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Optimal single phase smart meter design

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Abstract: This study presents a new generation of smart meter that can optimally manage the energy demand. This device optimises the consumer's overall energy cost in a real-time environment by giving the customer an opportunity to set a minimal electricity tariff. It consists of giving both utility and consumers of the electricity an opportunity to manage the supply and demand of the energy. From the supply point of view, this is based on the conceptual framework of the standard advanced metering infrastructure. While on the consumer side, an additional optimal design strategy is added into the device that can communicate with all electrical systems by automatically switching on and off some specified loads. This application is developed based on the scheme of configuring into the smart meter two principal supply setting systems which contain some non-optimal and optimal supply nodes. As a compact optimal smart meter system, it will ensure appropriate control and reduce the cost of electricity. Moreover, it can encourage the use of renewable energy resources and resolve several issues of power system integration.

1 Introduction

Currently, smart grid technology is considered to be the answer to several imperfections in the electrical system. Smart grid technology also provides an opportunity to develop greater efficiency in the power system so as to optimise the supply according to the demand for energy [1]. Furthermore, it must be necessary to remember that the extension and progress of any electrical system are based on its capacity of interaction, reliability, resilience, and flexibility from the energy producer to the energy consumer. The smart grid is considered as a future power system that can enable the achievement of the energy efficiency of smart buildings, by being interconnected and designed in the framework of the intelligent electrical system [2]. The smart building, when it is incorporated in the context of optimising the energy efficiently with renewable energy integration, offers several advantages to the consumers [3]. One of the most important factors of smart building development is its capacity of introducing advanced technology that gives a novel approach to an energy efficient framework [2–10]. This strategy is designed in the context of several scenarios, by using a smart grid, which introduces a smart meter, data, and signal processing [1–5] to set the real-time system environment [1, 6–9]. Smart grid technology can also be considered as a sustainable development goal that can manage the energy demand of the electrical system [1–10].

The smart grid technology offers the opportunity to all users of electricity (consumers, suppliers and or generators) to trade electricity services, via a network, with reliability, flexibility, economy, and sustainability of an optimal supply [1–12]. It is devised by predicting the behaviour and actions of all users with an intelligent response system that coordinates the entire electrical grid from generation to the demand side. Smart grid technology has been promoted as a structure to enhance the performance of the power system. This scheme consists of combining the innovative products and services with control, communication, intelligent monitoring [2–14], and self-healing technologies [1]. It will meet the objectives of ensuring the optimum reliability, flexibility, security, efficiency, and quality of the electrical energy from generation to consumption through communication of important and relevant information. The significant aspects of smart grid technology and expansion are classified into keys, namely, power system enhancement, test bed, communication and standards, environment and economics, and computational intelligence [1].

The reform of the electricity market in the core of the smart grid is performed on the one hand beneath the requirements of reliability, environmental friendliness sustainability, and energy price stability of the power supply. While, it can challenge all control activities in respect of the power distribution, and the design of the power grid. Several approaches are used to reconfigure the electricity market to improve the capacity of the network, the efficiency of the energy flow, and the development of a scenario that can reduce the carbon emission by setting the system constraints [15]. Some of those strategies are demand side management [1–10, 12–16], demand response strategy [17–19], real-time electricity pricing environment, and day-ahead electricity pricing strategy [6–9, 20–24]. The promise of renewable energy development and integration is of significant value in the smart grid environment which can quickly facilitate a mixing of different generation resources in various electricity market configurations [20, 21, 24].

The implementation and design of a smart meter were widely settled in different scenarios and approaches for optimal cost efficiency on the electrical system [25–33]. These strategies were developed with external hardware and software, which could be affected by a communication problem with the devices. Some researchers have used a wireless signal to establish communication between the meter and appliances for an optimal strategy [25]. However, a wireless system sometimes can delay the communication strategy that could affect the performance of data transfer of control performance. It is also important to notice that several optimal strategies were developed using a real-time electricity pricing scheme of a smart meter [7–9]. In fact, it can be observed that a smart meter device can offer several advantages to the users either a supplier or a consumer; however, it cannot allow the customers of the utility grid to set their electricity tariff.

The principal goal of this research work is to determine its ability to assist the end users, to optimise and manage the energy usage remotely according to their consumption size. The device is designed with an optimal system that coordinates the demand according to the objective of the electrical system on the demand side. Moreover, the strategy of this new generation of the smart meter will also allow the reduction of the cost of energy, which could be defined directly through the device by using some additional nodes to connect the load. The difference of this system is the fact that the consumer can set their electricity tariff schemes which have to follow the system constraints to minimise the cost of energy to pay the utility. The Matlab/SIMpower library is used to implement the objective function of a model predictive control (MPC) in the framework of the optimal smart switching system controller.

The structure of this paper is organised as follows: Section 2 describes the system methodology, modelling, and design for an optimal electrical cost reduction of a residential home. The section also presents the proposed design strategy of the smart meter using Matlab/Simulink in the frame work of an MPC.

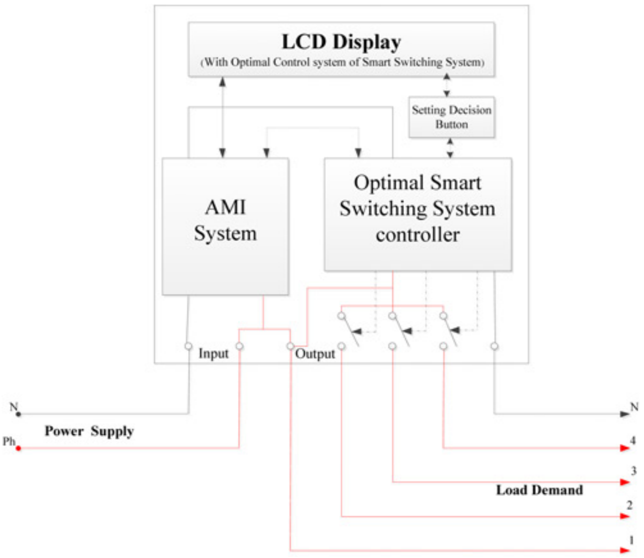

Fig. 1 *Optimal smart metering system*

Section 3 depicts the computed results, and also describes the analysis and; the paper is concluded in Section 4.

2 System methodology, modelling and design

2.1 Smart meter reconfiguration

The configuration of this new generation of the smart meter is described in Fig. 1. This scheme describes the model of an optimal smart meter design. The model is based on integrating an optimal load management strategy that could give the consumer an opportunity to optimise the cost of energy to pay. This approach consists of implementing a controller into the device with full access to the system protocol of the smart meter. It can be observed that through this optimal strategy, a smart metering system can operate with an excellent flexibility on demand side. The additional nodes on the output of the smart meter can be seen in Fig. 1. The nodes 2, 3 and 4 of the optimal smart metering system are considered as a part of the novel strategy on the device while node 1 is the common part of all standard smart meters. It can be noticed in Fig. 1 that setting a decision button on the device allows the consumer to set the constraint and the energy tariff that is different from the utility electricity tariffs.

2.2 Energy cost system

The advantages of the electrical smart meter are that it has the opportunity of introducing several electrical tariff schemes. However, all those structures are part of the utility energy supply. Therefore, with the new generation of the smart meter, the consumer could also introduce the electrical tariff structure that can enhance the optimisation of the power system. Table 1 describes a home load demand with the time of use (TOU) electricity tariff from the utility and consumer energy tariff (CET).

The cost of energy consumption for a given load is a function of installation area, time and kind of load [8, 9]. In fact, the cost of electricity to be paid to the utility grid is defined by (1). This equation describes the energy cost of a given time horizon which is set in 24 h with a sample equal to the unity in this research

$$C(t) = \sum_{i=1}^{N} P_{\text{et}} P_i(k) \Delta t, \qquad (1)$$

where C is the electricity cost, P_i the energy consumption of a given node i, P_{et} is the electrical tariff which could be either TOU or CET, Δt is the time increment that describes the sampling of time k.

Table 1 Load demand on the electrical system, household TOU electricity tariff and costumer electricity tariff (Rand/kWh)

Time, h	Power, kW	TOU, R/kWh	CET, R/kWh	Time, h	Power, kW	TOU, R/kWh	CET, R/kWh
00:00	0.60	0.348	0.348	12:00	0.84	0.841	0.348
01:00	1.72	0.348	0.348	13:00	0.62	0.841	0.348
02:00	0.46	0.348	0.348	14:00	0.56	0.841	0.348
03:00	0.90	0.348	0.348	15:00	4.34	0.841	0.348
04:00	2.18	0.348	0.348	16:00	7.02	0.841	0.348
05:00	5.72	0.348	0.348	17:00	2.82	0.841	0.348
06:00	6.98	0.841	0.348	18:00	2.48	3.116	0.348
07:00	4.82	3.116	0.348	19:00	8.48	3.116	0.348
08:00	1.44	3.116	0.348	20:00	3.66	0.841	0.348
09:00	4.24	3.116	0.348	21:00	3.00	0.841	0.348
10:00	1.16	0.841	0.348	22:00	2.58	0.348	0.348
11:00	4.60	0.841	0.348	23:00	0.68	0.348	0.348

2.3 *System design*

By using (1) and the setting value of the electricity tariff in Table 1, the objective function of an MPC scheme can be described. Equation (2) defines the generic formulation of a quadratic equation in the framework of an MPC [7, 8, 16, 17]. It also describes the performance index of the system or the cost function that must be implemented in the optimal smart switching component of the device

$$J = (Y - R)^{\mathrm{T}}(Y - R), \tag{2}$$

where Y is the cost of energy with TOU and R is the cost of energy with CET. Equation (2) is subjected to a constraint system that is described as

$$Mu(k) \leq \gamma, \tag{3}$$

where M is the matrix constraint of a quadratic form, u is the system input that defines γ which describes the limitation value of the system. The energy flow on node 1 of the smart meter device as is depicted in Fig. 1 is considered to be an optional or a high-priority load that cannot be affected by the optimal switching system. Other nodes define the system sensitive loads. Therefore, the system constraint of nodes 2, 3, and 4 can be written as

$$E_i(k) < E_{i_{\mathrm{p}}}(k), \tag{4}$$

$$J < \mathrm{Cost}_{\mathrm{ref}}, \tag{5}$$

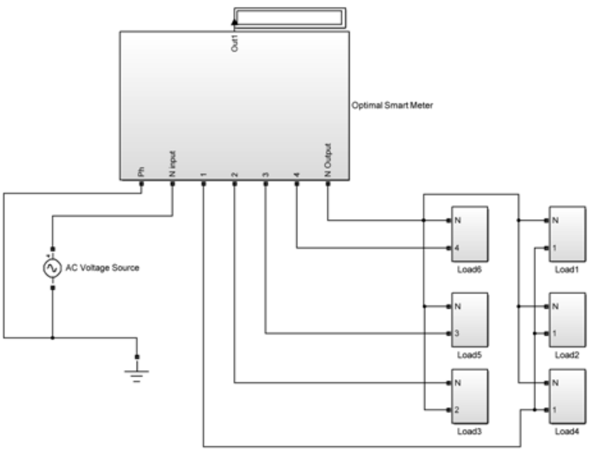

Fig. 2 *Smart Simulink single phase electrical system mode*

where $E_i(k)$ is the energy of node i at a sample of time k (with $I = 2$, 3 and 4), $E_{i\mathrm{p}}(k)$ is the peak of energy of node i at a sample of time k, $\mathrm{cost}_{\mathrm{ref}}$ is the reference cost of electricity. It can also be noticed that the quadratic equation of the performance index (2) could be rewritten in the Simulink model for the energy cost optimisation as follows:

$$J = (\mathrm{Cost}(k) - \mathrm{Cost}_{\mathrm{ref}}(k))^2. \tag{6}$$

Equation (6) restricts the optimal strategy of a switching system that could be implemented in the device.

2.4 *Electrical system design*

Considering a given single phase electrical system for residential usage, during the system design of this electrical home system some specific load can be set to be no-prioritised and while others being high-priority. Fig. 2 depicts a model of the electrical system in the smart meter environment. This structure is devised by using the energy consumption parameter of Table 1 that contains six major load demand system. This model is developed by using the theory of household electricity load profiled that is defined in [34]. Therefore, loads 1, 2 and 4 which are designed as high-priority loads that cannot be affected by the optimal approach of the smart metering devices are shown in Table 2. However, the loads 3, 5 and 6 that are, respectively, supplied by nodes 2, 3 and 4 are presented in Table 3.

3 Results and discussion

In this section, simulation results of the optimal switching energy management of the device and overall optimal cost of energy for a residential load are presented. The analysis is made with the approaches of following the impact of switching systems which consist of implementing the optimal hourly demand by use of the MPC function in the device as a quick managing strategy. This approach achieves the MPC function block in a discrete mode with the sample of time equal to one (hourly energy demand) that is different with the sample of time of the Simulink, configuration solver. This scheme consists of simulating the electrical system of Fig. 2 in a smart grid environment to optimise the cost of electricity. Therefore, Tables 1–3 are used to analysis the behaviour of the system design.

Figs. 3–5 present the results of the implementation of the smart meter controller which come from nodes 2, 3 and 4 as described in Fig. 2. The results are all functions of the energy demand from loads 3, 5 and 6.

Through Fig. 6, the optimal result of the total energy demand measure on the smart meter is depicted. This arrangement means that the figure presents the combined values of loads 1, 2 and 3 with the optimal strategy of energy cost reduction that is described in Figs. 3–5.

Table 2 Daily power flow of high-priority load demand

Time, h	Load1, kW	Load2, kW	Load4, kW	Time, h	Load1, kW	Load2, kW	Load4, kW
00:00	0.15	0.05	0.00	12:00	0.4	0.00	0.40
01:00	0.15	0.05	0.12	13:00	0.00	0.00	0.40
02:00	0.00	0.06	0.00	14:00	0.00	0.00	0.00
03:00	0.40	0.06	0.04	15:00	0.48	0.00	0.00
04:00	0.40	0.06	0.04	16:00	0.48	0.00	0.00
05:00	0.40	0.06	0.04	17:00	0.48	0.34	0.00
06:00	0.40	1.32	0.04	18:00	0.48	0.00	0.00
07:00	0.40	1.32	0.04	19:00	0.48	0.42	0.10
08:00	0.38	0.00	0.00	20:00	0.48	0.42	0.10
09:00	0.40	0.70	0.04	21:00	0.48	0.42	0.10
10:00	0.40	0.70	0.06	22:00	0.48	0.00	0.10
11:00	0.40	0.70	0.06	23:00	0.15	0.05	0.00

Table 3 Daily power flow of switching load demand

Time, h	Load3, kW	Load5, kW	Load6, kW	Time, h	Load3, kW	Load5, kW	Load6, kW
00:00	0.40	0.00	0.00	12:00	0.40	0.00	0.00
01:00	0.40	1.00	0.00	13:00	0.40	0.18	0.00
02:00	0.40	0.00	0.00	14:00	0.38	0.18	0.00
03:00	0.40	0.00	0.00	15:00	2.00	0.00	1.86
04:00	0.40	1.28	0.00	16:00	2.00	2.68	1.86
05:00	2.00	1.28	1.94	17:00	2.00	0.00	0.00
06:00	2.00	1.28	1.94	18:00	2.00	0.00	0.00
07:00	2.00	1.06	0.00	19:00	2.00	4.82	0.66
08:00	0.00	1.06	0.00	20:00	2.00	0.00	0.66
09:00	2.04	1.06	0.00	21:00	2.00	0.00	0.00
10:00	0.00	0.00	0.00	22:00	2.00	0.00	0.00
11:00	3.44	0.00	0.00	23:00	0.48	0.00	0.00

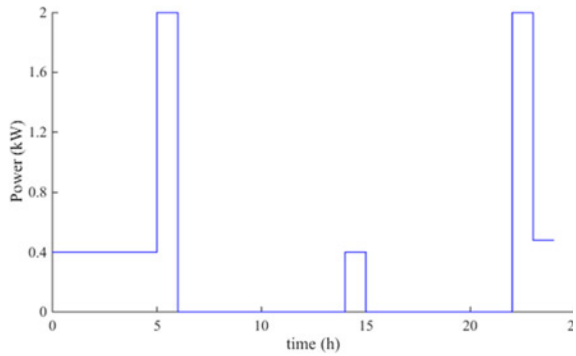

Fig. 3 *Optimum power supply of load 3*

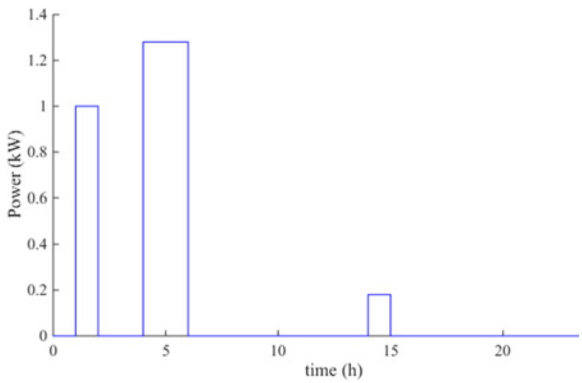

Fig. 4 *Optimum power supply of load 5*

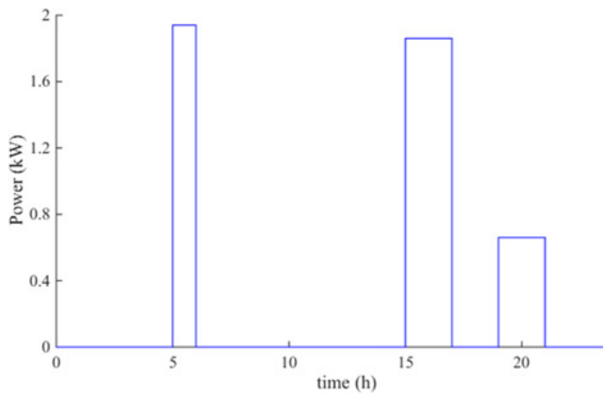

Fig. 5 *Optimum power supply of load 6*

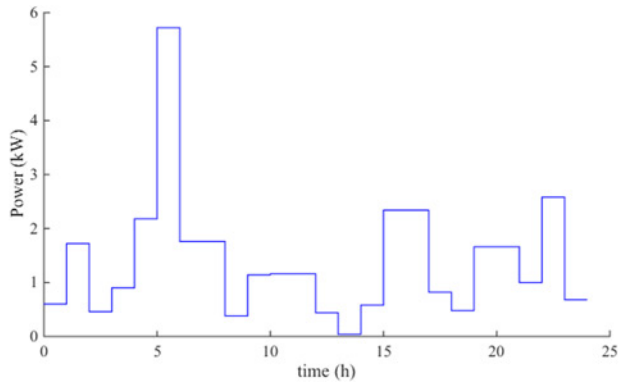

Fig. 6 *Optimum power supply of the electrical system*

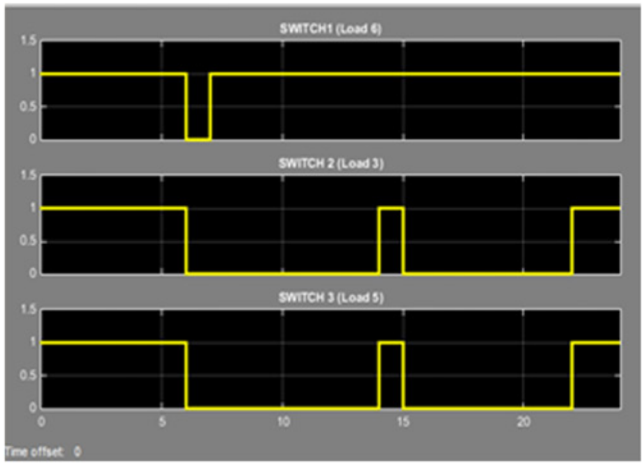

Fig. 7 *Optimum power supply of the electrical system in discrete mode*

Table 4 Daily cost analysis of energy consumption

Normal cost to pay the utility grid (UT)	Cost with TOU and CET	Cost with TOU and optimal
R101.973	R42.91402	R30.38602

Fig. 7 shows the switching strategy on the smart meter that defines the optimal strategy incorporated on the meter. This figure also presents the selected energy demand system as shown in Table 3 that is supplied by nodes 2, 3, and 4 of the designed device. Therefore, it is observed that the switching system of the smart meter optimises the energy demand regarding the CET.

This optimal structure is also detected by comparing Figs. 3–6 with their respective loads as shown in Table 3.

Table 4 presents the daily energy demand of the system. It can be seen that the cost of energy flow on the electrical system is expected to be reduced by 42.1% when the system is mostly implemented with the cost of energy set by the consumer. Moreover, when the optimal strategy is incorporated in the device, the energy cost can be reduced by 29.8%. Regarding the electrical system that is combined with this new generation of the instrument, it could be seen that this procedure provides an optimal opportunity to the end users of a smart meter.

4 Conclusion

This research has presented the new generation of smart metering systems that can optimise the energy demand in the framework of a quadratic equation by using MPC strategies to control the electrical system while minimising the overall operating cost in real time. The study begins by highlighting information from the literature in a smart grid environment. Relevant methods of the intelligent network in smart metering infrastructure were described, and the most significant benefits and issues of using such approaches were also discussed. The strategies were studied regarding their contribution to the major advantages of the end-users. In this brief, the optimisation of the energy in the demand side can be ensured by using a smart meter device successfully in discrete time. It has been found that this compact device could also be used to minimise the price of electricity in real time. It has also been concluded that the approach in energy demand is robust enough to satisfy the objective functions which are subjected to the system constraints concerning energy optimisation and management.

Future research will focus on the integration of renewable energy into the electrical system to ensure the continuous supply of maximum energy and on the ability to measure in real time the electricity pricing strategy from different power generation. Moreover, it will also concentrate on the implementation of the switching system and communication protocol of the smart meter.

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