
REVIEW

A comprehensive analysis of smart home energy management system optimization techniques

Tesfahun Molla¹, Baseem Khan^{1*}, Pawan Singh²

¹ School of Electrical & Computer Engineering, Hawassa University Institute of Technology, Hawassa, 05, Ethiopia

² School of Informatics, Hawassa University Institute of Technology, Hawassa, 05, Ethiopia

ABSTRACT

Development of smart grid technology provides an opportunity to various consumers in context for scheduling their energy utilization pattern by themselves. The main aim of this whole exercise is to minimize energy utilization and reduce the peak to average ratio (PAR) of power. The two way flow of information between electric utilities and consumers in smart grid opened new areas of applications. The main component is this management system is energy management controller (EMC), which collects demand response (DR) i.e. real time energy price from various appliances through the home gateway (HG). An optimum energy scheduling pattern is achieved by EMC through the utilization of DR information. This optimum energy schedule is provided to various appliances via HG. The rooftop photovoltaic system used as local generation micro grid in the home and can be integrated to the national grid. Under such energy management scheme, whenever solar generation is more than the home appliances energy demand, extra power is supplied back to the grid. Consequently, different appliances in consumer premises run in the most efficient way in terms of money. Therefore this work provides the comprehensive review of different smart home appliances optimization techniques, which are based on mathematical and heuristic one.

Keywords: home appliances energy management system; heuristic techniques; mathematical techniques; energy management system

ARTICLE INFO

Received: March 20, 2018

Accepted: April 10, 2018

Available online: May 15, 2018

*CORRESPONDING AUTHOR

Baseem Khan, School of Electrical & Computer Engineering, Hawassa University Institute of Technology, Hawassa, 05, Ethiopia; baseem.khan04@gmail.com

CITATION

Molla T, Khan B and Singh P. A comprehensive analysis of smart home energy management system optimization techniques. Journal of Autonomous Intelligence 2018; 1(1)

1. Introduction

Due to the ever growing demand of electrical energy, the percentage of renewable energy generation is greatly raised along with the increased in energy prices. Various environmental constraints also posed a limit on energy generation from conventional energy sources^[1]. These all the challenges motivate power industry to shift their focus on smart demand side management techniques. According to^[2], out of 100% of energy utilized in USA by residential and commercial consumers, at least 30% energy is wasted. The advancement of information and communication technologies (ICTs) increased the demand of reliable and quality power supply^[3]. These ICTs are important part of smart grid system that transfers information from one system to another one. This information transfer is very helpful to control and coordinate various smart grid technologies to respond immediately under varying demand situation. Smart grids can use local renewable energies like wind and solar energy to solve environmental Problems, increase reliability of equipment and system and reduce the costs of infrastructure^[4]. Further to control the demand from consumer premises, these ICT systems are very helpful. These are the integral part of smart home appliances energy management system, which is a one aspect of smart grid^[5].

Today, the concept of micro-grid is being used for purpose of helping the environment through using several renewable and available resources such as wind and solar energy, along with other energy generators such as micro-turbines and fuel cells to reduce generation costs and reduce environmental pollutions. The resources are not only interrelated, but also the interaction continues in higher levels such as distribution networks. Restriction of fossil fuels and increasing growth of demand for energy, enhanced living standards,

global warming and environmental problems have led to increasing advancements in technology and use of modern energies. The idea of smart grid was begun with idea of Advanced Metering Infrastructure (AMI) to develop demand management, increase energy efficiency and a self-repair electric grid, so that it could improve reliability and responding to natural disasters or deliberate sabotage^[4]. Advancement of smart grid system allows consumers to reduce their energy consumption through proper scheduling of different appliances. This is possible with the information of real time electricity pricing (RTEP). The demand side management (DSM) techniques are very old in power system that incorporates DR techniques with load shifting and energy efficiency and conservation program. Shifting of consumers' loads from peak hours to off peak hours is the main function of DR techniques. For that purpose incentives are offered to consumers^[6].

DR programs transfer customers' load during periods of high-demand to off-peak periods by offering them incentives and can reduce critical peak demand or daily peak demand^[6]. In smart grid environment there are different DR pricing schemes. The most common pricing schemes include real-time (RTP), time of use (TOUP) and critical peak (CPP).

In this paper, authors present a comprehensive study of optimization techniques of smart home energy management system. In Section 2, the architecture of smart home energy management system is studied under a home area network (HAN) protocol. In section 3, authors reviewed HEMS optimization methods based on mathematical and heuristic techniques. Section 4 presents a comparative analysis between different methods followed by the conclusion

2. The structure of home energy management system in smart grid

It is assumed that a smart home consists of

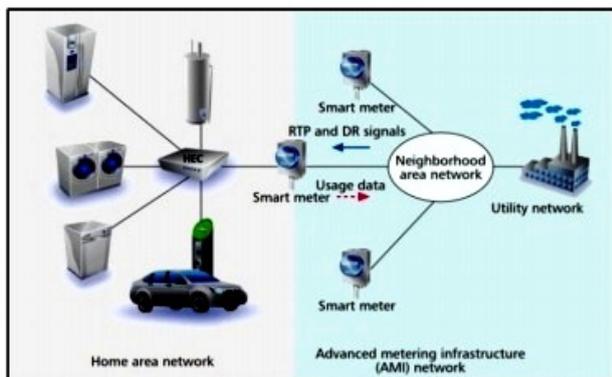


Figure 1. Home energy management system architecture^[1]

various appliances having the adequate and proper communication interfaces in order to facilitate the exchange of information with the EMS. It also assumed that each of the appliances communicates with the EMS only and cannot communicate with each other.

Figure 1 presents the structure of home energy management system with different data communication domains, those domains includes the internet domain, home area network (HAN) domain and the smart meter domain (AMI). The internet domain enables consumers to monitor and control their power consumption profile, the scheduling of their appliance power consumption and etc. through an in-home display (IHD) which consists of computer, tablet or smart phone. The smart meter domain includes a large number of interconnected smart meters called “Automatic metering infrastructure (AMI)” which is installed and monitored by utilities companies in order to transmit load information and DR signals between the smart homes and power market. Based on RTP signals received 24 hours day ahead, the home energy management system (EMS) schedules the electricity usage pattern for the next day.

3. Literature Review

3.1. Mathematical Techniques

3.1.1 Mix Integer Linear Programming

Arikiez *et al.*^[7] investigated the use of linear programming based heuristics for solving the cost minimization problem of air conditioning system for residential and commercial loads. Melhem *et al.*^[8] proposed an optimal residential load scheduling model by using the mixed integer linear programming. Sou *et al.*^[9] solved scheduling problem of smart home appliances for reducing electricity cost by using mixed integer linear programming. Angelis *et al.*^[10] developed an approach, which is based on mixed-integer linear programming technique. The developed approach provided an optimal solution in terms of minimum power consumption with an integration of renewable energy resources. Yao *et al.*^[11] investigated a problem of a smart home energy management system (HEMS). It consist of photovoltaic (PV) module and the household appliances with three different types of load characteristics (*i.e.*, interruptible, uninterruptible and time-varying). To solve the HEMS problem mixed integer linear programming

(MILP) algorithm was used. Kim *et al.*^[12] developed a mixed-integer linear programming based model for an effective scheduling of the operational periods and power levels of home appliances. Arora *et al.*^[13]. Proposed a mixed integer linear programming based optimal scheduling technique for centralized air conditioning load. Same author proposed an optimal scheduling mechanism for residential appliances in a smart home equipped with photovoltaic panel and energy storage device^[14]. In order to reduce both the CO₂ emissions and the electricity bill, Paridari *et al.*^[15] proposed a novel based on MILP method for smart home appliances scheduling and batteries, Same author^[16] proposed a robust approach based on MILP model for scheduling of smart home appliances by incorporating electrical energy storage system (ESS) in active buildings with the aim of minimizing both the CO₂ emissions and electricity billing. Zavala *et al.*^[17] developed a proactive energy management framework based on online solution of mixed-integer nonlinear programming. It is an integrated predictive dynamic home models and day-ahead forecasting of disturbances which affects the efficiency of the system and electricity costs. In order to jointly monitor the electricity consumption of home appliances and plug-in EVs, Hossain *et al.*^[18] proposed an optimal centralized scheduling method, which is based on MILP. For an efficient management of smart home appliances under real time pricing (RTP) environment, Wang *et al.*^[19] proposed a Mixed Integer Linear Programming (MILP) based rolling optimization. The proposed smart home equipped with a Battery Energy Storage System (BESS) and a solar PV system in order to maximize the efficiency of the system.

3.1.2 Linear Programming

Giorgio *et al.*^[20] proposed the design of a Smart Home Controller which provides an efficient management of electric energy in a residential building. To solve the problem, binary linear programming scheme was used. Dogaheh *et al.*^[21] optimized the performance of smart grids in relation with residential energy centres equipping with solar power units or PV. For that purpose authors utilised YALMIP toolbox in MATLAB software. Mohammadi *et al.*^[22] proposed a real time integer linear programming based Home Energy Management system (HEMS), to manage home appliances and storage system.

3.2. Heuristic Techniques

3.2.1 Particle Swarm Optimization PSO

Hussain *et al.*^[23] proposed a particle swarm optimization (PSO) based scheduler using demand side management (DSM) technique based on demand response (DR). Six shiftable appliances are considered in 24 hour time horizon. PAR is not included as objective function. Shah *et al.*^[24], presented a HEMS using multi-agent system (MAS) for smart homes. The HEMS uses priority techniques with the integration of electrical supply system (ESS). Further, bio-inspired technique, binary particle swarm optimization (BPSO), is used for the optimal scheduling of appliances in a smart home. Mahmood *et al.*^[25], proposed a realistic scheduling mechanism (RSM) to reduce user frustration and enhance appliance utility by classifying appliances with respective constraints and their time of use effectively. Further, binary particle swarm optimization (BPSO) is utilized for optimal scheduling of appliances with constraints. Huang *et al.*^[26] studied a convex optimization problem to manage the energy consumption of different households in an automatic way. In addition to this optimal scheduling is performed by hybrid PSO-DE algorithm. Zhu *et al.*^[27] utilized cooperative PSO algorithm for developing the optimal schedule and control of energy and time shiftable appliances in smart homes. Abdalla *et al.*^[28] studied the energy management of chiller plant in optimal way. PSO and Fuzzy are utilized for optimally managing the energy consumption of plant. To find the set point, fuzzy is utilized while for optimizing the objective function PSO is used. For plug-in hybrid electric vehicles, Chen *et al.*^[29] developed an optimum energy management method under uncertain driving conditions. Authors utilized PSO for optimizing the threshold parameters for the rule based energy management scheme.

3.2.2 Gray Wolf Optimization

Kazemi *et al.*^[30] developed a method that depends on Gray wolf optimization and genetic algorithm to achieve the optimal schedule for appliances in terms of cost and PAR. Interruptible tasks are divided in to smaller sub tasks, in terms of time, using GWO algorithm and the output of this component was the input of genetic algorithm scheduler (GAS). The inclining block rate (IBR) pricing model was proposed to restrict the overusing electricity power

in each time slice. Even if it takes large time to converge to the solution, the performance of the optimization technique seems interesting and had a good result than other methods discussed above.

3.2.3 Genetic algorithm GA

Zhao *et al.*^[31] introduced an EMS in HAN based smart grid. Further, GA is utilized to solve the problem of energy scheduling for home appliances. An EMS and automated DR structure for household is developed by Khomami *et al.*^[32] to schedule the different appliance in smart household. Further, for optimizing the results GA is utilized by the authors. For optimal DR management in smart grid Meng *et al.*^[33] developed a real time pricing technique. A Stackelberg Game and Genetic Algorithm Approach are utilized for that purpose. Talha *et al.*^[34] evaluated the performance of heuristic Algorithms: GA and Artificial Fish Swarm Algorithm (AFSA) for Demand Side Management. Li *et al.*^[35] developed an EMS for industrial microgrids with high renewable energy penetration. The scheme is developed for both isolated and grid connected mode with day ahead operation. For optimizing the results, regrouping particle swarm optimization (RegPSO) is utilized by the authors. To reduce the PAR and energy cost, Naseem *et al.*^[36] scheduled the residential loads by four different heuristic optimization techniques i.e. GA, Binary Particle Swarm Optimization (BPSO), wind driven optimization (WDO) and Bacterial Forging Optimization Algorithm (BFOA). A comparative analysis of all the above mentioned techniques is presented by the authors.

3.2.4 Evolutionary algorithm

For future smart grid with large devices, Logenthiran *et al.*^[37] developed a DSM scheme that depends on load shifting. Evolutionary Algorithm (EA) is utilized for optimizing the results. Allarding *et al.*^[38] focused on a flexible EMS for Smart households. A “plug-and-play” type Evolutionary Algorithm is developed for optimizing distributed generation.

3.2.5 Bee colony

Zhang *et al.*^[39] proposed an EMS for household appliances. It is also utilized to implement DR schemes for residential consumers and for facilitating integration of renewable energy sources. For optimizing the results an improved artificial bee colony algorithm is used.

3.2.6 Bacterial colony

An internet of things (IOT) based EMS for households are proposed by Geng *et al.*^[40]. For finding an optimum scheduling scheme, discrete multi-objective bacterial colony chemotaxis algorithm (DMOBCC) is utilized by the authors. Lin *et al.*^[41] presented an EMS for micro grid system. For optimizing the results of economic dispatch, enhanced bee colony optimization (EBCO) is developed by the authors.

3.2.7 Ant colony

Rahim *et al.*^[42] developed an optimization model for DSM that combined tariff and block

Table 1. Comparative analysis of Mathematical and Heuristic based methods

S. No.	Properties	Mathematical Technique	Heuristic Techniques
1.	Model Formulation	Model is used to simulate a system when the system is not extremely complicated.	Meta-heuristic Techniques try to imitate natural phenomenon to solve the complex practical problems.
2.	Prerequisites	Physical laws are derived and utilized to find the relationships between system parameters.	Dependent on data to determine the structure and parameters
3.	Non-linearity integration	Possible if prior knowledge of the nature of the non-linearity exists.	The prior information of the nature of the non-linearity is not required.
4.	Hypothesis	Simplify the problem or incorporating assumptions to make model more understandable.	No need to simplify the model and/or add assumptions
5.	Precision & Accuracy	Provide highest level of accuracy.	Provide greater precision and accuracy.
6.	Efficiency	Time consuming in complex problem	repetitive and time-consuming tasks easily carried out with efficiency
7.	Renewable Energy Integration	Requires complex mathematical modelling	With meta-heuristic model renewable energy, source incorporation is easy.

rates. Multiple knapsacks are utilized to form the optimization problem and ant colony optimization is utilized to solve it.

4. Comparative analysis of various optimization techniques

In this section, a comparative analysis of different home energy management optimization methods is presented, which are reviewed in previous sections. Table 1 presents a comparison between mathematical and heuristic techniques based smart home energy management optimization methods. This comparison is based on different factors such as model formulation, prerequisites, nonlinearity integration, hypothesis, precision and accuracy, efficiency and renewable energy integration. From the presented comparison it is clear that both techniques has various advantages and limitations. Based on the formulated problem one can select suitable technique.

5. Conclusion

The problem for smart home appliance management is developed as a mathematical MILP and liner programming (LP) or heuristic optimization problem with the decision variable. The number of appliances can be increased to add more types of appliances in a home area network (HAN). Optimized appliance scheduling can be studied with the other existing dynamic pricing models. Smart home energy management is becoming more important in smart grid environment. It is capable to deal with demand response and management techniques. The main objective of home energy management problem is to optimize the schedule of various home appliances so that the overall energy consumption minimised. Hence, in this work authors presents a comprehensive review of solution techniques and methods used for optimization of smart home energy management system. Different heuristic techniques used for optimization of smart HEMS are further discussed. At last, a comparative analysis among different smart home energy management techniques is presented. There are still many constraints and non-linearity, which should be incorporated in future smart home energy management problem. Problems related to mathematical validation, deregulated market constraints, contingencies incorporation, renewable sources integration are latest challenges for future smart home energy management problems.

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