A Novel DSM strategy for micro grids consisting of higher penetration of water heater loads

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***Abstract* – The work presented in this paper proposes an energy management strategy suitable for micro grids consisting of higher penetration of water heater loads. In the proposed control strategy water heater loads are considered to be non-critical in nature and are scheduled in an efficient way to achieve certain benefits like reduction of peak loading, power rampage and electricity bills paid by the consumers. The noncritical loads are operated in different power saving modes instead of curtailing them completely. The required level of power saving is directly decided by the users, which in turn results in utmost consumer satisfaction. The scheduling of water heater loads is performed using electric springs. Electric springs are connected in series to the water heaters and based on the power savings specified by the users the heating loads are operated in different power saving modes. The robustness of the proposed methodology is tested on a 14 bus micro grid system and the simulation studies are carried out in MATLAB**

Index Terms- Demand side management; Water heater loads; AC Electric springs; Energy saving

I. INTRODUCTION

Demand side management is an energy management technique which will be benefitting the consumers as well as the utility in some (or) the other aspects. In other words DSM strategies can be termed as load management strategies, which help the utility to reshape the electricity curve, so as to bring it close to the generation pattern [1]. One of the methods adopted to implement DSM is popularly known as indirect control where the consumers are given the choice to schedule their appliances in order to attain certain incentives and also to lower the electricity bills paid [2]. In general in order to implement the DSM strategies at the consumer level loads are classified as critical and non-critical loads. It is important to note that the DSM strategies can only alter the power consumption pattern of the non-critical loads.

Domestic water heaters fall under the category of non-critical loads and also contribute to a larger share in residential demand [3]. It has been observed that, in most of the developing countries like India the electricity consumption of the water heaters amounts to 23 % of the total residential demand [4]. From the figures it is evident that these water heating loads can contribute in a better way to the DSM programs and will be definitely helpful in re-shaping the load curves in an effective way. Interestingly the load profile of the water heaters is almost similar and repetitive [5]. Different studies have been performed to estimate the benefits of using domestic heating loads for various services, like the DSM [6]. Different demand side management strategies have been proposed by taking water heaters as non-critical loads. In order to reduce the peak demand on the power system during different times in a day, an optimization algorithm which uses direct load control has been presented in [7]. The algorithm presented in [7] optimizes the given problem by implementing proportional and integral methods. Similarly, the authors in [8] also presented a direct load control scheme to regulate the occurrence of peak loading in the system. A hierarchical energy management model and sectionalized control of temperature model has been adopted for the study. An incentivized linear optimization model to control the water heater loads as a part of demand side management program has been presented in [9]. The methodology presented in [9] requires one way communication and focuses more on cost saving of the consumers. Further, different methods to control water heater loads at domestic level has been presented in [10], [11] & [12] and the potential of hot water loads in reducing the daily peaks occurring on the system is projected in [13].

From the works reported by variety of authors in [4] – [12] it can be understood that electric water heaters are scheduled using different methods or by solving the presented mathematical models. Interestingly the authors in [14] presented an energy management model for aggregated water heater loads by controlling the voltage supplied to the water heaters. In the work presented in [14] water heaters are considered as constant impedance loads and reduction in the

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power during peak times of the day is achieved by controlling the supply voltage. Unlike the work presented in [14], the authors in [15] presented a hybrid strategy for scheduling the electric water heaters based on price, load and voltage control. The methodology presented in [14] & [15] is different from other works presented in literature because the authors tried to achieve power conservation by adjusting the voltage supplied to the electric water heaters.

The work presented in this paper proposes a new type of demand side management strategy for micro grids, having higher penetration of electric water heaters. In this work, in order to reduce the peaks in power consumption, power rampage and electricity bills paid by the consumers, the usage of AC electric springs in series with water heater loads is suggested. Electric springs when connected in series with the water heaters suppress a reasonable amount of voltage being supplied to them (whenever required), which in turn results in power conservation. The difference between the work presented in this paper and other works, refereed in [14] & [15] is that, by introducing electric springs into the system, the system gets reactive power support along with voltage suppression function, which in turn improves the voltage profile at the critical nodes of the system. Also, this injection of reactive power into the system will be very much useful during power rampage because, the voltage in any healthy system gets affected because of the drastic changes in the loading.

Going little ahead towards the concept of AC electric springs (ES), for the first time electric springs were introduced as a new smart grid technology in [16]. Since their introduction, springs have been used for different applications like reduction of battery storage requirement [17], mitigation of voltage and frequency fluctuations [18], power factor correction [19] and reduction of main grid dependability [20]. A detailed review of different applications has been presented in [21]. From the literature on springs it can be clearly understood that springs have been used for variety of applications but not used in micro grids consisting of higher amount of water heating loads. The work presented in this article focuses on developing a different, user defined DSM strategy solely considering water heater loads as non-critical loads. This presented work will be useful in reducing the daily peaks, power rampage occurring on the system along with the provision to inject reactive power into the system. Further, as the proposed methodology is completely user defined the users will be in a position to reduce the electricity bills paid by them, which is also an added advantage of inheriting the projected algorithm.

II. BASICS OF ELECTRIC SPRING

In the recent past electric spring emerged as a new smart grid technology, falling under the category of input control devices unlike the traditional control devices like the STATCOM which operate under output control schemes. Detailed operation principle and its interpretation with mechanical springs can be found in [16]. The basic connection diagram of the same is as shown in Fig. 1.

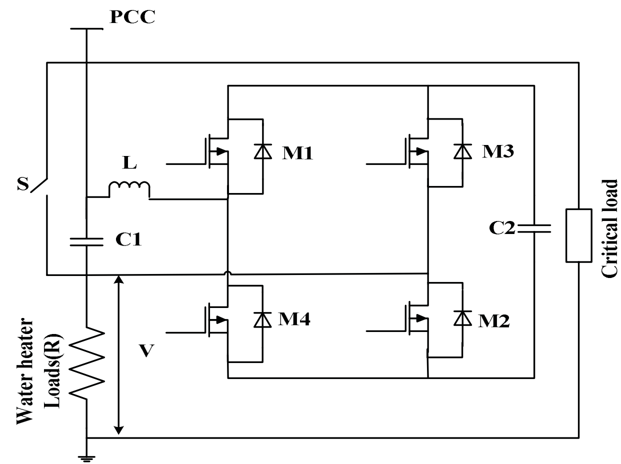


Fig.1. Connection diagram of ES [16], [17] & [22]

As depicted in Fig.1.electric spring circuitry consists of four MOSFET's, one bypass switch 'S', an AC filter capacitor 'C1' and a DC filter capacitor 'C2'. In this work Water heater loads are considered as non-critical loads and are expected to operate at a voltage tolerance of around 20 % from the rated value. In order to do so water heater loads are connected in series to the ES and this complete setup of what is called as smart load appears in parallel to the critical loads (voltage sensitive loads). As the springs are capable of supplying reactive power during their operation, the critical loads get the benefit of better voltage regulation. The operation of springs is as follows, during normal operation i.e. whenever there is no necessity to suppress the voltage being supplied to water heating loads the switch 'S' will be closed and hence the voltage appearing across heating loads and critical loads is one and the same. Further, whenever there is a necessity to suppress the voltage supplied to water heaters the switch 'S' is made open and based on the voltage that is allowed to appear across the filter capacitor 'C1' the voltage appearing across the heating loads will be decided. Detailed explanation about the operation of the same can be found in [16], [20] & [22].

The phasor diagram corresponding to the voltage at the PCC and heating loads is as shown in Fig.2. It can be understood from Fig.2. that during voltage suppression function of ES the voltage appearing across filter capacitor(Va) should be out of phase to the voltage appearing across water heating laods(V) and the resultant of both the voltages will lead to voltage appearing across PCC(Vpcc). Further, the current flowing through the electric water heater loads is denoted as 'I'.

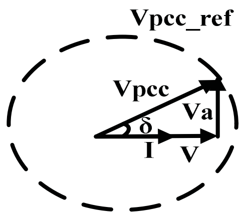


Fig.2. Voltage vectors during the operation of spring

The power supplied to the water heater loads can be written as follows

$$P_{wh} = \frac{V^2}{R} \quad (1)$$

Where P_{wh} is the power consumed by the water heater loads. By looking at Fig.2. it can understood that the voltage appearing across the water heater loads during the operation of spring is the difference between the voltage appearing at the PCC and voltage appearing across 'C1'. Therefore power consumption during operation of spring (P_{wh}^{ES}) can be written as follows

$$P_{wh}^{ES} = \frac{(V_{pcc} - V_a)^2}{R} \quad (2)$$

Hence from (1) & (2) it can be understood that the power consumption of the water heater loads during the operation of springs is lesser when compared to their absence and hence the inequality of the same is as stated in (3). Also it has to be noted that, whenever ES is not in operation V_a becomes zero.

$$P_{wh} \geq P_{wh}^{ES} \quad (3)$$

Hence by looking at (3) it can be understood that by operating ES in the system during the required times in a day there can be substantial reduction in the real power consumption. Further the reactive power supplied by the spring (Q) can be understood from the following equations.

$$Q = V_a . I \quad (4)$$

$$Q = V_a . \left(\frac{V}{R}\right) \quad (5)$$

III. PROBLEM DESCRIPTION AND METHODOLOGY

The broad aim of this work is to reduce the power rampage, daily peaks and also to reduce the electricity bills paid by the customers. Along with the reduction in power rampage and daily peaks the proposed algorithm is expected to supply reactive power to the system. The power pattern of the system during rampage can be written as follows

$$P_j = P_{(j-1)} + \Delta P_{(j,j-1)} \quad (6)$$

The real power during j[th] hour (P_j) is nothing but the power during previous hour ($P_{(j-1)}$) and the net incremental power. As the objective of the work is to minimize the power rampage (6) can be re-written as follows

$$\text{Minimize } \Delta P_{(j,j-1)} = P_{(j-1)} - P_j \quad (7)$$

The minimization of the power ramping is achieved by operating the water heater loads in power saving mode, as defined by the consumers. Further, it has to be understood that even during peak loading conditions in order to reduce the same water heaters are scheduled using springs which in turn reduces the peak loading. Similarly due to the operation of water heaters in the system in power saving mode the electricity consumed by them also will reduce, which in turn results in lesser electricity bills paid by the customers.

In order to attain the said objectives a completely user defined energy management algorithm is presented in this study and the pseudo code of the same is as follows

Pseudo code

Step 1:- Start the process

Step 2:- Read the hourly water heater load data of the day

Step 3:- Get the hourly percentage saving in the power specified by the consumer, pertaining to the water heater loads

Step 4:- Read the user preference; j=1

Step 5:- Schedule the water heaters as per the specified power saving for the j[th] hour by altering the voltage supplied to them using ES; else go to step 6

Step 6:- Is j=24?? ; Yes go to step 2; else j=j+1, go to step 5

The presented Pseudo code reads the preferences of the users and schedules the water heater loads accordingly. In this course of work the water heater loads are assumed to operate at a larger voltage tolerance level of about 18 % from the rated value. The presented algorithm schedules the heater loads present in the power system for the entire duration of day based on the user requirement and hence re-shapes the existing load curve to a possible extent. One of the assumptions made in this study is that the water heater loads in all the customer premises are fitted with electric springs like the setup show in Fig.1. One more advantage of placing ES is that they are also capable of providing better voltage regulation to the voltage sensitive (critical) loads, if they are connected in a manner shown in Fig.1.

IV. RESULTS AND DISCUSSIONS

In order to test the performance of the presented methodology, a 14 bus micro grid system which has higher penetration of electric water heater loads has been considered for the study. The electric load appearing on the system is divided into two components, one is the general load and the other is the Hot water load. The details of the considered micro grid system can be found in [23]. It is assumed that all the loading on the system is balanced and the entire system operates at an AC voltage level of 220 volt, 1-phase and at a frequency of 50 Hz. The daily aggregated load curve of the system at different time instances and the cost of energy is shown in Fig. 3 & 4 respectively. From, Fig.3 it can be observed that the rampage in the total power(sum of general and hot water loads) and maximum peak occurring on the system can be very well controlled by scheduling the hot water loads in an effective way.

As the presented algorithm is user centric, the user is free enough to give a power saving choice ranging from 0 to 100 % based on the requirement. It has to be understood that the least possible voltage that can be applied to the hot water loads is 180 volt, which means that whenever the user specifies the power saving to be 100 %, it means that the control algorithm is expected to supply a voltage of 180 volt to the water heaters.

Similarly, if the user specifies that there is no need to save any power then a voltage of 220 volt (similar to that of critical loads) shall be applied to the water heaters. Further, the actual load data of the system is distributed throughout the 14 buses of the system but for calculation simplicity the same is assumed to be lumped nature.

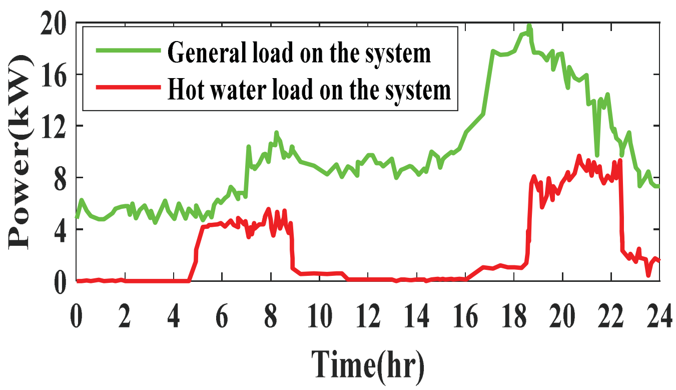


Fig.3.Daily aggregated load pattern of the micro grid [23]

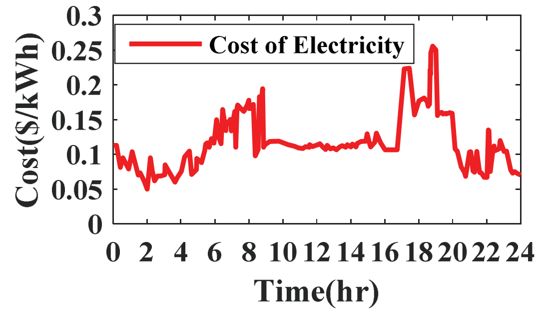


Fig..4. Cost of Energy [23]

In this article two case studies are considered. In the first case the complete system is operated under 100 % power saving mode for the entire duration of the day and for the second case and in the second case the system is operated at 50 % power saving mode. In order to calculate the net savings in power, reactive power injected into the system the hourly hot water loading on the system is represented in terms of resistance and the same has been presented in Fig.5.

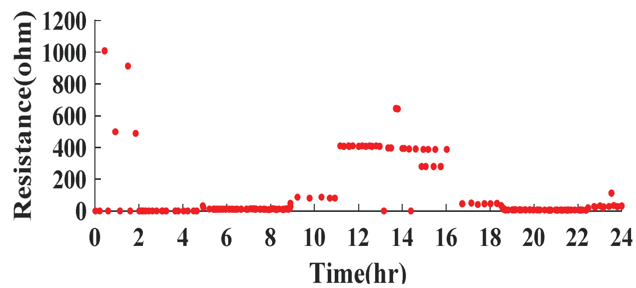


Fig.5. Resistive load on the system

During normal operation of the day, i.e. whenever there is no power saving mode opted the hourly cost paid for the usage of general and hot water loads is as shown in Fig.6. The total cost of electricity bill payable for one complete day, considering both general and hot water loads is $ 282.

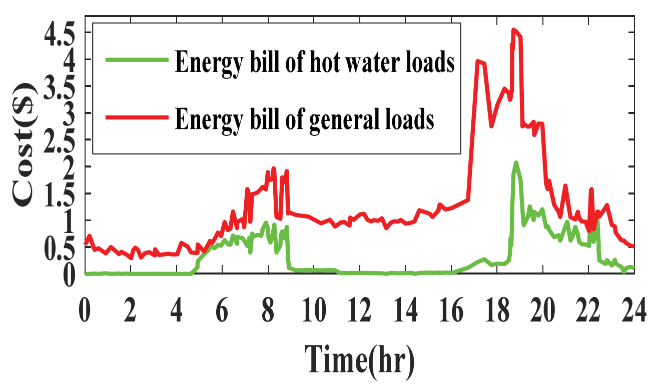


Fig. 6. Aggregated hourly electricity bill

The total power consumed by the hot water loads when operating at 100 & 50 % saving modes is as shown in Fig.7. Further, it should be taken into account that the power consumption pattern of the general loads will remain un-effected due to the operation of ES.

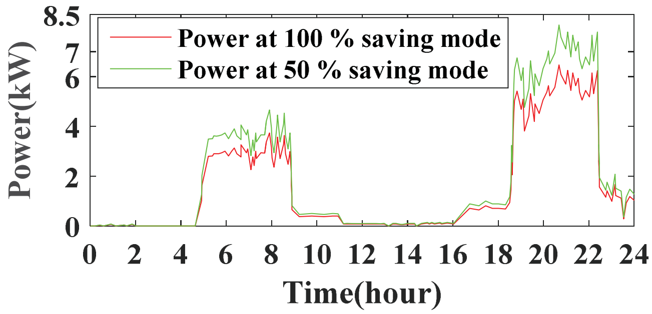
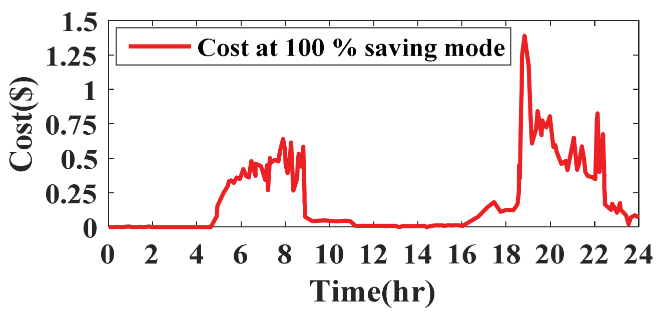
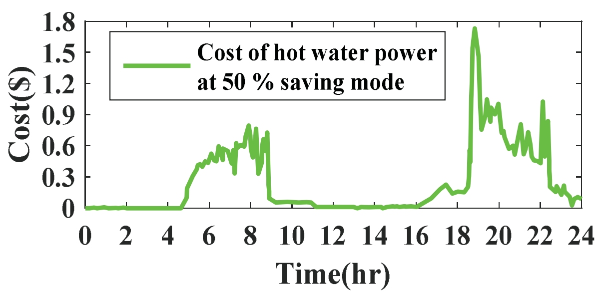


Fig.7. Power consumption of the hot water loads during power saving mode

By comparing Fig.3 & 7 it can be understood that the power consumed by the hot water loads during the operation of electric springs is lesser in comparison to their absence. Also the total cost of energy paid for the operation of water heater loads is also lesser, which can be understood by comparing Fig. 6 & 8.



(a)



(b)

Fig.8. (a) & (b) Hourly cost of electricity bill for the hot water loads during the operation ES

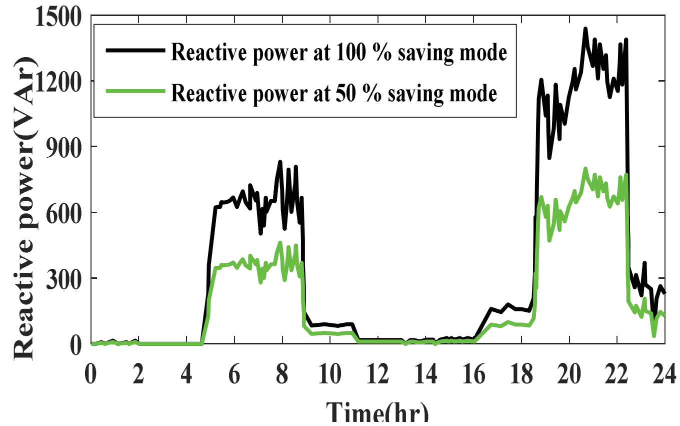


Fig. 9. Reactive power supplied by electric springs

The total cost of energy for the entire system during operating the system at 100 and 50 % saving modes is around \$ 260 & \$ 271 respectively. Hence the net reduction in the cost is about 8.5 and 4 % during 100 and 50 % power saving modes. Also it has to be understood that the maximum peak on the systems occurs during the 18th hour of the day and is about 26.27 kW, which is the combination of general and hot water loading. During operating the system at 100 % saving mode it has been observed that the peak on the system has reduced to 23.5 kW, which is once again a reduction of 11 %. Similarly during 50 % saving mode the peak has reduced to about 24.7 kW, which means that there is a reduction of about 6 % from its original value.

The power ramping rate on the system can be controlled to a certain extent because the total loading on the system can be effectively controlled by operating the hot water loads in power saving modes, especially from 5th to 9th hour and 17th to 19th hours of the day. In addition to the above ES is capable of providing reactive power support to the system and the same is illustrated in Fig.9.

V. CONCLUSION

The work projected in this article presents a different energy management algorithm, which schedules the hot water loads based on the requirements of the user. From the results obtained it can be clearly established that the proposed control strategy is capable enough to re-shape the existing load curve and also helpful in achieving cost cutting. Further, in this work the tolerance level of voltage considered for water heater loads is completely arbitrary. The minimum permissible value of voltage that has to appear across the water heaters can be adjusted to a greater or lesser value based on the requirement of the utility and customers. The future scope of this work can be on developing a control strategy which reshapes the load curve based on the availability of generation.

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