Finding Optimal Operation Schedule for Electrical Appliances using Demand Response in Residential Sector

Nilima R. Das

Abstract: ***Rapid growth in building infrastructure, global population and improving life standards has raised the electricity demand exponentially and it is expected to grow further. It is generally accepted that buildings are the most important man-made contribution to today's world, as they impact on every aspect of our lives. Unfortunately, since their initial construction, these energy-hungry entities do not stop consuming energy until they reach the end of their lives and are demolished. This appetite for high energy consumption is not only associated with buildings themselves, but also with the devices/goods inside them. People generally use the energy concentrated appliances during their preferred times resulting in high demand during peak hours(high pricing hours) which in turn increases the pressure on the electric Grid. In such situation the supplier tries to avail more energy from the sources and sometimes to meet such high demand it can buy energy from expensive sources, which may result in increased cost of energy. The high demand of energy may make the Grid system unstable and unreliable. High demands of electricity result in increased production of electricity using fossil fuel based plants leading to increased level of CO2 in the atmosphere which is considered as the main reason of climate change. The development of intelligent energy-efficient control technologies will both soften negative effects of the climate change on the environment and enhance the service quality of the power system. The improved performance of the grid system, reduced peak loads and availability of electricity can reduce the green house gas emission. There is a need of proper scheduling of the operation times of the appliances. When optimal scheduling is used it can reduce energy consumptions of the users during peak hours making the Grid more reliable. The work in this article is mainly focused on optimal load scheduling for energy cost minimization and peak load reduction without considerably compromising user satisfaction. To achieve the objective a Demand Response(DR) model has been designed that motivates the consumers to take part in the system leading to a balanced energy system. The objective is to not only reduce costs and improve reliability but also to enhance consumer acceptance of a DR program by restricting the dissatisfaction level of the consumer by using renewable energy sources that provides greater flexibility in using the appliances at consumer's preferred times without reducing the amount of consumption required in a day. The optimization method proposed in this work reduces the consumer demand for electricity during peak hours by using an optimal schedule for the operation of the electrical appliances for the whole day. When the consumer follows the schedule generated by the optimizer the electricity payments is minimized. Simulation results reveals the effectiveness of the proposed method in providing reduced load during peak hours and minimized cost.***

Index Terms: Smart grid, DSM, Demand response, Renewable energy sources, TOU pricing, GA, PSO.

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Nilima R. Das, Faculty of Engg. & Tech., Siksha 'O' Anusandhan (Deemed to be University), India

I. INTRODUCTION

With economic development and increased population, the electricity demand has increased to a great extent and is expected to grow further resulting in high demand during peak hours. To safeguard the reliability and robustness of the grid system it is required to reproduce and supply adequate amount of electricity to fulfil the demands of the consumers that in turn needs extension of the existing grid infrastructure. This expansion of the grid structure may increase the price of electricity because the operational cost is increased in installing more number of power generating factories and transmission lines in order to increase the availability of electricity. These power plants may enhance the level of carbon dioxide gas in the environment. Expanded grid system may incorporate more faults and complexities which reduces the efficiency and reliability of the system. However not meeting the required demand may result in the failure of the grid system. So there is a need to upgrade the grid infrastructure without installing new power plants and distribution systems. The grid has to be smart and intelligent to handle these problems and maintain its efficiency. This upgraded smart and intelligent grid is called as Smart Grid(SG). SG is an uprising concept in electrical grid systems. It claims the advancement of technology and information system with highly advanced electrical infrastructures that can increase the reliability, security and efficiency. Reliable operation of grid requires an absolute balance between supply and demand [1]. However maintaining balance is a very challenging task as it is difficult to control the demand of the consumers. This can be possible with the implementation of smart grid. The smart grid can improve the energy efficiency in producing and using of electricity. Smart meters are a key component in the smart grid system that can help utilities control the demand, reduce expensive peak power usage and provide a better deal for consumers by allowing them to see and respond to time varying prices. To meet high demands the utilities generally depend on more fossil fuel based plants, but uncertainty in generation forces them to keep higher surplus of resources which can increase the cost of electricity. The other way to maintain balance is to use new techniques that give importance to user involvement.

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The standard procedure is to fulfil all the demands of the consumers, but these new methods try to motivate the consumers to manage their demand in a response to the current capacity of the grid. In order to maintain a proper balance between the demand and supply the smart grid requires the integration of Demand Side Management (DSM) techniques. DSM incorporates energy conservation and energy efficiency programs, demand response (DR) programs, and residential or commercial demand management programs [2]. DSM programs are accomplished by utility providers to guide and regulate the energy consumption behaviour of the users [3]. These programs when implemented increases the efficient use of the available energy instead of building new production and transmission framework or infrastructures. If the users can be made aware of the actual energy prices they can change their usage pattern and use more energy efficient appliances to save energy. Along with this if the users can shift some of their consumption to low peak periods then the peak time demand can be reduced which is very much required for a stable grid system. The main objective of the DSM programs is to reduce or change the time of consumption [4]. DSM programs make the consumers able to know and understand the actual electricity market scenario which helps them to manage their consumption efficiently in order to maintain a balance between the demand and the available supply. An important feature of the grid system is to provide more electricity to satisfy the global demand. With DSM programs it is easy for the utilities to handle or manage the consumer loads. The utility implements load control and management programs by following bill saving schemes or incentives for the consumers. The most important activity in DSM is Demand Response (DR). DR motivates the consumers to change their consumption pattern so that it can match with the available supply. The DR scheme employs intelligent techniques to increase the efficient use of energy at the demand side. It provides phenomenal opportunities for the forthcoming efficient electricity markets. There are different approaches of DR. Some are price based and some are incentive based. The utilities follow different DR schemes based on the users' demands. DR can effectively maintain a balance between the demand and available supply. Using the DR schemes the consumers can get awareness of efficient energy usage patterns resulting in electricity cost savings. The DR schemes can help to have a more efficient smart grid system. Many challenging issues like increased number of consumers' participation, developing decision making tools and using time varying pricing tariffs instead of flat pricing can make demand response a powerful and productive part of the smart grid[4]. The rest of the paper is organized as follows. Section 2 provides a detailed discussion on DR. Section 3 presents recent research works on DR. Section 4 describes the proposed DR model. Section 5 describes the optimization process and compares the results obtained from GA, PSO and GAPSOH(Hybrid of GA and PSO). Finally section 6 presents the conclusion.

II. Demand Response

DR programs are devised with a purpose to motivate consumers to reduce electricity consumption or shift it from peak to off-peak periods based on their comfort and priorities. When there is an imbalance between demand and supply it is difficult to pressurize the supply side, because some sources may take more time to operate fully, some sources may be very expensive and sometimes the demand can be larger than the available power supply. So in place of increasing the supply the DR tries to control and modify the demand so that demand can never be more than the current supply. This may reduce the cost of electricity in wholesale markets which in turn, results in reduced electricity costs in retail markets. DR is a technique to reduce the peak demand to avoid system emergencies. It encourages the consumers to change their pattern of energy utilization in a response to the current price. The main objective is to manage user consumption dynamically according to the current price which reflects the current supply conditions. DR includes dynamic demand management mechanisms to be used by the consumers to regulate or reduce the use of electricity in acknowledgement to supply conditions. Utilities encourage the consumers to use smart meters with different pricing techniques to implement DR. These techniques include time-of-use pricing (TOU), real-time pricing(RTP) and critical peak pricing(CPP) tariffs. These are also referred to as time-based rate programs in which different rates are used for different hours in a day. The consumers may adjust their demand by delaying the operations of some appliances, or may choose to pay a higher price for their electricity use. Some consumers may shift part of their consumption to off peak hours of the day or may use other power sources (renewable energy sources). This voluntary control is practised by giving some kind of monetary benefits to the consumers. For example utilities can offer lower rate per unit of consumption when the consumers reduce their consumption during peak periods. The main purpose of DR is to actively involve consumers in altering their consumption pattern in response to pricing signals. The goal is to reflect supply expectations through consumer price signals or controls and enable dynamic changes in consumption relative to price [5]. Now-a-days DR programs are used in commercial as well as residential area. The programs may apply load shedding being influenced by the wholesale market prices. Services (lights, machines, air conditioning) may also be reduced during emergencies.

A. Need of DR

The utilities employ DR to avoid the higher costs of energy production by preventing building of new power plants to meet the increasing demand of the consumers. Consumers can also make some savings in their electricity bills by reducing their use during peak periods [6,7,8]. As there is a reduction in overall demand due to demand response activities the dependency on expensive sources is also reduced which again decreases the overall electricity price. There can be several benefits of DR which are summarized below:

- **Financial benefits.** In order to get financial benefits and incentives the consumers can control their electricity usage in high pricing hours. The electricity bill of the consumer is reduced due to less energy usage during those periods. The consumers being a part of the DR program may also be given some financial payments by the utilities for adjusting or reducing their usage.
- **Increased reliability of the Grid.** Along with monetary benefits the users may also get reliability benefits when they become part of the DR programs. When demand becomes higher than available resources then there are possibilities of blackouts and outages. But DR can avoid such situations by reducing demand during those critical periods. It results in increased reliability of the grid system. Reliability reduces the risk of being deprived of the service provided by the grid. The more the consumers adjust their load the more they get financial and reliability benefits.
- **Reduced wholesale and retail market prices.** Demand response programs have a great effect on the supply costs of electricity and system reliability which motivates the utilities to implement DR programs. Since the consumers adjust their energy usage during high pricing periods the utilities do not have to supply additional electricity to the consumers and not have to buy more electricity from the sources. As a result the supply costs of electricity and the wholesale market prices are reduced. It further avoids investment for additional generation, transmission or distribution capacity infrastructure. As a result there can be a significant saving in the costs which the utilities would have to bear in such investments.
- **Increased flexibility of the consumers.** It can provide more options to the consumers to manage their electricity usage and cost in varying pricing environment.
- **Reduced power play of the suppliers.** The utility providers may reduce the supply with a motive to increase the prices. But price-responsive demand can avoid this possibility because the consumers can reduce their demand during high prices which may increase the risk for the suppliers to be priced out of the market. As a result the suppliers cannot exercise power in the market which again results in less manipulation of the suppliers in the market.
- **Reduced green house gas emissions.** Use of DR helps in avoiding new infrastructure which could have resulted in more CO_2 emissions and resources utilisation.

B. Categories of DR Programs

- DR programs are categorised mainly into 2 different types based on the consumer incitement and the conditions responsible for activating load reduction programs. Table 1 summarizes the possible categories of DR programs.

Table I. Types of DR

Load Response	Price Response
Direct Load Control	Time of Use Pricing
Curtailable Load	Real Time Pricing
Interruptible Load	Critical Peak Pricing
Scheduled Load	Extreme Day Pricing
	Extreme Day Critical Peak Pricing

- Load-Response Programs. When the utility providers provide some incentives to the consumers for reducing demand during system's peak periods, the method is called load response. In emergency periods the utilities use load response to induce consumers reduce their load to alleviate the limitations of generation or transmission of the required amount of energy. This is termed as emergency DR. Load-response programs can be divided into following categories.
Direct Load Control: Direct-load-control (DLC) programs are usually implemented for small commercial and residential consumers. Consumers give their consent for the program so that the utility can control predetermined load usage of the consumer. The air conditioning loads are the commonly controlled loads in residential area and lighting loads are controlled in commercial area. Water heating and pool pumps also come under residential load control programs. The consumers taking part in DLC programs get fixed monthly payments and one-time participation payment added to their electricity bill. Some utility providers give some remittance for the load reduction. The utility sets up agreements with consumers that states the maximum number of load control programs to be held during a year (e.g. up to 30) and the maximum time span of a program (between 2 to 8 hours, but normally 4) [9]. Most of the DLC programs empower the consumers to ignore an event when they face any problem, but some programs charge fines for not following the agreement. These programs make the utilities assured of the fact that they can reduce the loads when it is essential to do so. The technologies used in these programs like control switches and smart thermostats are generally not so expensive and also extremely dependable and competent of bringing up to 60 percent load reduction for small consumers.
- Curtailable Load: Curtailable load programs involve medium and large consumers. The consumers who want to be part of the program give their consent to reduce or turn off a part of their load for a particular time period after getting information from the utility. They can do it manually or automatically, depending on the agreement and availability of control technologies. Generally utilities provide advance notification to the consumers regarding the upcoming event. Like direct-load-control programs, the utility provides information regarding the number of such programs and period of each program to be held during the current year. After agreement the consumers are severely penalised if they override the agreement.
- Interruptible Load: Consumers taking part in interruptible load programs remain in agreement to shut off larger portions or if possible all of their loads for particular time period. Only some largest consumers can participate in interruptible load programs. The consumers use backup generators during an interruptible event.

The program is implemented through two-sided agreements between a utility and a consumer. Severe penalties are charged for not following the contract.

- Scheduled Load: Scheduled load reductions are decided with mutual agreement between the utility and consumers. The electricity bill for the consumers taking part in these programs gets reduced. The users can reduce their loads according to their convenience on the pre-decided days. However, on these days the utilities may not need any load control and when they actually need it they may not be able to implement it on short notice.
- Price-Response Programs. When consumers willingly reduce or change their demand in response to the market prices, the program is called price response. Consumers try to decrease load during those periods when the cost of reducing load is lower than the cost of generating it. Utilities may use communication signals (telephone or Internet) to inform participants regarding the upcoming events that need load response for which the utilities can make some extra payments to the consumers. Alternately they may encourage consumers to implement DR at their side by using different pricing tariffs. The pricing tariffs used by the utilities reflect the actual cost of providing electricity. In price response, utilities design the prices in such a way that they remain high during hours of either peak demand and supply constraint. Price remains lower at off peak periods. In real-time pricing, utilities reveal the fact regarding the actual situation of the wholesale markets and the resulting unstable price structures to the consumers. These programs allow consumers to voluntarily reduce their demand in response to pricing signals. DR programs are mainly categorised by pricing mechanisms and the amount of advance notification. Advanced communication technologies and smart meters are required to implement price response programs.
- Various pricing techniques are used by the utilities, for example fixed pricing rate and dynamic pricing rate [10, 11]. Flat pricing schemes are used in systems where the consumer understands the possible target of achieving reduction of bills by using low electricity for the entire day. But in varying pricing methods the users get flexibility in using their loads. They don't have to reduce their consumption for the whole day; rather they have to reduce it during some specific periods of the day in order to reduce their bill. Different pricing techniques used by the utilities are described below.
- Time-of-use (TOU) pricing: TOU pricing program uses variable pricing tariff based on the time of the day or days of the week. It incorporates a peak time price, an off-peak time price and occasionally a shoulder-peak rate for predetermined blocks of time decided by the utility [12]. A TOU tariff may impose consumers 5.5 cents per kilowatt-our (kWh) consumed on weekends and weekdays from 9:30 PM to 8:30 AM, 8 cents/kWh on weekdays from 8:30 AM to noon, and 6:00 PM to 9:30 PM, and 12 cents/kWh on weekdays from noon to 6:00 PM[9]. TOU rates do not reflect fluctuating costs of the wholesale markets in emergency periods; rather they represent the prices used in normal market conditions. The consumers receive some incentives for shifting their load to off peak periods. It results in bill savings for the consumers. It also induces the users to invest in new smart home appliances. TOU rates can attain moderate load shifting on a daily basis, involving a reduction of energy usage from 4 to 17 percent.
- Critical peak pricing (CPP): CPP is a variation of TOU tariffs that tries to represent the unpredictability and instability of market costs incurred due to increased production and supply of electricity. In Critical Peak Pricing (CPP)[13], at a particular period of time in a day or a week, there is a substantial increase in the prices because of unavailability of the resource according to the current demand. Accordingly the consumers are informed about the sudden increase in the price, generally one day before. The CPP tariff sets a time-dependent rate which is higher than regular rates. A critical peak event can be called before some hours of their actual execution. For example, an agreement can be made that a critical peak rate of 24 cents per kWh can be charged for 4 hours up to 30 days every year [9]. CPP programs can be implemented for both small and large consumers. In case of non-availability of the consumers at home, automated load control can be implemented using smart appliances and advanced communication technologies.
- Real-time pricing (RTP: RTP pricing tariffs reflect the uncertainty and instability of the wholesale power market costs. The electricity price represents the actual supply costs borne by the utility for each hour of the day [14]. The prices are declared to the consumers before every hour or before some hours of actual execution. The main challenge in RTP is that it needs a continual monitoring of real time data which depends on two way communication of the smart grid with the development of smart controller in practice. Maximal involvement of the consumers is required in this scheme to make it effective. Consumers manage their consumption in response to higher or lower price information. Implementation of RTP program requires advanced price prediction and notification techniques and improved communication and billing systems. In practice, only a small group of the largest industrial and commercial consumers can participate in these programs. These consumers who have backup generation or separate production units can take part in this program. Automated control technologies for consumers can be used to maximize performance and savings. Load management technology or energy management systems, are generally not able to respond automatically to the signals sent by utilities. Most of the consumers require technical and financial support from the utility so that they can install automated systems to implement DR. RTP based DR can be used to switch off the building loads which are not so important for the consumers.
- Extreme Day Pricing (EDP): EDP is nearly similar to CPP. But high price is used for all 24 hours during critical days and TOU price for other days. The critical days are more than that in CPP.

- Extreme Day CPP (ED-CPP). ED-CPP is a variation of CPP in which the critical peak price is applied during critical peak days but there is no TOU pricing on other days.
- With each of these tariffs the consumers experience different price variances and can reduce their expected price by taking more risks.

III. RECENT RESEARCH WORKS ON DR

Recently a lot of research has been made on different scheduling methods applied in DSM programs in residential grid networks. Even if they are different in their methodologies their main aim is to reduce the consumers' expense of energy and demand during peak hours, because increase in peak load leads to higher production costs and reduced supply of electricity. The scheduling methods provide schedules that help to guide the consumption pattern of the users so that the peak load and consumption during peak hours can be reduced. Various DR techniques have been proposed by different authors. Some the methods are discussed here. A dynamic programming based method is presented by Hsu and Su [15] to reduce the peak load by cycling off consumers' air conditioners. The consumers are divided into some groups. The air-conditioners for a particular group are held off for a fixed time period with their acceptance. When the control period is over their demands are restored and for some other group the loads are held off for the same time span. This procedure is repeated for all the groups for the whole day. Kurucz et al. [16] have proposed a Linear Programming (LP) model to control the peak load by controlling the loads in commercial, industrial and residential area. By offering lower prices for electricity the utility tries to control the load during different periods. The residential load control is done for some particular appliances such as pool pumps, air conditioners and water heaters. In [17] the authors Zhu, Tang, Lambotharan, Chin and Fan have described an Integer Linear Programming (ILP) based optimization method which reduces the peak time load and calculates optimal power and operation time for user appliances. The technique tries to reduce the peak hourly load of the consumers. Every house is connected with a smart meter that produces an optimal schedule for all the connected appliances in the household. The system also supports multiple users where many smart meters are connected together in order to achieve a cooperative scheduling. There is a central control node that takes the information about the appliances belonging to individual houses from their respective meters and tries to optimize the operation schedules for all the appliances connected to the system. They have also proposed a consumption scheduling mechanism using a combination of integer linear programming (ILP) and game theory approach to minimize the peak time load[18]. The authors H.K. Nguyen et al., 2012 follow a game theory approach for generating optimized schedule for the consumers. In this work the game is played between the users and each user tries to minimize its cost [19]. Z. Md. Fadlullah et al. have described a game theory based optimization procedure where the game is played between the users and the utility provider [21]. In the game the user's strategy is to minimize its electricity payment and the strategy of utility provider is to adjust the energy price parameter to reduce users' consumption. Hazem M. Soliman and Alberto Leon-Garcia have used a non cooperative game theoretic method to optimize the energy consumption of the users so that the peak to average load is reduced[22]. A novel cost function has been introduced that can handle the scenario where the users can sell their accumulated energy back to the utility providers and the energy accumulation is done using storage devices. H. Chen et al. followed a game-theoretic method to find optimize schedule for the appliances[23]. They have used a distributed approach to guide the energy consumption of the individual users. Raj et al. used a real-time based energy management system that depends on the real time consumption information of the users which is communicated to the grid through smart meter [24]. Using this information the grid is able to predict the next demand which can help to avoid overload situations. Samadi et al. have proposed a Vickrey-Clarke-Groves (VCG) mechanism which implements the utilitarian welfare function for implementing DSM programs[25]. It encourages efficient energy consumption among users so that social welfare may be maximized. An optimization problem has been formulated to maximize the aggregate utility and minimize the total cost for all the users. The utility function of each user is derived from its preferences and energy consumption patterns. The optimization process is based on the assumption that every user possesses a smart meter containing an energy consumption controller (ECC) unit in it. The ECC unit tries to control the user's energy consumption and maintain coordination between the user and the energy provider. All the smart meters are connected to the energy provider through a local area network. Using this network each user can share its demand information with the energy provider. By executing a centralized mechanism, the energy provider determines the optimal energy consumption level for each user, and broadcasts a specific electricity payment for the user. Bu, S. and Yu, F. R. have used a real-time pricing tariff in their work[26]. A real-time demand response scheme is used to manage the load demand of the consumers so that the cost of electricity can be reduced and the usefulness from the consumption of electricity can be maximized. The model is described with the help of a Stackelberg game. The initial stages of the game analyze how the retailer should make decisions regarding the selection of sources of electricity, the amount of electricity to be bought and the optimal retail price for the consumers, in order to get maximum profit. Then the consumers adjust their demand based on the current price to reduce the cost to be paid and maximize the utility they get from the energy consumption. A demand-side energy consumption scheduling scheme for both the time-shiftable and the power-shiftable appliances has been proposed by Liu et al.[28]. It tries to maintain a uniform load demand during the day time. In addition, the schedule generated by the optimization process takes the consumers preferred usage requirements into consideration while finding optimal energy consumption and operation time for the appliances.

Similarly, a home area energy management system (HEMS) for smart homes has been proposed by Zhao et al. [29]. It can manage different load types with photovoltaic generation with energy storage. The HEMS optimizes the utilization of local renewable and reduces energy wastage due to AC and DC conversions and storage charging and discharging. The objective of the system is to minimize the total daily energy cost for all the consumers. A fully distributed DSM method presented by Barbatoa et al.[30] is based on a game theoretic approach which minimizes the peak demand of a group of residential users. It uses a real time pricing tariff. The authors have considered two practical scenarios. In the Single-Appliance DSM case each appliance decides autonomously its scheduling time in a distributed fashion, so each appliance is a player in the game which can make independent decision regarding the starting time of its execution and the time appropriate to buy energy from the grid so that its contribution towards the overall electricity payment is minimized. In the Multiple-Appliance DSM case each user has to find schedules for all his home appliances. The householder is the player in this game who chooses the schedule of all its appliances according to its preferences with an aim to minimize its electricity payment.

Most of the works in literature use both linear and non-linear programming method to solve the DSM problem. However these programming techniques cannot handle a large number of controllable devices which have several computation patterns and heuristics [30]. The Linear programming methods may not find a feasible solution for NP-hard problems. The computational time is also very large for the problems that belong to NP-hard, non convex programming or Mixed Integer non linear programming. However heuristic-based evolutionary algorithm can provide a fast and near optimal solution [31,35]. The heuristic based methods like genetic algorithm, Ant Colony Optimization and Particle Swarm Optimization (PSO) can search very large spaces of candidate solutions and find globally optimal solution in polynomial time. The author in [32,33] has given importance on advanced computational techniques which are needed for optimization and better control of grid systems. As distributed and coordinated intelligence is required at all levels of the electric grid like generation, transmission and distribution, the author has emphasized on the computational intelligence mechanisms that include artificial and bio-inspired intelligence paradigms exhibiting an ability to learn and adjust to new situation, generalize and abstract the existing situations and find association between different situations which in turn help to develop effective and robust algorithms for grid management. Motivated by these facts some heuristic-based optimization techniques have been used to solve the DR problem in this article. The proposed techniques try to find optimal operation schedule for the smart appliances present in a household. The appliances are connected with a smart meter which is connected to the grid. The power is received by the appliances through the smart meter. The smart appliances are embedded with some control units. The control unit controls the operation of the appliances. The smart meter contains the scheduler that calculates the schedule for the appliances and sends signals to the control units of the appliances so that they can operate at scheduled time. When the appliances operate at the scheduled time the electricity bill of the consumer can be reduced. It also reduces the peak demands and peak hour demand of the consumer.

IV. System Model

A smart home plays a very significant job to implement DR in household sectors. A smart home consists of some smart appliances which are connected with each other through some communication link. Every appliance is embedded with some operating system that can control the operation of the appliance. DR also needs smart meter for each house which is connected to all the appliances present in the house. The smart meter is also connected to the grid from which it receives information regarding the price and the upcoming events. Generally there is a two way communication link between the grid and smart meter. Required information from the user can also be sent to the utility through the link. The smart meter is embedded with a scheduling algorithm which when executed calculates the schedule for the operations for the appliances connected to it. When the appliances are operated based on the calculated schedule there is a significant saving of the electricity bill of the consumer and along with this the user demand during peak hours is also reduced. It is the responsibility of the smart meter to send start and stop signals to the appliances for their operation according to the schedule generated. Fig. 1 depicts such a scenario where there is a smart meter connected to the appliances and controls their execution.

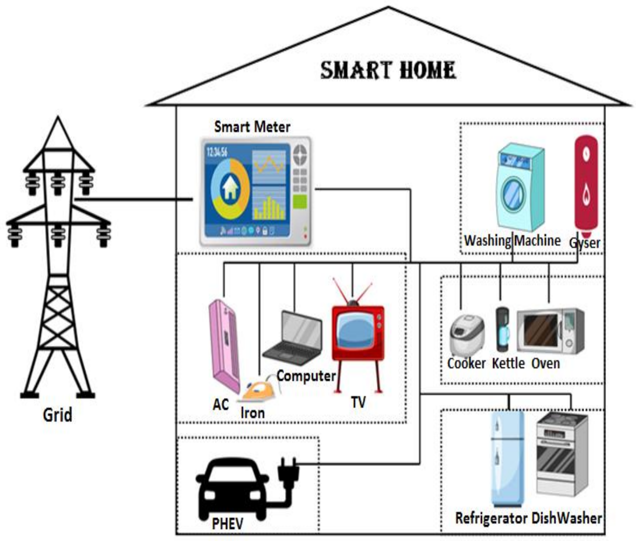

Fig.1. Smart meter controlling smart appliances in smart home

A. Daily Energy Consumption

The schedule is calculated for an entire day before the day starts. The time horizon taken for simulation is a complete day which is divided into 24 time slots. Every appliance has a specific time period during which it can operate. The energy requirement for an appliance *a* for a time slot *t* can be denoted as a^t. The total energy consumed for a time slot t for *n* number of appliances is represented as:

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$$e^t = \sum_{a=1}^{n} a^t \quad (1)$$

The hourly energy consumption is bounded by an upper limit which means the hourly energy consumption can never be greater than a preset limit. This constraint is defined as:

$$e^t \le l \quad (2)$$

Where, l is the preset limit for hourly energy consumption. The total energy consumed in a whole day is calculated as the sum of the amounts of energy used during each time slot in the day. Let it be E which is defined as:

$$E = \sum_{t=1}^{24} e^t \quad (3)$$

The users can use distributed renewable energy sources (RES) such as PV panels and wind turbines etc. The RES are used to satisfy the energy demand locally. It is assumed that the house is fitted with PV panel using which the can generate its own energy. PV panel generates solar power depending on solar radiations. Solar power output depends on radiation amount, direction of panels and transfer efficiency. The generated energy in a time slot t is represented as e_r^t and it is calculated by the following expression [34].

$$e_r^t = 10 \times \frac{1}{2\pi\sigma} \exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right) \quad (4)$$

Where, μ is the mean of distribution and σ is the variance. The hourly RES energy must be greater than zero during day time. The daily energy supply from RES is denoted as R which is estimated as:

$$R = \sum_{t=1}^{24} e_r^t \quad (5)$$

When the users use energy from RES the energy amount to be brought from grid will be reduced. The energy to be brought from grid for a time slot t can be represented as e_g^t which is described as:

$$e_g^t = e^t - e_r^t \quad (6)$$

Now the total energy to be brought form grid denoted as E_g can be defined as:

$$E_g = \sum_{t=1}^{24} e_g^t \quad (7)$$

According to eq. 6 E_g can also be described as:

$$E_g = E - R \quad (8)$$

B. Energy Cost Function

The cost of energy for a complete day denoted as C is calculated as the sum of the hourly costs of the day. It is defined as:

$$C = \sum_{t=1}^{24} c^t \quad (9)$$

Where, c^t is the total cost of energy to be brought from grid during a time slot t and it is calculated as follows.

$$c^t = p \times e_g^t \times \log\left(e_g^t + 1\right) \quad (10)$$

The energy cost during a time slot is assumed to be proportional to the energy consumed during that slot. When the amount of energy consumption is increased the cost calculated by the scheduler is also increased. p is the cost parameter that helps to control the consumption of the user during a particular time slot because its value is more during the peak hours of the system and less during the low peak hours similar to TOU pricing.

C. Objective Function

The objective of the system is to minimize the daily energy cost incurred by the user which is possible by shifting a fraction of the daily load to off peak hours. The cost minimization function is defined as:

$$\text{minimize} \quad \sum_{t=1}^{24} c^t \quad (11)$$

V. Heuristic Optimization

Heuristic optimization algorithms like Genetic algorithm (GA) and Particle swarm optimization (PSO) are used in this work to find the optimal schedule for the appliances. GA is an evolutionary algorithm that follows natural selection of fittest individuals from a random population and applies repeated modification of the individual solutions until a satisfactory solution is reached. PSO is another evolutionary optimization technique. However it is motivated by the social behaviour of birds forming a group, fish schooling and swarm theory. Another technique has also been used here which is an amalgamation of GA and PSO. It can be called as a hybrid of GA and PSO. Here it termed as GAPSOH(GA and PSO Hybrid). The steps of GA like evaluation of the fitness function for all the individuals, selecting the fittest ones, performing the crossover and mutation based on the taken crossover and mutation probability are first applied on the population and then the resultant population becomes the input for the PSO algorithm.

A. Simulation Results

The algorithms are compared based on the simulation results. In fig. 2 a comparison is made between the energy usage pattern of the user without optimization and with optimization. The daily consumption graph(without optimization) is similar to the graph used in [34]. It is obvious that the demand during peak hour becomes low when optimization is followed. Some portions of the load is shifted to non peak hours(before 8am and after 8pm).

Fig. 3 shows a comparison between the monthly costs before and after optimization for multiple users. The fig. 4 shows the convergence of the three algorithms. It can be seen from the figure that the GA algorithm converges faster than the other two algorithms. However the function values calculated by the hybrid algorithm are better than the values calculated by GA and PSO. The fig. 5 compares the algorithms based on the cost values calculated by each of them for 25 days. It can be seen that the cost values generated by the hybrid algorithm are better than the other two algorithms. Fig. 6 depicts the effect of optimization on daily energy cost with high loads for a consecutive 60 days.

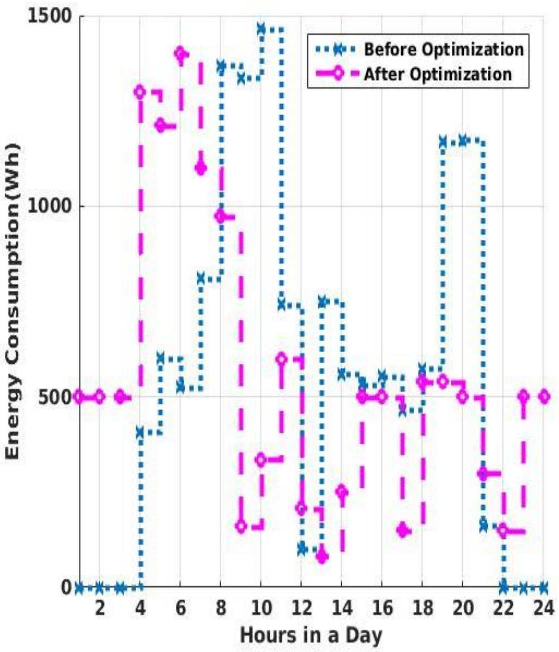

Fig. 2. Energy Consumption reduced during peak hours

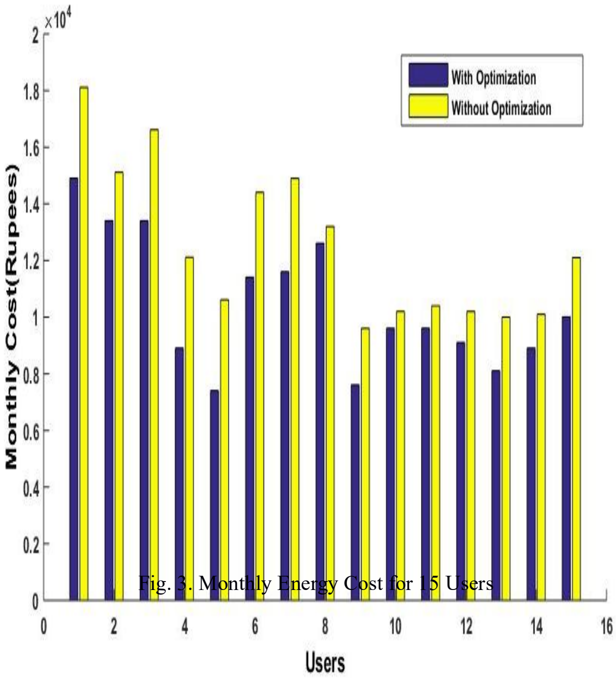

Fig. 3. Monthly Energy Cost for 15 Users

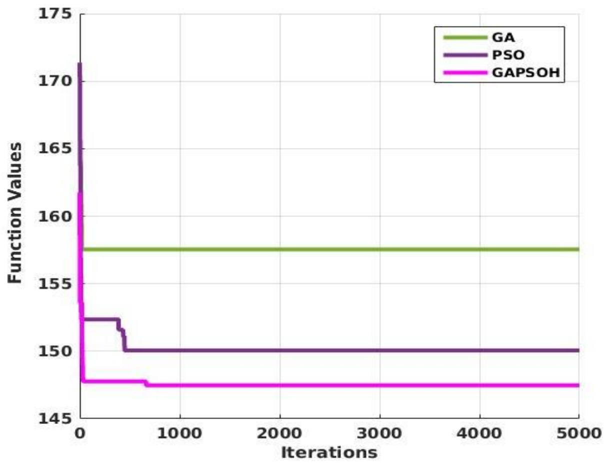

Fig. 4. Convergence of GA, PSO and GAPSOH

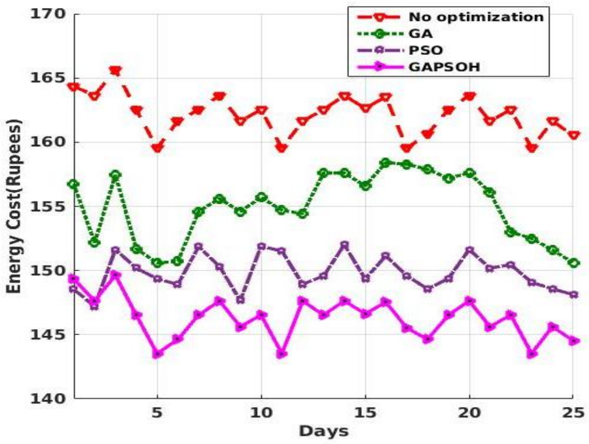

Fig. 5. Cost graphs for without optimization/GA/PSO/GAPSOH

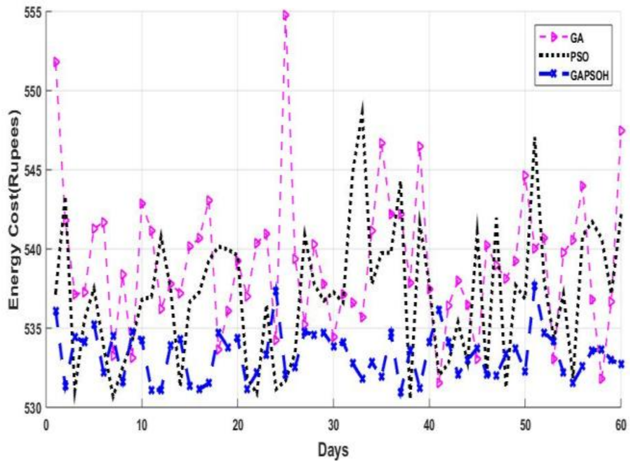

Fig. 6. Cost graphs of GA/PSO/GAPSOH for 60 days with high loads

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VI. CONCLUSION

The work includes a detailed study on the DR techniques used in smart grid. It has focused on several benefits of using DR. A model based on DR strategies has also been developed. This model makes use of optimization techniques to enable the flattening of the daily electricity load curve by shifting a fraction of the demand from later time periods to earlier time periods or from earlier to later in response to time of day prices. Using the system the consumers can minimize the costs of the energy they need. It reduces the consumer dependency on the grid by using energy from RES. Along with this the optimization is used to reduce the peak demand and demand during peak hours. The optimization techniques have also been compared based on their performance. Among them the hybrid method seems to be more effective for the DR problem. A possible extension to the work has been outlined in the following:Regarding DR strategies, results have been illustrated assuming a time horizon of 24 hours and a particular load curve in all the cases of study. The effect of considering wider time horizons has not been assessed and it is interesting to analyse how the load curve can be flattened when several days are included.

In particular, the hourly prices configuration is one the most important factors to take into account since the load will be shifted to those time periods when lower energy prices are expected. Thus an RTP based pricing scheme can be used in the optimization process.

The model can be designed based on individual activity of the consumers. The system can be made reactive that can react to unplanned activities of the consumer.

Scalability Analysis of the proposed technique with respect to number of devices and users can be done. New pricing scheme for better DR in smart grid environment in context of appliance scheduling can be designed.

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AUTHOR'S PROFILE

Nilima R. Das, did her M.Tech. in Computer Science and Engineering from Utkal University, Odisha in 2008. She is currently pursuing her Ph.D. from Siksha 'O' Anusandhan (Deemed to be University), India.

She is working as an Assistant Professor in Faculty of Engineering and Technology, Siksha'O'Anusandhan (Deemed to be University), India. She has published 6 International Journal papers.