A Real-Time Architecture for Smart Energy Management

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***Abstract*—Smart energy management has two major aspects, the smart grid (transmission and distribution system) on one hand and programmable smart appliances on the other. This paper presents an architecture that enables the smart grid to provide real time demand and price feedback based on aggregate load conditions to select smart appliance control panels. The panels on receiving the signal automatically control the smart appliances to not only reduce peak loads but also distribute the demand so as to reduce the load variability. This dynamic demand re-distribution leads to lower operating costs for suppliers, lower energy costs for consumers and ultimately lower damage to the environment by reducing the rate of generation and transmission capacity expansion. The architecture of the smart energy management system makes use of sophisticated OLTP systems which decide the load conditions using aggregate demand data from AMIs and supply data from SCADA. High volume OLAP systems combine real time pricing with consumption data from individual appliances to provide customers deep insight into their consumption patterns in the form of costs per appliance.**

Keywords- AMI, OLTP, OLAP, smart appliances, smart grid, smar t meters

I. INTRODUCTION

Electrical power is one of the most important infrastructure inputs necessary for the rapid economic development of a country. The rapid economic development is in turn causing huge stresses in the existing generation, transmission and distribution systems as they are not able to keep pace with the increasing demand. Installation and incorporation of a large number of electrical power generation units with increased capacities to deal with the surging demand has an adverse impact of the environment therefore efficient energy management is imperative. Conventional instrumentation has proven inadequate for the purpose of managing the extensive and complex power systems.

Intelligent systems driven by microprocessors and computers need to be employed for online monitoring and control of modern large-scale power systems, in generation, transmission and distribution to overcome the complexities and drawbacks of the conventional instrumentation schemes. These intelligent systems form the basis of the smart grid. The smart grid (transmission and distribution) by itself does not completely solve the problem of the existing demand-supply mismatch. The smart grid needs to be complemented with smart (programmable) appliances at the customer sites to efficiently re-distribute the demand to provide the benefits of lower costs for customers and operational efficiencies for suppliers.

The main objective of this paper is to provide a framework for utilizing the real time cumulative demand data available at the distribution centers in a feedback loop which enables the smart appliances at the customer site take intelligent decisions automatically. The key is to decide whether the demand is off-peak, mid-peak or on-peak dynamically and relay this information to smart appliances of select customer groups based on available supply.

II. ARCHITECTURE OF SMART ENERGY MANAGEMENT SYSTEM

A Smart Energy Management System (SEMS) has many elements like smart appliances, smart meters, advanced metering infrastructure (AMI), communication facilities, data collectors, interfaces, distribution automation, FACTS, hardware and software systems. A smart energy management system should be able to effectively integrate the information from different nodes of the electrical network. By coupling the smart grid with smart appliances, the feedback loop can be closed. By making the information regarding cumulative demand arising out of the actions of numerous customers available to each of the customer in real time, the "co-ordination problem" is solved resulting in the re-distribution of the demand. When a smart appliance is informed by the smart grid that it is operating under peak load conditions, it automatically takes the corrective action of lowering the consumption thereby reducing the demand.

The following architecture revolves around end to end collection, processing and dissemination of appropriate real time data at various nodes of the smart grid starting from generation to consumption. The architecture facilitates the collaborative functioning of the smart grid and smart appliances that is necessary for efficiently distributing demand.

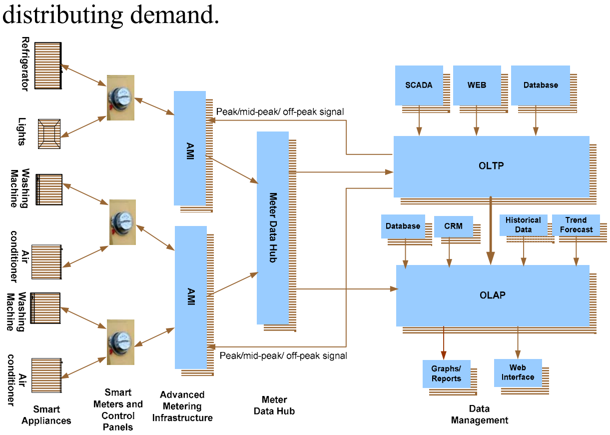

Figure 1. Architecture of Real Time Smart Energy Management System with Smart Grid and Smart Appliances

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The detailed description of some of the major components of a SEMS is given below [1].

A. *Smart appliances and control panels*

The smart appliances which play a crucial role in the Smart Energy Management System should not only be able to generate, transmit and share information but also be programmable so as to be able to react to signals from the local utility which flow through the control panels. The smart appliances would be generating and transmitting consumption information to the control panel and obtaining instructions from the control panel which in turn is fed demand and pricing signals from the power company. The smart appliances would also have the ability to delay some operations from occurring during peak demand hours enabling the utility to manage peak load conditions. On the other hand consumers can also benefit from the dynamic pricing by being notified of peak pricing on a display on their appliances letting them know when higher rates are in effect. Appliances will be programmed to avoid energy usage during that time but consumers may choose to override the program, giving them ultimate control. The smart appliances also significantly reduce cognitive load on the customers because of their ability to react without manual intervention.

B. *Smart meters*

A Smart Grid will need to utilize smart meters at customer service locations. Smart meters are microprocessor based customer meters used for recording and reporting interval data (kilowatts-hours, kiloVAR-hours) and outage (loss-of voltage) information. Each meter is equipped with standard facilities, such non-volatile data storage, tamper detection, remote connect/disconnect capabilities, and two way communication facilities. These are time-of-use meters that have the capability to receive signals from the utility and switch to higher or lower rates as the actual cost of providing power to a customer goes up and down and can be read automatically without the need to send a meter reader to the customer site periodically. The meters could also have a display that tells interested customers their current rate of electricity use, and its costs which would help them make informed decisions. The meters could send the consumption information back to the substations over the power line and then on to the utility company by a radio link. The large amount of data made available to operations and planning by the smart meters can be used to achieve better reliability and better asset management.

However, the biggest advantage of these advanced meters is their potential to reduce peak demand and equalizing distribution system loading patterns by interfacing with smart appliances for collecting consumption information and relaying it to AMI and relaying demand signals and pricing information from AMI back to smart appliances. From a design perspective, peak demand is a key driver. If peak demand per customer is reduced, feeders can be longer, voltages can be lower, and wire sizes can be smaller [2].

C. *Advanced Metering Infrastructure*

Advanced Metering Infrastructure is the central nervous system of the smart energy management architecture. AMI is responsible for collecting consumption data from smart meters and transmitting it to the meter data hubs and also relaying demand signal and pricing information from the OLTP systems back to the smart meters in near real time completing the feedback loop. AMI involves interfaces and high speed communication facilities for communication between smart meters, meter data hubs and OLTP systems. The data collectors need to be installed at strategic locations to enable optimal communication with maximum number of smart meters and collect the meter data at an appliance level to be transmitted to meter data hubs [2].

D. *Meter Data Hubs*

Meter data hubs collect the energy consumption data at an appliance level from a number of smart meters with the help of AMI and transmit them to OLAP system. Meter data hubs are real time databases capable of storing enormous amounts of data generated in very small time intervals.

E. *OLTP for power companies*

An OLTP system for power companies is akin to an ERP system which would typically contain a meter data module for processing demand and supply data, sales and billing module for keeping track of customers, their profile and billing information, asset management module for managing fixed assets, financials module, a real time pricing engine for calculating prices reflecting true costs of supply based on load conditions and a portfolio management module for improved buy and sell decisions. The block diagram below shows a typical functional architecture of an OLTP system for power companies.

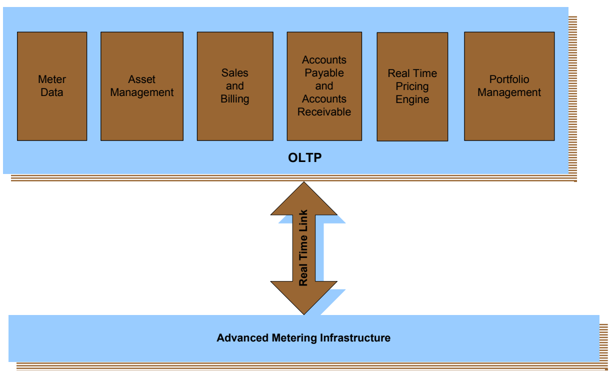

Figure 2. OLTP for power companies

F. *Interface between Meter Data Hub and OLTP*

The complete energy consumption data with a clear break-up of power consumed by each appliance in each time bucket of different customers are uploaded into the meter data hub with the help of AMI. A data transformation process in place aggregates the appliance energy consumption data across customer groups in the meter data hub and pushes the data into the OLTP system to arrive at the aggregate consumption.

G. *Interfaces between SCADA and OLTP*

Measured data for the sources (generators / transmission lines / substations) of power and energy is required for deciding whether the demand is on-peak, mid-peak or off-peak requires in real time. SCADA which is used by transmission and distribution utilities of all sizes makes it possible to monitor and control generators, transmission lines, substations, distribution lines, and in-line equipment and devices [4].

Typically, data acquisition function collects real-time measurements of voltage, current, real power, reactive power, breaker status, transformer taps, etc. from substation RTUs and other nodes of the distribution system every few seconds to get a snapshot of the power system in steady-state. The complete supply information is uploaded into the OLTP system which is processed in real time. For real time processing, high bandwidth communication is required between the SCADA and OLTP systems and the OLTP databases should be able to provide extremely fast data access [1, 3]. The existing SCADA infrastructure may be used or the next generation AMI can also be used for the purposes of collecting supply information in real time.

H. *Interface between OLTP and AMI*

The OLTP should obtain supply information at distribution centers from SCADA and the aggregated customer demand information from the meter data hubs at predefined intervals. Depending upon the extent of the demand-supply mismatch, the OLTP system dynamically decides whether the load is peak, mid-peak or off-peak and this signal is relayed along with the pricing information to a sub-set of customer groups identified using intelligent algorithms to re-distribute demand. Once the AMI receives the demand signal and pricing information from OLTP, it is sent to smart meters which in turn send a control signal to the smart appliance control panel (HAN) to which multiple smart appliances are attached. The demand signal arrives at the AMI after a specific time lag and it persists till the next signal is received from the OLTP system.

I. *Benefits of real time architecture*

The real time architecture provides numerous benefits to the suppliers and customers. The power companies can exercise control over the demand which increases the reliability of grid operations, helps in obtaining power at lower costs from other distribution companies because of the increased accuracy of demand forecasting. Suppliers can also use real time information of existing demand and supply to efficiently trade excess power with other distribution companies or for re-generating purposes like pumping the water back to the reservoirs or charging the batteries. Short term demand forecasting can be significantly improved by analyzing the information present in the smart control panel (HAN) settings. By deducing the upper and lower bounds of demand of the customers based on historical data the suppliers can achieve significant reliability in terms of power distribution as well reduce the maintenance costs and capital expenditure costs like conductors, insulators and transformers. The capacity margin observed over a period of time can help investors and supplier make informed decisions about capacity expansion.

The customers benefit because they have an opportunity to reduce costs by obtaining immediate feedback about the costs of their consumption.

III. BILLING ANALYSIS CASE STUDY (RESIDENTIAL CONSUMER)

Providing the customer with a deep insight into his electricity consumption patterns in the form of costs incurred per appliance is vital not only for reducing her energy costs but also for the re-distribution of the demand as a whole during peak loads. This can be achieved by an OLAP system which can not only analyze huge amounts of customer energy consumption data at the appliance level but also combine it with real time pricing information. This non aggregate data can also be provided to the customer for analysis through a web based interface.

The following case study has been developed to illustrate the significant benefits that can accrue to the consumer in the form of lower costs if she is able to re-distribute a small portion of her consumption in the peak hours to mid-peak or off-peak hours. Currently many utilities usually pre-define unit rates for a given range of total consumption as shown in the table below.

TABLE I. TARIFF RATE

Units(Kwh)	INR/ Kwh
0-50	1.45
51-100	2.80
101-200	3.05
201-300	4.75
>300	5.50

With the present energy meter the consumer and the utility service provider can only get the data shown in the table below.

TABLE II. CUSTOMER CONSUMPTION DATA

Total connected load	Total consumption per month	Energy charges per month
7.8 Kw	284.38 Kwh	INR 918.305

The consumers do not know have enough insight into their daily energy consumption, their daily/hourly demand, which appliances are consuming more energy, how much energy they are consuming compared to their neighbors and how they could manage their consumption better. In case of smart grid, real time rates can be calculated based on the state of demand like shown in the table below.

TABLE III. ENERGY PRICES UNDER DIFFERENT DEMAND CONDITIONS

Energy Consumption	Rate (INR/ Kwh)
Mid Peak	3.5
On Peak	6.5
Off Peak	1.5

In case of AMI, the cost of consumption more accurately reflects the costs of production under different demand conditions as show in the table below.

TABLE IV. COST OF CONSUMPTION USING AMI

Energy	Consumption (Kwh)	Cost of consumption (INR)
Off peak	108.32	162.48
On peak	38.46	249.9
Mid peak	137.6	481.6
Total	284.38	893.98

Power companies can provide a login to customers so that they can login to their account and they can watch their real time consumption in a graphical view over the internet. Customers can also be provided with highlights of their bill, including a breakup of the energy costs by appliance as shown in the figure below.

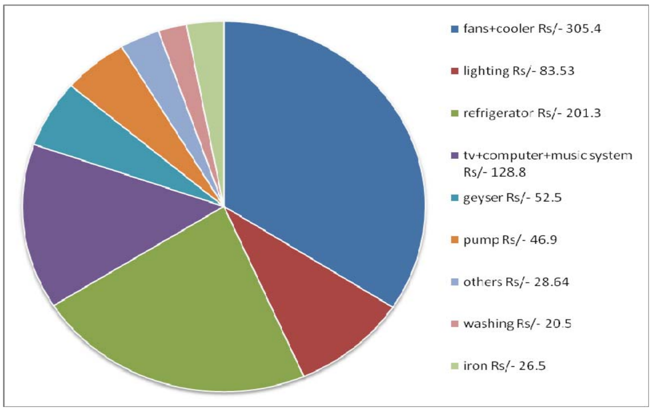

Figure 3. Energy costs of using each appliance

Power companies can also provide analysis which helps customers understand why their bills have changed from the previous period, like identifying the impact of factors such as billing cycles, the weather, or increased appliance usage. Sophisticated customers concerned about their bills can be provided with several tools like a rates calculator that lets them know how they would have fared on different rates, bill-to-date calculation at any time in the month, and a load shift calculator that identifies strategies for shifting usage from the peak to the off-peak.

Power companies would have the information to create customized products as well as offer targeted services and rates e.g. move customer to a different plan, based on the consumption patterns of their customers. By continuously observing the consumption data over a period of time, the power companies can mine the data for atypical consumption patterns and plan accordingly. The appliance energy consumption and usage data in the OLAP system can be used innovatively. It can be used to provide customers insight into their appliances' performance, for conceptualizing new products and features by appliance manufacturing companies and identifying leakages by the power supply companies.

IV. CONCLUSIONS

In twenty years, the distribution systems will have advanced metering, robust communications capability, extensive automation, distributed generation, and distributed storage. Through the integrated use of these technologies, Smart Grids will be able to self heal, provide high reliability and power quality, be resistant to cyber attacks, operate with multi-directional power flow, increase equipment utilization, operate with lower cost, and offer customers a variety of service choices. Smart appliances should be used in conjunction with smart grid for reducing the peak demand. Real time information feedback regarding peak load conditions sent to smart appliances at customer site can help in redistributing demand which can reduce demand-supply mismatch significantly. Reduced variability in consumption leads to lower breakdowns and lower operating costs. OLTP system can be used to decide the load conditions based on aggregate consumption data and supply data and this information can be relayed to smart appliances control panels of select customer groups for automatically adjusting demand. OLAP systems can be used to combine appliance wise power consumption at each customer site with real time price information which is a function of demand. This information can be made available to the consumer using a web interface and helps the customer analyze the energy consumptions of different appliances in terms of cost and program the smart appliances better. Smart appliances need to be programmed to intelligently to deal with demand signals from the smart grid e.g. not shutting down when they are very close to the completion of an operation or in case they are performing a critical operation. The proposed architecture provides numerous other benefits like better demand forecasting, providing information for trading and investment decisions. Smart grid used with smart appliances has the potential to revolutionize the energy management as it reduces and re-distribute demand automatically, provides valuable insights to customers which ultimately save the environment by reducing the carbon footprint of power companies.

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