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Simulation based Energy and Cost Optimization for Home Users in a Community Smart Grid

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Abstract- Smart grid is the future electrical power grid with cutting-edge features and two-way flow of electricity and communication. One of the main challenges of the future self-sustainable smart grid is the integration of wireless technologies. Wireless communication technologies play a key role in the future power grid due to real time pricing, monitoring instant power consumption, meeting extra power demand, enabling smart battery status, routing power sharing message etc. The main goal of this research is designing, modeling and simulating a smart grid architecture by utilizing renewable energy sources (wind and solar) and wireless technologies. One reference and a novel proposed, single line future smart grid (SLSG), scenario of smart grid has been designed and evaluated. The states of the proposed scenario are off-peak smart grid (OfPSG), on-peak smart grid (OnPSG) and mid-peak smart grid (MPSG). A novel simulator was designed and implemented by using Turbo C++ to evaluate and optimize the energy and cost for the users. Results showed the highest gain of up to 88.11% and 88.06% of energy saving and cost reduction is possible comparison with the reference scenario, respectively.

Keywords Smart grid, power scheduling algorithm, demand side management, renewable energy, smart meter.

1. Introduction

Conventional power grids are characterized by centralized power generation plants, vertically integrated utilities and demand side management (DSM) of electricity [1]. Conventional grids are facing hassles from different aspects due to recent trends such as deregulation of electricity markets, distributed generation, accommodation of intermittent renewable energy sources, DSM and increasing consumption [2-5]. A next generation power grid system entitled as smart grid (SG) promises to revolutionize the traditional power grid by improving power reliability and quality. DSM, smart metering, real time pricing and effectuating extra demand are the key features of a smart grid technology, achieved by enhancing the capacity and efficiency of an existing electric power networks. It has facilitated and expanded the deployment of renewable energy sources, accommodating distributed power sources, presenting opportunities to improve the grid security [6-7]. Generation of electrical energy from electric power sources is variable due to their limited natural resources and environmental dependencies [8]. In order to support DSM in smart grid, the reliability of data communications system of smart grids becomes a crucial feature to ensure efficient, continuous, and secure operations of the grid [9]. SG uses two-way flows of electricity and information to create a widely distributed automated energy delivery network [10]. Laverty *et. al* [11]. Proposed a reliability analysis and design of smart grid wireless communication system to support DSM. The existing SG standardizations have been reviewed and concrete recommendations are given by various researchers for future SG standards [12]. Vasconcelos [13] outlined the potential benefits of smart meters, and provided a short overview of the legal framework governing metering activities and policies in Europe. Smart metering allows users to monitor their smart home appliances, uses to shape electricity consumptions. By using Power scheduling algorithm in smart grid framework, proposed by many scientist [14-15]. Consumers are encouraged to shift some of their tasks from peak to off-peak hours in return for some benefits as a results of less unit pricing. Reducing peak demand is in the interest of utilities, enables them to abbreviate the usage of peak plants which are commonly more expensive compared to base plants, and therefore reduce their running costs and improve reliability of the supply [16]. In SG, wireless communications technologies can play a significant role for metering and controlling data exchange between smart meters and the central data processing unit (CDPU) in a community. Users' home appliances can be wirelessly connected via smart meters for various purposes such as- billing, energy monitoring, alarm signalling etc.

Figure 1 depicted a typical power distribution framework in Europe where the primary sub-stations works between 110KV and 20/10KV in the medium voltage level. Primary sub-stations have an important role in power distribution infrastructure and it can transform the medium voltage level to the low voltage level. The secondary distribution section (illustrated by green box) is the main focus of this current research because terminal power consumers are connected via some local dedicated feeder lines originated from this station. In here, low voltage level of primary distribution section is transformed to the domestic user level that can be transmitted into local feed lines through feeder lines.

As shown in figure 1, the architecture of the power distribution section is supported by wireless communication technologies such as Wi-Fi, ZigBee, WiMAX or LTE. These provide the two-way flow of electricity and communication between the end uses and the CDPU as a result of using smart metering system to monitor demand response, extra demand, and alarm signal, power sharing, joining or leaving a new user. In this paper, a new scheme of smart grid architecture entitled as single line future smart grid (SLSG) has been proposed for a distribution framework. A simulator has been designed and implemented on SLGS with an advanced power scheduling algorithm (PSA) for energy optimization, aiming at reducing energy cost for the residential users [17].

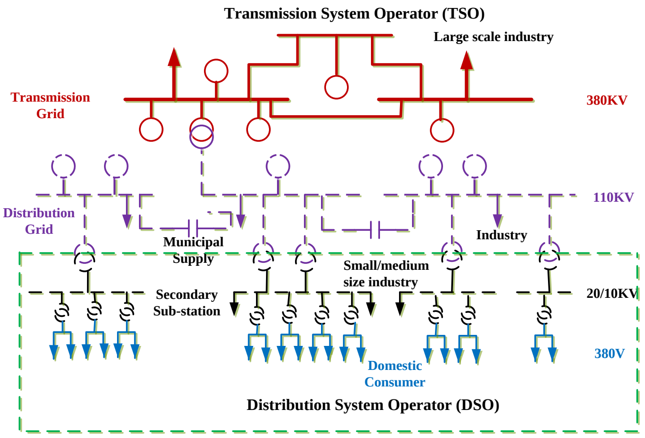

Fig.1. A typical power distribution network in Europe [3]

2. Smart Metering Architecture

Smart meters (SM) are used to record electricity consumption, exchange information between utility and consumers, and manage usage by switching on/off some appliances, and track consumption over time and scheduling appliances [18]. Smart home provides an interface for a user to track consumption and take necessary optimized decisions.

Fig.2. Smart Metering Architecture

They can also be used to show generation capacity and storage constraints [19]. Smart meters connect all smart appliances and allow user to shift consumption from peak to off-peak hours [20]. It is capable to detect the energy consumption rates in real-time by capturing the voltage, frequency and power factor for smart measurement. A typical smart metering system illustrated in Fig. 2, consists of metering and communication infrastructures. The metering section of an SM includes time-of-use pricing control, DMS, and automatic meter reading framework. The communication infrastructure allows a bidirectional data flow to enable the SM. Hence, SM enables them to communicate with remote centers and to run the control commands [21-22]. Home/business/industrial area networks (HAN/BAN/IAN) are deployed within residential units, commercial buildings, and industrial plants for connecting multiple electrical appliances to smart meter. Several types of communication network infrastructure, such as IEEE 802.15.4 (ZigBee), IEEE 802.11 (Wi-Fi), IEEE 802.16m (WiMAX), or cellular networks (e.g., GPRS, 3G, and LTE) are used for demand response of these areas [23-24].

3. Problem Statement

A local community smart grid of a limited number of residences is considered with renewable energy source (wind mill and solar cell) support, battery storage, and smart meters equipped with wireless communication technologies such as Wi-Fi, WiMAX, ZigBee, LTE etc. Each smart meter sends and receives the instant energy consumption, pricing and extra power demand information to and from the (CDPU) located on the secondary sub-station in distribution section. CDPU is the main controlling unit of the smart grid. It may consist several sub-data center which play important role of the CDPU by cooperating, sharing and updating smart meter's data via wireless links. If any user requires extra power, his smart meter will send demand message to the CDPU unit via wireless communication medium.

After receiving this message, CDPU begins a process to find the battery state of all other local power consumers via broadcasting message to all smart meters in that coverage area. All users' smart meters are powered by residential renewable energy source (energy-harvesting). For any particular hour, if any user's power consumption is higher than the battery storage then the extra demand is met by one of its neighbor user. If such mechanism is not possible, the user's power demand will be assisted by the utility [25-26].

Total hourly basis daily energy consumption and the cost will be evaluated. If users, choose off-peak hours to use their home appliances the energy cost will be less than peak-hours. Because, in peak hours the price rate of electricity is always higher which is set by utility companies. In addition, during the mid-peak hours, energy price is regular compared to other time slots. To overcome the peak-hour time demand may be used renewable energy sources stored in smart batteries. If the battery is not sufficient enough to meet the demand, it will contact to the CDPU. It will manage power by forwarding a power sharing message among the whole community and the nearest node will share power according to the request. In such a way, peak, off-peak and mid-peak optimizer was introduced to maintain the energy rate at a flat level for the home users all around the year [27-32].

4. Traditional Power Distribution Systems

Traditional power grid or power distribution system is unidirectional power supply systems which allow power flow throughout the end users to meet their regular power demand. The electric utility system is usually divided into three subsystems which are generation, transmission, and distribution. In this section will discuss about traditional power distribution system with a schematic diagram which will outline the different entities of this system.

Figure 3, shows the architecture of a traditional power distribution system, addressing domestic users that consume electrical power, supplied by the utility. Domestic load consists of lights, fans, refrigerators, heaters, televisions, washing machines etc. In each house, there is an electrical energy meter to record the consumed power in KWh and convey back the collected data to utilities. The utilities report back the monthly power consumption bills to the domestic users. After that the power consumers pay for the power consumption. In general, there are three categories of electrical load depending on daily load cycle. maximum, minimum and average. The maximum load of a utility consumer is the greatest demand during a given period in a day. It varies from time to time. The maximum value of all the demands that have occurred during a given period is the maximum load. The maximum load is generally less than the connected load because all the consumers do not switch on their connected load to the system at a time. The knowledge of the maximum load is very important as it allows in determination of the installed capacity of the user's home. The average demand occurs in a given period during a day or month or year. The daily average demand is the ratio of total number of power units consumed by the users in a day to the total hours (24hrs) in a day. The minimum load of a utility consumer is the lowest demand during a given period in a day.

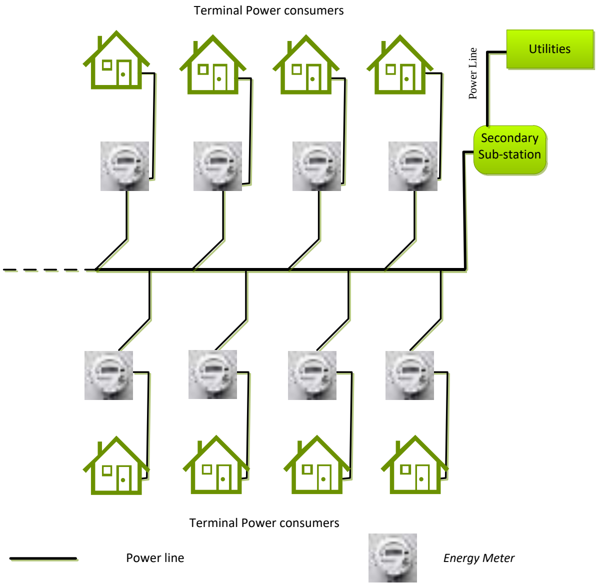

Fig.3. Traditional power distribution system (TPDS)

5. Proposed Smart Grid Architecture

Proposed single line future smart grid (SLSG) scenario architecture has been illustrated in figure 4. In this scenario, all users have the support of both renewable energy and local utility. Users use their renewable energy as primary source and utility as secondary source in case of scarcity. Users can store their excess energy (renewable) in smart batteries. Each house is equipped with smart meter, these smart meters are connected with all smart home appliances via four different wireless connections (Wi-Fi, ZigBee, WiMAX, and LTE).

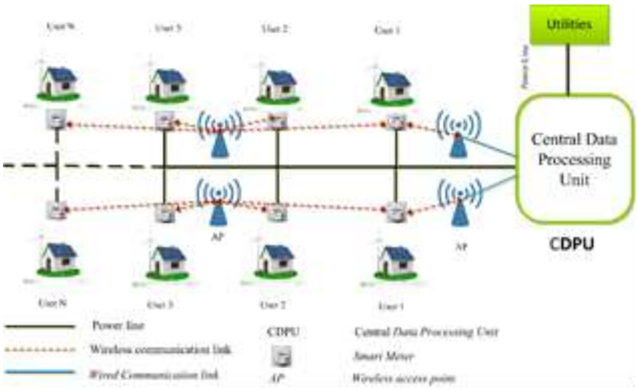

Fig.4. Schematic design of proposed single line smart grid (SLSG) architecture

These meters can send and receive information form CDPU and allow users to control their home appliances remotely. Smart meters of this community are designed in such a way that allows them to be monitored by CDPU. If any user needs extra power, smart meter will send message to CDPU. After receiving message, CDPU will execute an advanced PSA in fig.5 to sequentially fulfill the user demand. Frist, CDPU will forward a demand message in the whole community. If neighbor user can meet the extra demand, CDPU will channel the excess stored energy of neighbor to the desired user. If demand can't be fulfilled by neighbor users, power will be acquired from local utility. Three power consumption states have been considered such as peak-hour, off-peak hour and mid-peak hour. For home users usually morning is the off-peak hour, noon or after noon is the mid-peak and evening is the peak-hour. To implement this scenario, a simulator has been designed and developed to evaluate the hourly and daily basis energy consumption and price for the home users. To evaluate the simulation results the simulator has been run and results were averaged over the 10 iterations. Each simulation collects the results of 7 days (24 hours per day).

6. Flow Chart for Power Scheduling Algorithm

The proposed algorithm shown in Figure 5 runs according to the following steps:

1) Set the total number of iteration equals to 10 to run the program ten times to get more precise results.

2) Open a text file to store the final output results
3) Set smart battery capacity
4) Input the investigated data
5) Generate the random values
6) If the user battery capacity is greater than or equal to the maximum capacity then user battery equals to the maximum battery capacity.

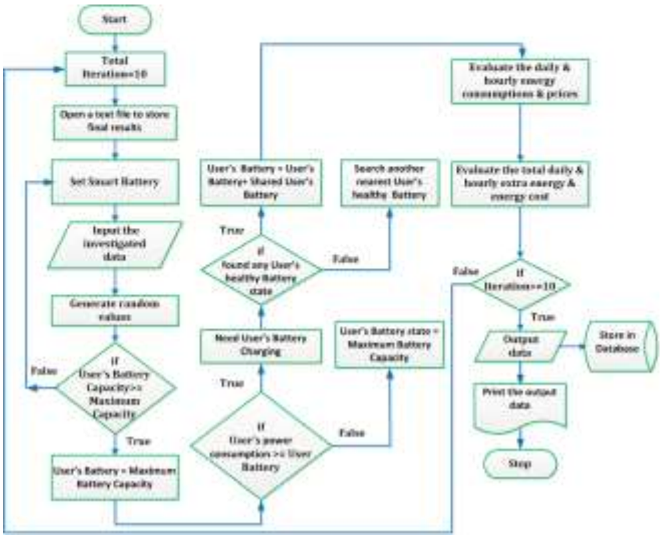

Fig.5. Flow Chart for power scheduling algorithm (PSA)

7) If the user power consumption is greater or equal to the user battery capacity, then user battery charging is needed or take battery power from neighbor user. Otherwise, user battery state is the maximum capacity.

8) If found any user's healthy battery state then user battery equals to the sum of shared user's battery. Otherwise, search another nearest healthy battery.
9) Evaluate the daily and hourly energy consumption and price.
10) Evaluate the total daily and hourly extra energy and energy cost.

11) If iteration greater than or equal to 10 then go to output results. Otherwise continue iteration.

12) Store the results in a database.

13) Print the results.

14) Stop the simulation.

7. Simulation Parameters

The simulation environment employed with the parameters for proposed scenario smart grid, shown in table 1.

Table 1. Simulation Parameters for proposed Smart Grid Architecture

Parameters	Values
Total days in a week	7
Total hours in a day	24
Total users	20
Total number of iterations	10
Smart meter power consumption	0.001 Watt
Energy price	0.072€/kWh
Smart Battery Capacity	400WAh

8. Simulation Results

Usually the use of electricity starts increasing from 6 am to 8 am due to light, fan, electric appliances again it decreases after 8 am because most of the users go outside for Office, University, and Business etc. On the other side, from 6 am to 5 pm this time slot indicates mid-peak hour due to comparatively less energy use during this period. Most of the home users stay outside during this period. However, during the weekend the pattern of electricity use a bit different than regular use due to all users want to use their home appliances for cleaning and other purposes. From 11 pm to 5am indicates off-peak due to less energy used by the users and most of the users sleep during those time span. Depending on above described power consuming pattern, three states of power scheduling have been considered, those are on-peak-hours (5pm–10pm), off-peak-hours (11pm–5am) and mid-peak-hours (6am–5pm).

Figure 6 depicted the total energy consumption of users during 24 hours for seven days. In traditional power distribution system (Reference) the power consumption during off peak hours, 11pm to 5am, differs from 10-20 kWh and it increases dramatically throughout mid-peak hours, 6am to 5pm, ranging from 11-23 kWh. Meanwhile in on-peak hour during 5pm to 10pm energy consumption increases to 25kWh till 8pm and then decreases to 21 kWh at 10pm.

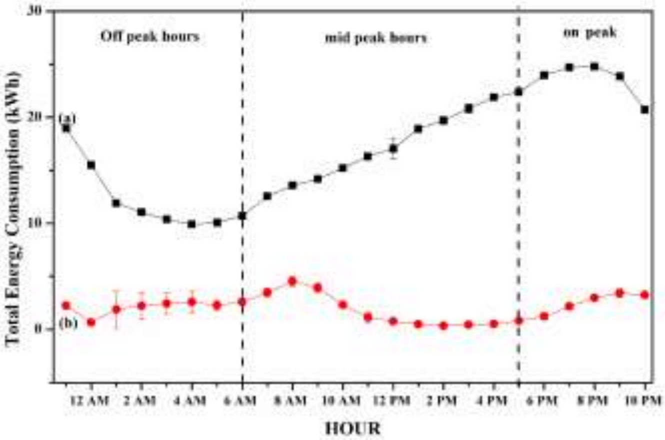

Fig.6. Time vs energy consumption for (a) reference and (b) Proposed SLSG scenario.

On the other side, in proposed scenario, the power consumption pattern is zigzag type. It is approximately 2kWh in average in off-peak hours which is 82.84% less than reference. During mid-peak hours, consumption slightly increases after 6 am and continues to rise till 8 am which is around 5 kWh and after 8am consumption goes down until 11am. From 11 am to 5 pm the energy consumption is nearly steady at 2kWh. In average 90.26% energy can be saved in this time frame by proposed SLSG architecture. However, consumption starts to increase from 2kWh to 4kWh in the course of on peak hours and that is 88.95% less energy consumption compared to reference scenario. The figure 7 shows the total energy cost with respect to hour. The black line indicates the reference scenario and the red line indicates the proposed scenario. In case of reference scenario cost of electrical consumption varies from 0.8 euro to 1.4 euro during 11 pm to 6 am. Consumption cost increases dramatically from 0.9 to 1.7 euro during 8 am to 5 pm. The highest energy cost has been found at 7 pm.

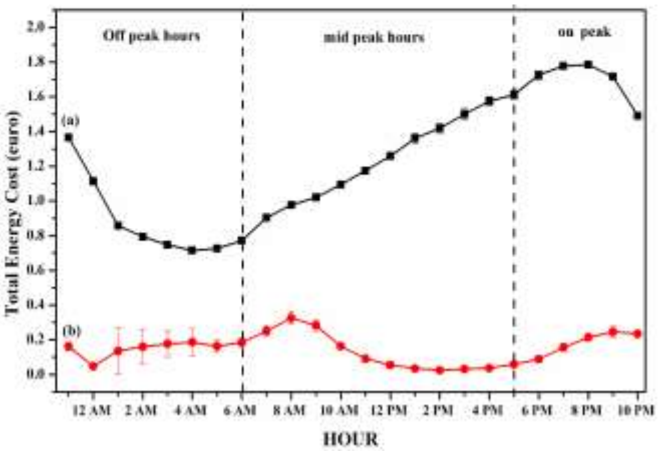

Fig.7. Time vs energy consumption cost for (a) reference and (b) proposed SLSG scenario.

Table 2. Summary of the power consumption and cost of energy for reference and proposed scenario.

States	**Power consumption**			**Cost of energy consumption**		
	Ref. kWh	**SLSG kWh**	**Saving (%)**	**Ref. (€)**	**SLSG (€)**	**Redu. (%)**
Off peak	98.5	16.91	82.84	7.09	1.22	82.8
Mid peak	192.57	18.7	90.26	13.8	1.36	90.23
On peak	117.9	13.04	88.95	8.49	0.94	88.95
Total	**409.7**	**48.7**	**88.11**	**29.4**	**3.52**	**88.06**

From table 2, in case of proposed (SLSG) scenario, during off-peak hour lies between 11pm to 6 am energy consumption cost varies from 0.05 to 0.2 euro which is 82.86% less than reference scenario. In mid peak hours cost varies from 0.2 to 0.4 euro which is 90.23% less than reference scenario. Cost varies from 0.1 to 0.3 euro during on peak hours and results in 88.94% energy consumption cost reduction compared to reference scenario. In 24 hours scale, proposed SLSG system can save up to 88.11% energy consumption from utility. This lower consumption of electricity from utility results in 88.06% less utility bill compared to traditional system.

9. Conclusions

A new smart grid architecture has been modeled and presented to minimize energy and cost. A community smart grid supported by renewable energy sources and managed by CDPU in order to share and meet energy demand among the community. A simulator was designed and developed to evaluate the residential users' energy and cost for reference and SLSG architectures. The optimization of cost and energy was achieved by sharing power among the home users through this novel power sharing algorithm (PSA). By implementing our proposed smart grid architecture, it is possible to save energy up to 90.26% during mid-peak hours and 88.11% in a day. Lower consumption of energy results in lower utility bill and this novel approach is the best solution for any residential community

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