

Architecture for Smart Grid based Consumer End Solution

Shailendra B.*, Sanjay SINGH*, Omkar KARANDE*, Samir CHATURVEDI*, Shashank DHARIWAL*,
Varun MOHAN**.

**Electronics and Telecommunication Department, SVKM's NMIMS, Shirpur, Maharashtra, India.*

*** Information Technology Department, SVKM's NMIMS, Shirpur, Maharashtra, India.*

b.shailendr@gmail.com, sanjay.thepro@gmail.com, karande.omkar1989@gmail.com,
chatursamir@gmail.com, shashank7289@gmail.com, varun_mohan1989@hotmail.com

Abstract— The following paper proposes the architecture for a consumer – end solution to smart grid implementation. The objective of the on-going research is to arrive at a system that can easily be integrated with the current electricity distribution infrastructure, with minimal modifications. The system consists of two entities present on the consumer premises – a central processing unit called Power Hub and an intelligent switch, called Slave, to which an appliance needs to be connected. The implementation can serve a wide range of applications such as restricting consumer electricity billing through inbuilt policies, implementing prepaid billing, energy market transactions, etc.

Keywords— Power Hub, Slave, Hub & Slave architecture, Appliance DNA, Current Sample Addressing, Energy Market Gateway, Universal Plug N Play, etc.

I. INTRODUCTION

Energy Distribution grid is one of the most primitive needs in a modern world. Sadly, it is also one of the few areas where changes had been resisted since its inception, until lately. Current scenario hosts a number of projects on various domains of Smart Grid such as IEEE P2030[7], developing a draft guide for smart grid interoperability, and Italy's Telegestore project[6], which networked large numbers of homes through smart meters working on narrowband Power Line Communications, etc. Other researches aim at providing a physical layer at consumer premises to digitize energy distribution at the application-end, and interface them with Smart Grid entities. These include IEEE P1901[8], developing a global standard for high speed Power Line Communication, and other commercial standards such as HomePlug1.0, HomePlugAV, focussing on Broadband over Power line, and HomePlug Green PHY, focussing on smart grid applications.

This paper focuses on implementation of a platform to deploy Smart Grid based technologies on the consumer side. Power Line Communication is proposed to be used for inter-communication within the network, with minimal changes in the existing infrastructure. The Block diagram of the consumer end solution is proposed in Figure 1.

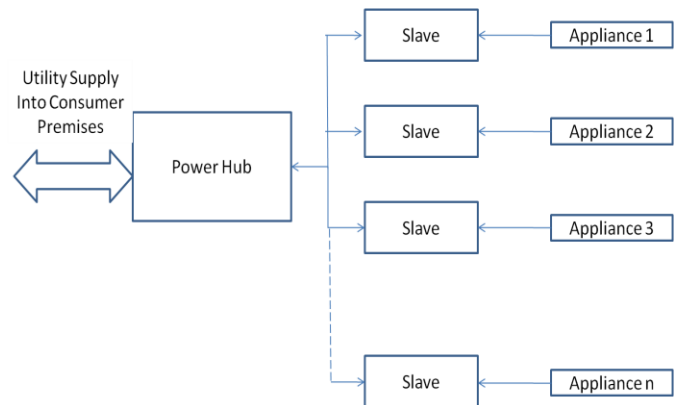


Figure 1. Block Diagram of Consumer End Solution

The proposed scheme consists of two functional entities.

A. Power Hub

A Power Hub is an innovative and advanced utility meter that records a business or consumers electricity usage in greater detail than the conventional analog electricity meters.

Since the inception of electricity deregulation and market-driven pricing throughout the world, government regulators have been looking for a means to match consumption with generation. Traditional electrical meters only measure total consumption and as such, provide no information of when the energy was consumed. Power Hubs provide an economical way of measuring this information, allowing price setting agencies to introduce different prices for consumption based on the time of day and the season.

Electricity pricing usually peaks at certain predictable times of the day and the season. In particular, if generation is constrained, prices can rise significantly during these times as more expensive sources of power are purchased from other jurisdictions or more costly generation is brought online. It is believed that billing customers by how much is consumed and at what time of day will force consumers to adjust their consumption habits to be more responsive to market prices.

The Advanced Metering Infrastructure will allow electricity to be charged according to demand based tariffs.

B. Slave

Slave is a smart switch that communicates with the Power Hub and accordingly controls the appliance connected to the switch. In the proposed scheme, each appliance has to be connected to the mains through a Slave, which will enable the users to set priority for each appliance, so that the lowest priority appliance is switched off first, in case of load shedding. This hierarchy will be followed until the required amount of load is shed. It will enable the utility to provide the much needed flexibility to the consumer, regarding the priority amongst the appliances. The Slave assumes a unique ID, based on the power consumption characteristics of the appliance and the set priority, every time an appliance is switched on, thus making the process highly dynamic. The proposed scheme tries to emulate a Plug and Play mechanism, the objective being convenience at consumer end.

II. ARCHITECTURE

A. Power Hub

Functional Blocks within the Architecture of Power Hub are explained in the figure 2.

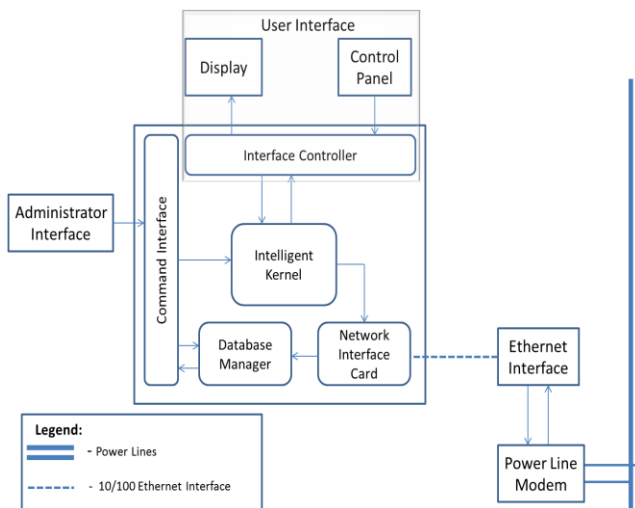


Figure 2. Architecture of Power Hub

1) Network Interface Card: The NIC provides a physical link to a network. It converts the data sent by Hub into a form which can be used by the network cable, transfers that data to Slave, and controls the data flow between the Hub and Slave. It also translates the data coming from the cable into bytes, so that the Hub can read it.

2) Database Manager: The Database manager is a module that can manage any number of database instances from Slaves and the Grid. It consists of a Command Line Interface (CLI) that links to the Database Server, and exchanges information with it. The CLI can receive requests locally, as well as remotely from the administrator interface. The Database Manager performs the following functions.

- to maintain power consumption logs received from the Slaves,

- to check the database for ambiguities in IDs of the online appliances,
- to display index keys, and orders,
- to display table statistics, and performs table encryption.

3) Intelligent Kernel: The Intelligent Kernel provides decision making capabilities to the Power Hub. It processes instructions given from the administrator interface, and executes them according to optimized algorithms. It adds the following functionalities to the system.

- to decide and update current tariffs based on instructions from the grid,
- to implement the power cut instructed by the Grid, and optimize the switching based on priorities and policies adapted by the user,
- to transact energy with the grid, and thus, establish open market for energy transactions,
- to monitor performance of each appliance, a regular check is maintained on the server. The power consumption patterns over a period can indicate degrading performance of an appliance. Such problems which may be indicated at nascent stages of failure may not be detected visually.

4) User Interface: User Interface (UI) has been integrated in the system for interaction with the client through a display and a control panel. The user gets a choice to see the statistics of his power consumption and can also opt for different policies available.

5) Ethernet Interface: Ethernet Interface converts the data from protocol used in the network, to the standard Ethernet data format.

6) Power Line Communication: The Power Line Modem is a transceiver that provides a reliable communication link over power lines. It utilizes Binary Phase Shift Keying for modulating digital data over a 2 MHz frequency carrier signal.

B. Slave

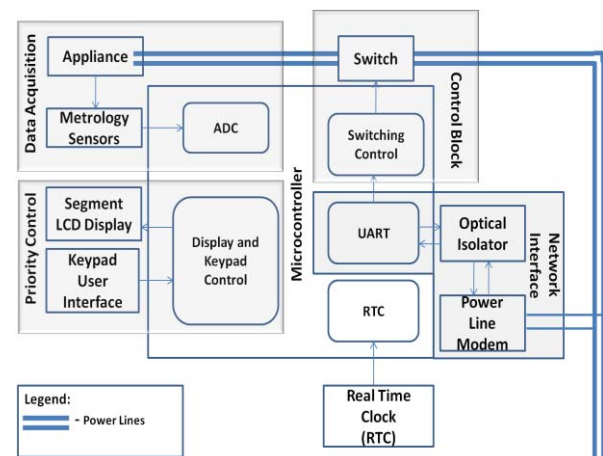


Figure 3. Architecture of Slave

The Architecture of the Slave can be broadly divided into four sections.

1) Data Acquisition: This section is responsible for acquiring power consumption data such as Line Voltage, and Line Current of the appliance/nodes. The data is obtained through metrology sensors, and given to a moderate resolution ADC. This data is sent to the Power Hub over the power lines, where the data is processed to reveal details such as power factor, etc.

2) Priority Control: Priority Control allows the client to set priority of operation of the appliances. These priorities would be followed to switch off appliances during power cuts, so that the basic needs of a consumer are uninterrupted.

3) Control Block: It performs switching of appliances according to instructions issued by the Power Hub. It consists of AC switching elements such as TRIAC, controlled by the Slave.

4) Network Interface: Network Interface provides a physical link between the network and the Slave. It consists of a Power Line modem, interfaced to the serial interface of the Slave through an optical isolator.

III. SYSTEM IMPLEMENTATION

The Half-Duplex communication link would be established through the Power Line Modem on the physical layer. The functional block diagram is as shown in figure 4.

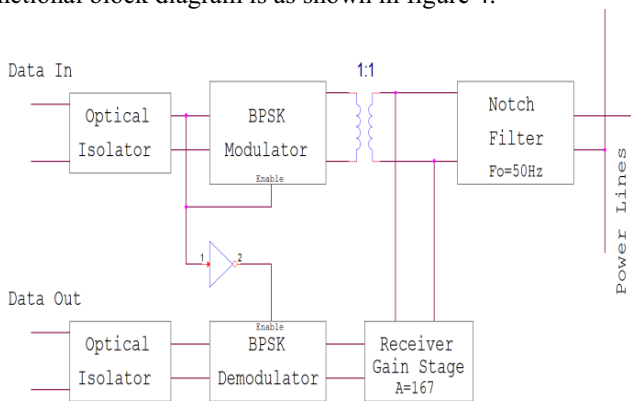


Figure 4. Functional Block Diagram of Modem

Each functional block of the modem can be explained as below.

A. BPSK Modulator

The modulation scheme employs a switched-resonator BPSK modulator. The bit rate and carrier frequency have experimentally been reported as 2.5 Mbit/s, at 5 MHz, respectively. [1]

The modulator, as shown in [1], doesn't require a carrier input, phase shifter, or a switch circuit as in traditional BPSK Modulators. The modulator consists of a Voltage Controlled Current Source (VCCS), a resonator and a limiting amplifier.

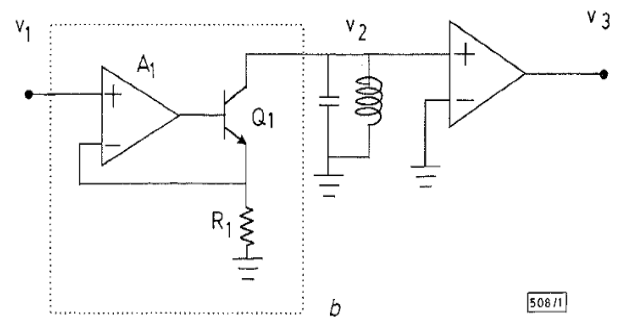


Figure 5. Switched Resonator BPSK modulator [1]

The VCCS, made by A, Q, and R, produces the NRZ current pulse stream and injects such a signal into the LC resonant circuit. If the resonant frequency f_r is an integral time of the bit rate, the resonator output voltage will be a BPSK signal. By adding a comparator or limiting amplifier following the resonator, we can compensate for the amplitude decay and still maintain the phase reversal. [1]

B. Notch Filter

The Notch Filter has been employed to protect the modem from large power at lower frequencies, in the Power Lines. The design requires a band-stop filter, with stop-band ranging from 40 Hz to 300Hz, and pass band extending to higher frequencies of upto 2 MHz. "The intrinsic high-frequency limitations of the low-frequency notch circuit are overcome by means of a coordinated parallel high-frequency path. The combination of the two is capable of the extremely wide frequency response." [2]

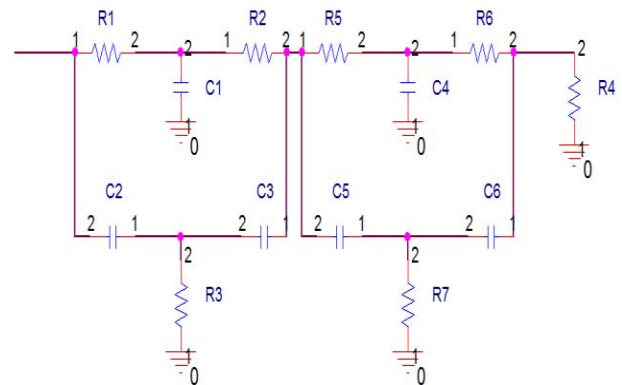


Figure 6. Symmetrical Twin-Tee Notch Filter

According to [2], the notch filter can be realized in three topologies, Resistive-Branch Notch Filter, Capacitive-Branch Notch Filter and Twin- Tee Notch Filter. Amongst the three topologies, a symmetrical Twin-Tee design stands intermediate between the other two topologies, and is suitable for a moderate bandwidth with a simple design.

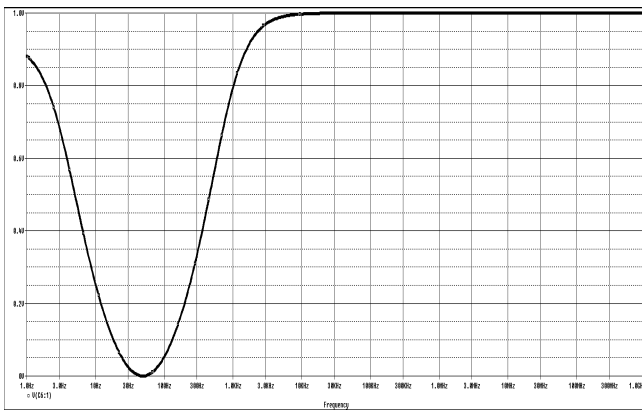


Figure 7. Frequency response simulation results of symmetrical Twin Tee notch filter

C. BPSK Demodulator

BPSK Demodulation can be achieved through several techniques, such as Squaring Loop and the COSTAS Loop. However, the main problem of the squaring loop design is that squaring devices are hard to implement using analog circuitry [4]. Due to higher power consumption and inferior tracking range of COSTAS Loop, low power BPSK Demodulator architecture proposed in [3] would be utilized in the modem. The block diagram of the demodulator is shown in figure 7.

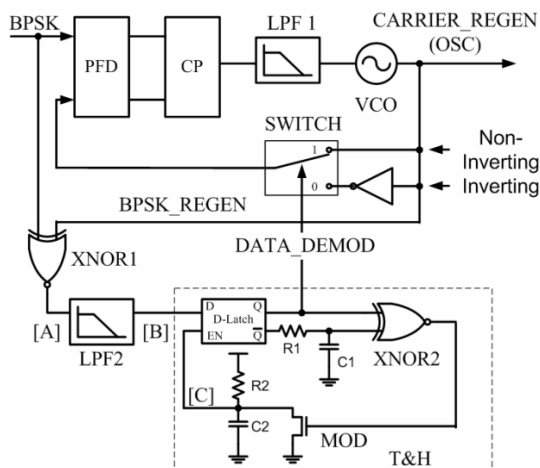


Figure 8. Low Power BPSK demodulator. [3]

The demodulator consists of Phase-Frequency detector followed by Charge Pump PLL, which theoretically has an infinite tracking range. [3] This stage is followed by a trigger & hold circuit.

IV. NOVEL ADDRESSING METHOD

The communication scheme employs an optimized custom protocol to transmit BPSK modulated data over power lines for communication between Hub and Slave. The protocol is in initial phase of development, and identifies slaves in the network by assigning unique addresses. The following approaches have been considered for address assignment.

A. Current Sample Based Approach

A novel approach for assigning addresses/IDs to the Slaves for the purpose of communication has been proposed. When any particular device is switched on, the first line current sample obtained from it is unique, if acquired using a high resolution A/D converter. Suppose the sample is acquired using an 8-bit ADC, the sample would consist of 256 quantums. The probability of these 256 quantums being identical is unlikely even for identical devices of the same manufacturer. The Slave acquires this sample and communicates it to the Hub.

The Hub checks its database for ambiguities with the ID's of existing online appliances. In absence of any ambiguities the ID is assigned to the Slave in question. If a rare conflict is encountered the Hub resolves it by adding a predetermined value to the ID until it becomes unique.

This kind of approach automates the address acquisition by the Slave. The process requires no additional computation and works on the existing data. The ID is lost as soon as the appliance is switched off, thus keeping the process highly dynamic. The emphasis of the approach is to achieve Universal Plug N Play for Slaves.

B. Appliance DNA

We propose a method to obtain signatures of appliances. These signatures are preserved in the database even when the appliance goes offline. The idea is based on the fact that every appliance when manufactured have some non-uniformities, or defects that do not reflect in the normal operation but become prevalent at microscopic and nanoscopic levels. If these non-uniformities can somehow be reflected in the power consumption pattern of the appliance, they can be treated as a unique signature of the particular appliance. Further research is in progress to make this approach acceptable universally.

V. APPLICATION SCENARIOS

A. Smart Grid Technologies

1) Device Management: In countries where demand of power exceeds generation, power cuts are a major problem in residential sectors, Small & Medium Enterprises (SMEs). Such scenarios can be easily manipulated with the help of the proposed architecture. As the architecture states a provision for specifying priority of operation of each appliance, during percentage power cuts or higher tariff rates, the Hub itself switches off the low priority appliances, without interrupting the essential electricity needs of the user. Thus the Hub and Slave architecture provides the platform to regulate monthly tariffs and efficient use of energy.

2) Prepaid Power: Prepaid tariffs can be implemented using the above architecture. This can be customized to daily, weekly or monthly tariff plans. The user can buy the power credits beforehand depending on the budget. The Hub will alert the user when the available power credits fall below a certain level. This will help the user to choose an economic approach towards energy consumption.

3) Energy Market Transaction: The proposed architecture provides us a platform for regulated Energy transactions between the Consumer and the Grid. The consumers targeted here are households and SMEs capable of producing power through Solar Panels, Boilers, Furnaces, etc. but not being able to store it. These consumers can transact the excess power with the Grid for energy credits. This will help the Grid to tap energy from discrete resources which would have otherwise been wasted.

Power Hub can act as a gateway to transact with the Grid. Many Power Hubs can communicate amongst each other to establish an Open Energy Market, wherein a consumer can buy power from multiple sources, creating a competitive scenario.

Figure 10 depicts a typical case wherein a customer has excessive energy which can be transacted with the Grid or other customers.

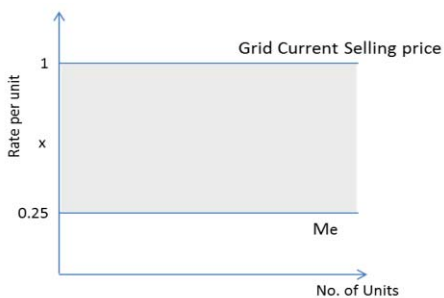


Figure 9. Typical Energy Market Scenario

The Grid has set a selling price per unit for particular duration. Let M_e be the minimum price per unit. The Grid would always be available to buy energy at this cost. This price would be logically set by the Grid, keeping in mind the profit margins to the customer after cost of production. If one has energy resources to produce energy then one would preferably look out for other customers willing to buy the energy at the cost of x which lies between the graph of unit 1 and unit 0.25.

Apart from power producing clients, passive consumers can also participate in energy transactions, by trading their power credits with other users, for an amiable price. Thus, both the Grid, and customers would be benefited by such an open energy market.

B. Other Applications

1) Breakdown Management: The above architecture can be effectively employed to centrally monitor performance of machines connected in a production plant. The database maintained in the Power Hub can be used to detect gradual increase in power consumption of a machine over a period. This performance can be analyzed at the Power Hub to reveal machines that need immediate attention. Such an analysis can help to identify degradation at an early stage which is otherwise not visually detectable until a complete breakdown of the machine occurs. In the presence of redundant machines, the servicing can be scheduled without disturbing the production routine.

2) Power Factor Correction: Power factor correction at appliance level can reduce load on utility to a considerable extent. Power factor can be corrected by the Slave with use of some additional hardware specified in [6]. This keeps the current and voltage in phase with each other, and reduces total harmonic distortion.

VI. CONCLUSIONS

The project implementation is still in nascent stages, and work is in progress for physical layer implementation of the architecture. This would be followed by development of an optimized custom protocol for communication between entities of the network.

The proposed architecture can be effectively deployed for implementing Smart Grid based technologies on the consumer premises. This paper reflects the new era of smart platforms for implementing power management policies. The architecture and hardware can also be scaled to increase the network throughput, and can be integrated with Home Area Networks for providing other services such as IPTV, Broadband over Power Lines, Home Automation, etc.

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