand response or load control applications can also be used to improve the system load factor to reduce losses in the distribution network. To assess the network losses the following method can be used. Consider a distribution substation serving N customers. Values of the KWHr, KVAHr and VRMS are collected from each meter. The average power factor \( \cos(\phi) \) is obtained from the following ratio \( \{\text{KWHr} / \text{KVAHr}\} \). The average load current \( I_{\text{rms}} = [\text{KVAHr} / \text{VRMS}] \). From this data, the active and reactive power consumption of the load can be calculated from the meter interval data as shown by the following equations.

\[
P_{\text{load}} = \text{KWHr}/\Delta T; \quad \cos(\phi) = \text{KWHr/KVAHr}
\]

\[
Q_{\text{load}} = P_{\text{load}} \times \tan(\phi)
\]

\[
P_{\text{load}}, Q_{\text{load}} \text{ and } \cos(\phi)
\]

\ can be calculated. If the substation SCADA metering transponder also deliver interval data in synchronism with the smart meter, then the total network losses \( P_{\text{loss}} \) is equal to the average SCADA measured real power \( P_{\text{sub}} \) minus the total average real power data from all N smart meters.

**Total network losses**:

\[
P_{\text{loss}} = P_{\text{load}} - \sum_{k=1}^{N} P_k
\]

\[
\text{Internal network VAR source} = Q_{\text{sub}} - \sum_{k=1}^{N} Q_k
\]

The network losses can be attributed to conductor losses and distribution transformer winding and core losses. For the \( \text{VAR} \) power, the difference between SCADA VAR data and the sum of all the customer \( \text{VARs} \) is due to capacitor banks and capacitance of underground cables \( \text{VARs} \). This capability allows utilities to develop strategies to improve the network load factor and \( \text{VAR} \) control.

For a feeder the voltage at each load can be monitored during the interval meter reading. The current can be obtained from any of the first 3 expressions in equations (1). Then each load can be replaced by an equivalent circuit. Combining the equivalent load impedance of each load with others and coupling them with the impedances of the supply lines and transformers of each lateral, one can construct the equivalent circuit of the laterals of a feeder. The voltages and currents at each feeder segment can be calculated. A dynamic equivalent circuit of the feeder is obtained providing a voltage profile along the feeder and the current at each of the segments. This capability becomes a valuable tool for optimizing the switching of capacitor banks and changing the voltage regulator taps for \( \text{VAR} \) and voltage control along the feeder.

Even though a 3-phase source can be perfectly balanced, due to uneven load distribution amongst the phases, especially along the distribution feeders, the unequal voltage drops on the different phases cause voltage unbalances at the various locations on a feeder. In 3-phase electric machines, negative-sequence voltages generate negative-sequence magnetizing currents. These negative-sequence magnetizing currents generate a rotating magnetic field, which rotates in reverse direction with respect to the rotor. This negatively rotating magnetic field creates a retardation torque and induce eddy current losses causing an increase in temperature of the machine...

**Operating engineers quite often prefer to express the unbalance in terms of dissymmetry, which is defined as the ratio of the negative sequence voltage to the positive sequence voltage. To express this in terms of the actual voltages, if the three phase line to line voltages form a triangle and the absolute voltages can be expressed as \( V = [V_a V_b V_c] \) and the third as \( c = |V_{ca}| \) then the Voltage Unbalance Factor is**:

\[
V = \sqrt{1 + \frac{x^2 + y^2}{6}} \quad \text{and} \quad \Delta V = \sqrt{1 + \frac{\Delta x^2 + \Delta y^2}{6}}
\]

In this expression, assuming that \( |V_{ca}| \) has the largest magnitude, \( x \) and \( y \) have the following values:

\[
x = b/a \quad \text{and} \quad y = c/a
\]

In many European countries the standards limit the unbalance to 2% at the medium voltage level. In the USA ANSI C84.1 Annex 1 and NEMA MG1, for voltage unbalances in excess of 1%, a de-rating of motors is needed. Unbalanced loading of a distribution feeder also dramatically increases the copper losses.

**POWER QUALITY MONITORING AND OUTAGE MANAGEMENT**

Recurring switching in and out of large motors can cause short duration voltage fluctuations. Monitoring the voltage and current on the feeders at strategic locations at specified time intervals of time and synchronizing these readings with interval meter reading can provide a means to identify the loads which cause voltage sags. Some smart meters can also
monitor the THD of the incoming voltage and current at the customer meter. Occasional polling at regular time intervals of these meters on each phase of a feeder can quickly determine the location of the source of distortions where the THD will be highest. This harmonic pollution patrol provides the utility the ability to detect high impedance faults and their locations.

Harmonics whether burst or steady state type affect the energy metering accuracy. These harmonics are generated by non-linear loads, improperly filtered power electronic devices for speed and torque controls of motors and invertors used by wind generators or solar panels. Electric vehicles charging systems are also possible sources of harmonics in the future.

Another possible application is to detect outages by constantly monitoring incoming data to the data base. Utilities have already implemented Selective Coordination of protective devices in their distribution networks. When a fault occurs on a feeder, the protective device nearest to the fault will open to isolate the fault from the substation bus. Non-responding meters indicate most likely that they are de-energized because of a power outage. These non-responding meters locations can be quickly identified from their electric network coordinates tags. Even faster outage mapping can be accomplished if the substation SCADA system can issue an alert signal to the AMI system. If the substation SCADA senses a fault current on a specific feeder or phase of a feeder, a polling sequence of the smart meters on the feeder where the fault is detected can be activated. The non-responding meters are assumed to be de-energized. By locating these meters from the circuit map one can identify which protective device has operated. The maintenance and repair crew can be immediately directed to the site and there is no need to patrol the line. This method is also useful for scheduling recovery work after storm damage to the distribution network. Polling the meters quickly identifies which circuit is still out of power.

Distributed generation is slowly making inroads. Issues involve energy exchange pricing policies, power quality, islanding, liabilities, etc. Smart meters also measures reverse power flow which provides useful information to the utility when the customer’s generation has excess unused capacity. Medium size co-generator connected to a feeder can be damaged due to islanding problems. This is true when the co-generator cannot handle the total feeder load and many induction motors act as induction generators when the feeder is disconnected from the bus. This islanding state causes frequency swings between induction generators and the co-generator which can damage the co-generator. Quick disconnect can be accomplished if the AMI communication can be used to quickly disconnect the co-generator from the feeder when the feeder is disconnected from the bus. The AMI system can issue a system alert to Smart Homes and commercial area networks to curtail demand when the generation spinning reserve is low. As a first step a SCRAM function can be used to shed all controllable loads. If the emergency condition is over, all the load control switches have to be reactivated. Knowledge of their locations in the network helps to control the re-activation process by doing it sequentially into groups to avoid the problem of cold load pick-up. Another possible application is for civil defense alert about impending danger such as flood, storm, etc.

**CONCLUSIONS**

An AMI system can use Smart Meters as remote sensing devices. When the sensing operations are properly time synchronized and the retrieved data time stamped, then smart meters essentially become syncho-sensors. Also by tagging to each data point the circuit information in the data base, it enables utilities to design operational strategies to support comprehensive demand response strategies. Reducing network losses and detecting local overloading conditions will increase the life of distribution equipment and also the service reliability to customers by improving the voltage profile on the feeders and detecting nuisance type problems due to poor power quality. Customer load profiling allows customers to participate with different types energy saving programs and provide customers with incentives through innovative billing strategies. The distribution grid, coupled with an AMI using Smart Meters and other intelligent devices and an MDM system is really becoming an intelligent neural network system.

**REFERENCES**