Optimizing Cost with Intelligent Energy Management System based on Fuzzy Logic

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Abstract - *In this paper an Intelligent Energy Management System based on fuzzy logic is proposed. The objective of the proposed strategy is to optimize the cost saving for the end consumer by determining the share of the power drawn from the grid or the Energy Storage Unit for each hour of the day, because the price of the energy varies each hour depending on the demand and is determined a day before. The strategy is based on Mamdani's Fuzzy Inference System. The proposed design will also avoid overloading the grid during the periods of high demand by shifting the load to the ESU.*

Keywords— Intelligent Energy Management System; optimization; fuzzy logic

1. Introduction

Energy consumption is increasing worldwide [1]; therefore it makes good sense to lower the consumption from the grid generated using traditional methodology to reduce mankind's footprint. The electricity bill of a large enterprise can be minimized by managing dynamic energy pricing [2] [3]. The wholesale electrical companies determine the cost of energy for each hour of the day at midnight before the day begins [4]. Consumers can use this information to optimize their energy consumption. The idea is to shift the load from a high price to a low price. In order to achieve this some basic infrastructure is assumed, such as a smart meter connected to the grid for two way communication of price [5] and load demand. Also an Electric Storage Unit to store the energy; when the price is relatively cheaper and release it when it is high and two switches one for drawing energy from the grid and the other for using the ESU for meeting the demand [6] [7]. Thus, one of the main ideas of smart grids is encouraging the consumer to participate in making decisions about energy consumption in an efficient way. In this paper we have come up with an Energy Management Strategy based on simple rules which mimic human thinking. This strategy provides us the ratio of the power drawn from the grid and the ESU at any particular hour of the day, to minimize the cost to the end consumer and also reduce the load on the grid during peak hours by not drawing from the grid [9] [10].
Fig. 1 illustrates the infrastructure of Large Enterprise using intelligent EMS.

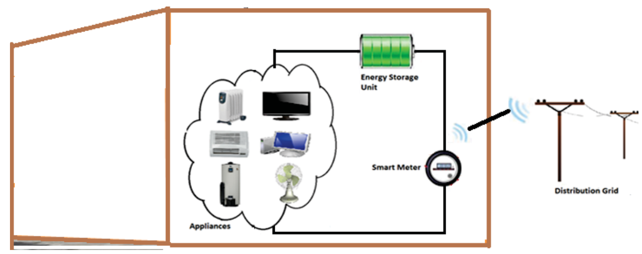

Fig. 1. Infrastructure of Large Enterprise for Intelligent EMS

Fig. 2 illustrates the hourly power price curve of a typical day. The lowest hourly price was at 15:00 and the highest hourly price was at 18:00 PM. Fig. 3 illustrates the hourly grid load curve of a typical day. Hourly prices were significantly affected by the hourly grid load. Therefore, the highest grid load also occurred at 18:00 PM [8].

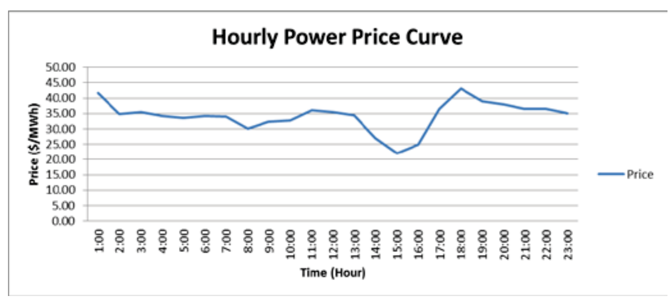

Fig. 2. Power price curve on Jan/1/2011[8]

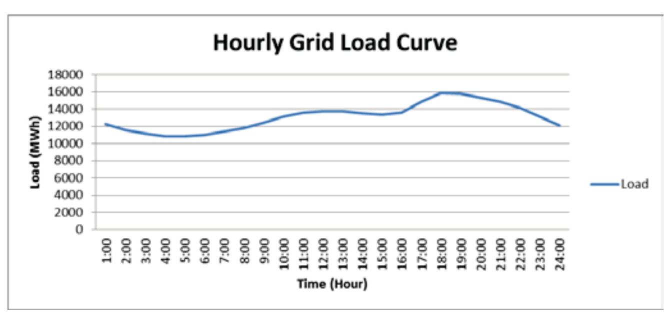

Fig. 3. Grid load curve on Jan/1/2011[8]

Fig. 4 illustrates the hourly cost of power consumption curve of a typical day computed by Equation.

$$Cost = Price * Load \quad (1)$$

In Fig. 4, the lowest hourly cost was at 15:00, when people are usually at work. The highest hourly cost was at 18:00, when people came home and used the energy for domestic needs [8].

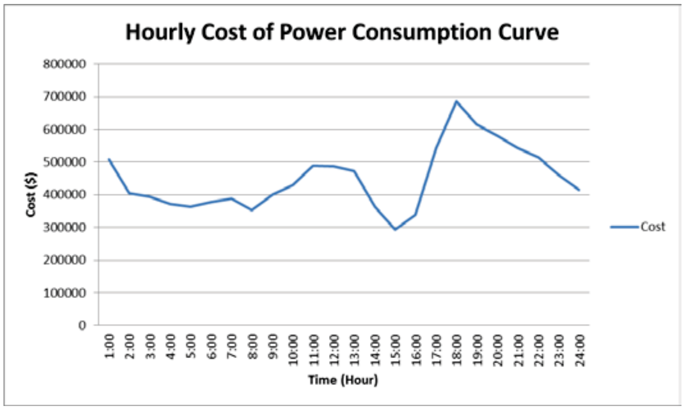

Fig. 4. Cost of power consumption curve on Jan/1/2011

The paper is organized as follows: Section II describes the basic concepts of Fuzzy Logic; In Section III, an Intelligent Energy Management System based on Mamdani's Fuzzy Inference System is proposed; In Section IV implementation of Mamdani's Fuzzy Inference System is discussed; Section V discusses the results and the cost savings obtained by using this Fuzzy Logic based approach.

2. Fuzzy Logic

The purpose of Fuzzy Logic is to map an input space to an output space with simple if-then-else rules which mimic human-thinking. All rules are equally evaluated, and the order of the rules does not affect the results. In general, fuzzy inference is a method that interprets the values in the input space and, based on some set of rules, assigns values to the output space [11][15]. Fuzzy Logic starts with the concept of a fuzzy set. Compared with a classical set, a fuzzy set is a set without crisp and clearly defined boundaries [12] [15].

In a classical set theory, the universe is black and white. Either an element belongs to the set with 100% membership, or it does not belong to the set at all. In fuzzy set theory an element can belong to more than one fuzzy set with a membership degree ranging anywhere from 0 to 100%. For example, Fig 5 illustrates classical sets. Fig 6 illustrates fuzzy sets. An element, say a price of 23, belongs to both the fuzzy sets Cheap and Medium. However, in classical sets price 23 will either belong to one set which is Cheap, and it can never belong to more than one set at the same time [13].

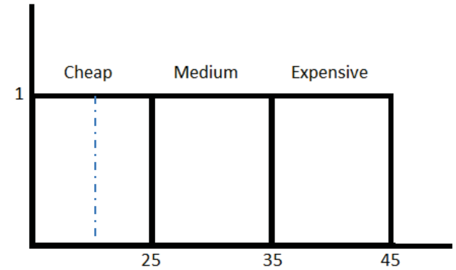

Fig. 5. Classical Sets

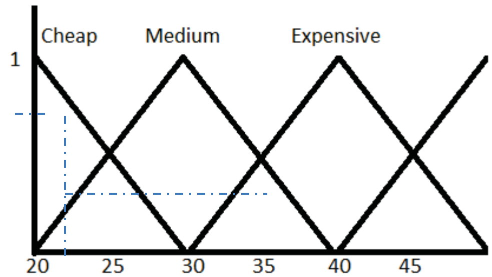

Fig. 6. Fuzzy Sets

If X is the universe of discourse, and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs. It is shown in Equation 2 [11] [12].

$$A = \{ x, \mu_A(x) \mid x \in X \} \quad (2)$$

$\mu_A(x)$ is the membership degree of x in A [14]. The membership degree maps each element of X to a value between 0 and 1[11].

There are two most widely used fuzzy inference systems: Mamdani's Fuzzy Inference System and TSK Fuzzy Inference System. Fuzzy inference systems have been successfully applied to the domains of automatic control, data classification, decision analysis, expert systems, and computer vision [14]. In TSK model the output is expressed as a mathematical equation.

Mamdani's Fuzzy Inference System is preferred when no relation between the input and output parameters is known and the relationship can express in the form of if-then-else rules. It was proposed in 1975 by Ebrahim Mamdani [12].

3. Mamdani's FIS Strategy

Fig. 7 illustrates the framework for Intelligent Energy Management System [13]. The integrated Mamdani's Fuzzy Inference System will process the input of price and load, and generate output which will be sent as a control signal to operate Grid Switch and Storage Switch. The control signal sent to Grid Switch will determine how Smart Meter directs electricity from the Distribution Grid to the Energy Storage Unit and other appliances [14]. The control signal sent to Storage Switch will operate the Energy Storage Unit and it will decide whether the Energy Storage Unit is charging or releasing [13].

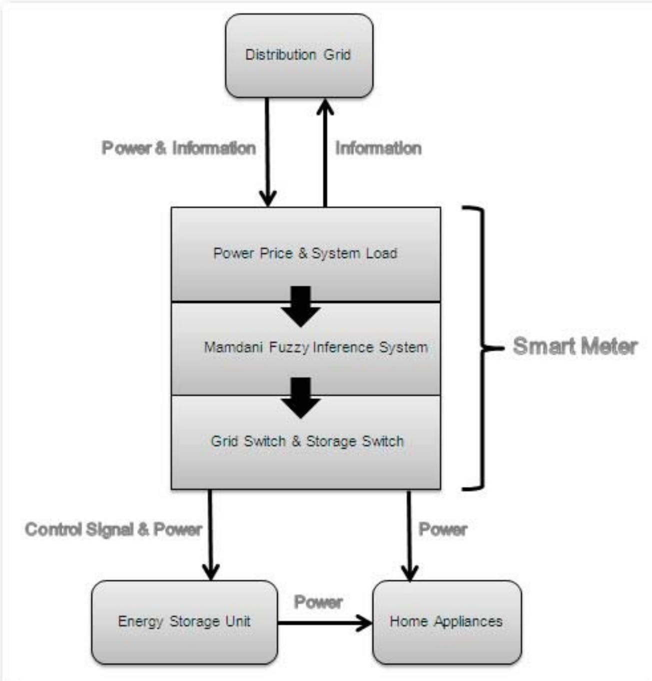

Fig. 7. Framework of Mamdani' FIS Strategy [8]

Fig. 8 illustrates Mamdani's FIS for Energy Management. The crisp inputs of price and load are presented to fuzzy inference system, which goes through the process of fuzzification, rule evaluation, and defuzzification to generate a crisp output to control the state of ESU which is either charging or discharging. All the six rules are listed below:

1. If price is cheap and load is low, then ESU is charging at 100% of the Load at that hour.
2. If price is cheap and load is high, then ESU is charging at 60% of the Load at that hour.
3. If price is medium and load is low, then ESU is charging at 20% of the Load at that hour.
4. If price is medium and load is high, then ESU is releasing at 20% of the Load at that hour.
5. If price is expensive and load is low, then ESU is releasing at 60% of the Load at that hour.
6. If price is expensive and load is high, then ESU is releasing at 100% of the Load at that hour.

The first rule is "if price is cheap and load is low, then ESU is charging at 100%." 100% charging means that ESU is charging to the capacity of the load at that hour, e.g. if the load at a particular hour is 2 KW, then ESU is charging to 2KW.

Similarly, if ESU is releasing at 20%, this means 20% of the total demand at that particular hour is being met by the storage unit, e.g. if the load at that hour is 10KW, then 2KW is being met by the storage unit and rest of the 80% which is 8KW is being drawn from the grid.

The following four trends emerge from the rules.

Trend 1: When power price is cheaper, ESU is charging more.
Trend 2: When power price is more expensive, ESU is releasing more
Trend 3: When grid load is lower, ESU is charging more
Trend 4: When grid load is higher, ESU is releasing more [8]

These four trends precisely simulate the process of decision making in a human mind. Trend 1 and Trend 2 are focused on cost reduction; while Trend 3 and Trend 4 are focused on avoiding overloading of the grid.

Mamdani FIS for Energy Management Unit is implemented with the following steps:

Step 1: Fuzzification of Inputs

In this step, input of power price and input of grid load are being fuzzified through membership function. Before the fuzzification, inputs of power price ranged from 19.94 to 558.55 ($/MWh), while inputs of grid load were from 8294 to 27707 (MWh) [4]. After the fuzzification, input parameter price was represented with three fuzzy sets: "expensive", "medium" and "cheap." Input parameter load was represented with two fuzzy sets: "high" and "low [8]."

Step 2: Evaluation of Rule Strength

Three fuzzified values for power price and two fuzzified values for grid load were generated from Step 1 and ranged from 0 to 1. In Step 2, fuzzy operators apply to these values through six rules. For example, Rule 1 is "if price is cheap and load is low, the ESU is charging at 100%." When 0.6 is the fuzzified value of cheap and 0.4 is the fuzzified value of low, then the rule strength is the fuzzy AND operation of two sets Cheap and Low which is 0.4.

Step 3: Truncation of Output Fuzzy Set Associated with the Rule

The consequence is truncated with the rule strength obtained in step 2. In this instance, the output ESU charging at 100% will be truncated at 0.4. This will be done for all six rules [8].

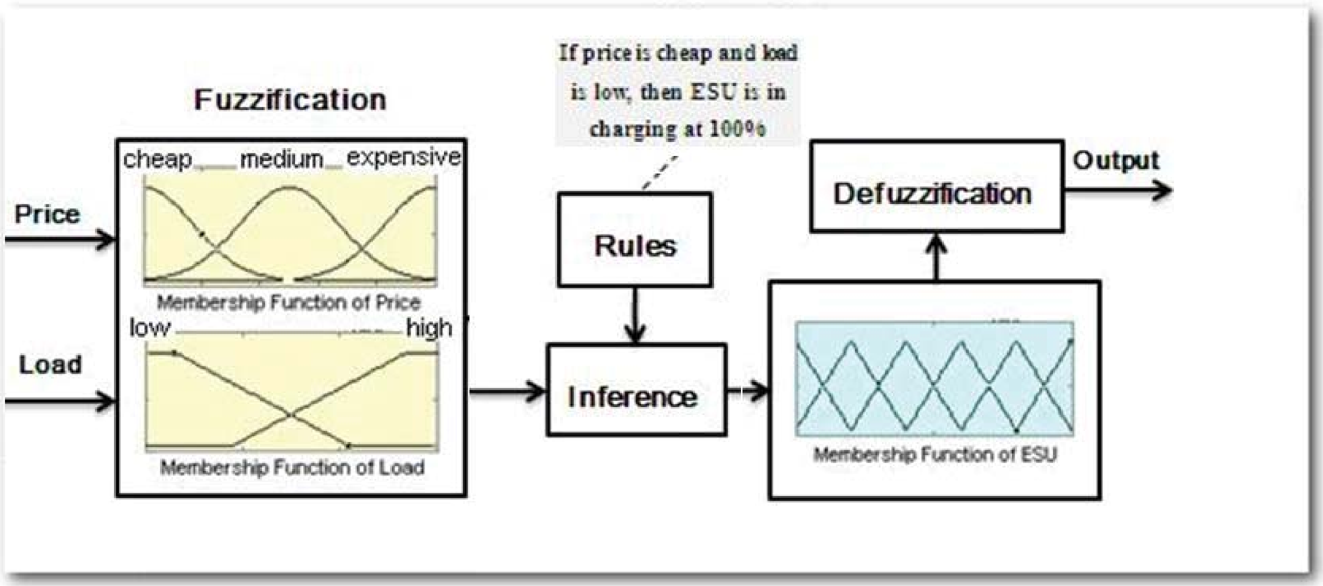

Fig. 8. Mandani's FIS for Energy Management [8]

Step 4: Aggregation of Output of Rules

The rules must be combined in some manner in order to make the decision. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set [15].

Step 5: Defuzzification

In this step, all the aggregate outputs from step 4 are combined together to give one crisp output which shows the state of ESU charging or releasing. The most popular defuzzification method is the centroid calculation, which returns the center of the area under the curve. Centroid calculation has been applied in the proposed design.

4. Methodology and Implementation

The Energy Management Unit is implemented in MATLAB using Fuzzy Logic Toolbox. Fuzzy Logic Toolbox is an integrated development tool of Matlab that provides Matlab functions, graphical tools, and a Simulink block for analyzing, designing, and simulating systems based on fuzzy logic. Fuzzy Logic Toolbox consists of the following five GUI tools to build, edit and view fuzzy inference systems [15]:

1. ***Fuzzy Inference System (FIS) Editor***
2. ***Membership Function Editor***
3. ***Rule Editor***
4. ***Rule Viewer***
5. ***Surface Viewer***

These five GUI tools are dynamically linked. Any changes made to the fuzzy inference system through one GUI tool will affect other GUI tools.

Fig. 9 shows the FIS editor displaying Mamdani's model for Energy Management Unit. Inputs are price of the power and load on the grid. Output is the state of Charge of ESU. "And method" computes the minimum of fuzzy sets. "Or method" computes the max of fuzzy sets. "Implication" is set to be min. "Aggregation" is set to be max. "Defuzzification function" is set to centroid.

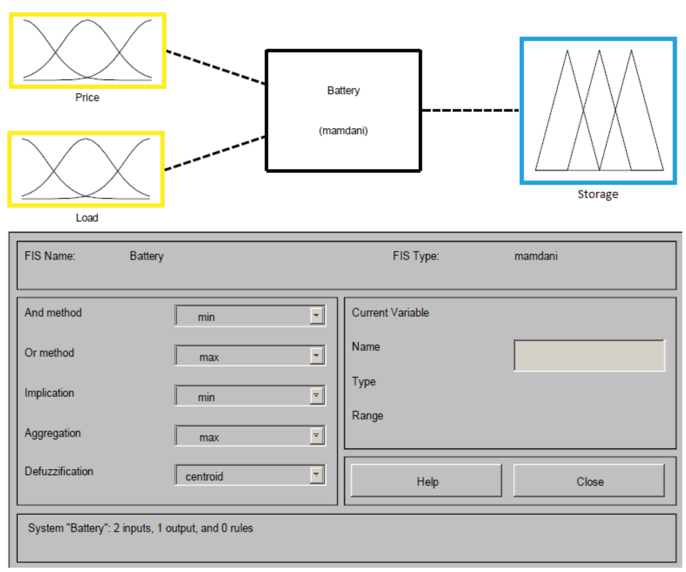

Fig. 9. Mamdani's model in FIS Editor [8]

Fig. 10 shows three membership functions for price: cheap, medium, and expensive. All three membership functions are set to be Gaussian type. Fig.11 shows two membership functions of Load: low and high. Both membership functions are set to be trapezoid type [8].

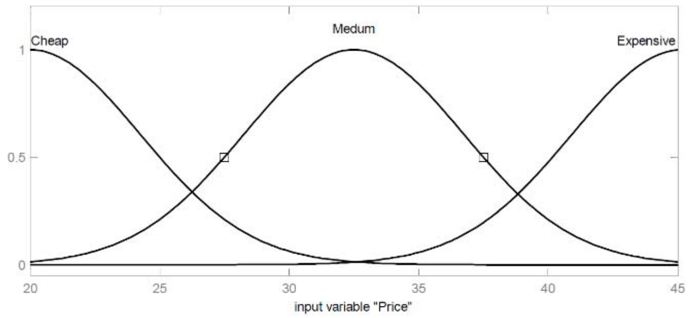

Fig. 10. Membership Functions of Price

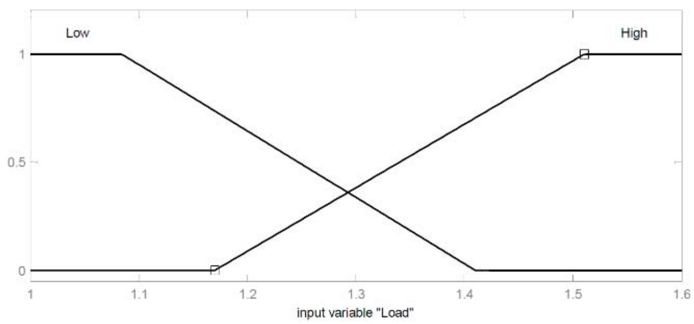

Fig. 11. Membership Functions of Load

Fig.12 shows six membership functions for ESU: releasing high, releasing medium, releasing low, charging low, charging medium, and charging high. All membership functions are set to be triangle type.

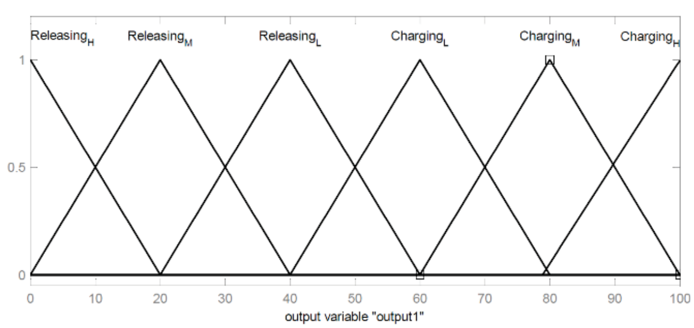

Fig. 12. Fuzzy Membership functions for output variables

Fig 13 shows a snapshot of the rules which fire for a given input of price and grid load. The output computed after defuzzification is 42.9 for proposed FIS [8].

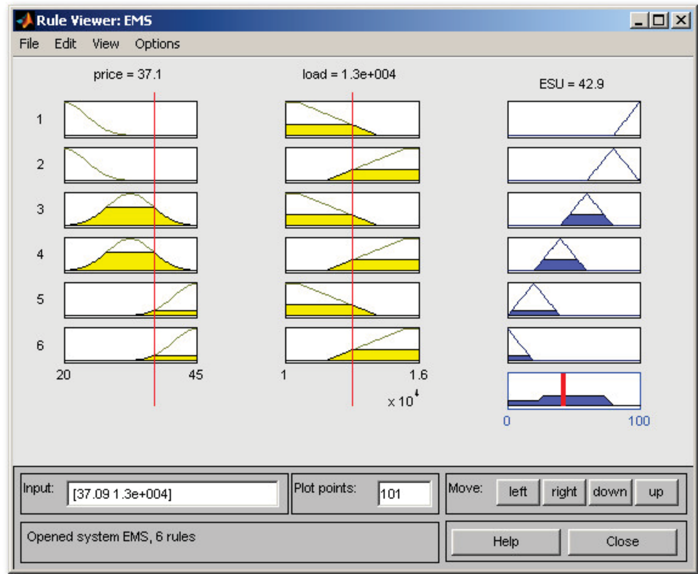

Fig. 13. Rule Viewer for proposed Mamdani's FIS based model

5. Performance Evaluation

Fig. 14 illustrates the hourly load curve of Mamdani's FIS strategy in a typical day and shows that the load is shifted from high price to the low price. By using Mamdani's FIS strategy it is clear that when the grid load is high, the Energy Management unit releases power and does not draw power from the grid, thus not contributing to increase the load on the grid and making the grid more stable.

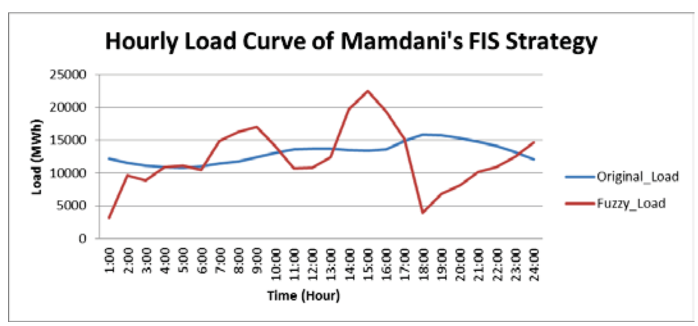

Fig. 14. Load curve of Mamdani's FIS on Jan/1/2011[8].

Fig 15 shows hourly cost of power consumption of Mamdani's FIS strategy in a typical day. When the cost of the power is high then the Energy Management unit releases the stored energy for the need of the enterprise thus saving cost for the consumer.

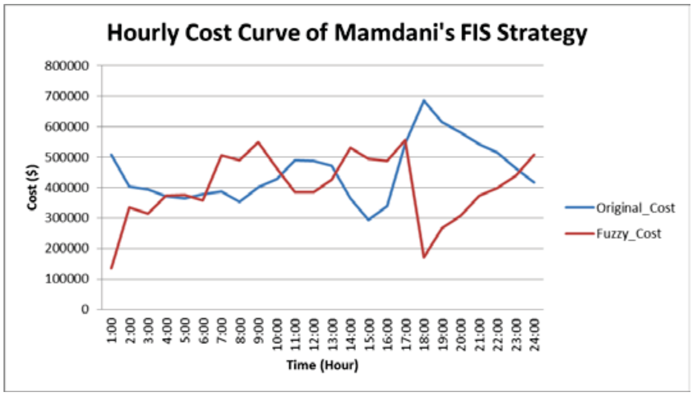

Fig. 15. Hourly cost of Mamdani's FIS on Jan/1/2011[8]

Table I shows the quarterly saving rates of Mamdani's FIS strategy [8]. The saving rates are from 11.4% to 30.1

TABLE I
QUARTERLY SAVING RATES OF MAMDANI'S FIS STRATEGY

Months	Original Cost ($)	Mamdani's FIS Cost ($)	Mamdani's FIS Saving
Jan-Mar	571.1	483.85	15.3
Apr-Jun	467.18	396	15.2
Jul-Sep	662.91	463.3	30.1
Oct-Dec	409.68	363.03	11.4

6. Conclusion

In this paper an Energy Management Unit (EMU) has been proposed for a large enterprise with consumption ranging in several MW. Mamdani's FIS approach is designed to reduce cost for the end consumers and avoid grid overload for the power supplier. The saving rates vary from 11.4% to 30.1%. Therefore, it has been demonstrated that Mamdani's FIS based approach resulted in cost saving as compared to the original cost without using any technique. This same approach can be applied to smaller dwelling units if the price of the energy varies every hour.

7. References

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