A New Choice based Home Energy Management System using Electric Springs

S Hari Charan Cherukuri and B Saravanan
School of Electrical Engineering
Vellore Institute of Technology(VIT)
Vellore, Tamil Nadu- 632014, India
haricharan3299@gmail.com & bsaravanan@vit.ac.in

K S Swarup
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai, Tamil Nadu - 600036,India
swarup@ee.iitm.ac.in

***Abstract* – The work proposed in this article proposes a different energy management scheme for residential consumers having higher penetration of solar power and heating loads. The presented methodology assumes the heating loads present in the residence as non-critical loads and tries to operate them in power saving mode, whenever necessary. In the considered scheme non-critical loads are connected in series with AC electric springs which in turn schedule them as per the requirement. The major scope of this work is to make the non-critical loads consume lesser power by pressing springs into action in the presence of solar power. It is expected that the springs compliment the efforts of solar panels in reduction of power consumed from utility grid, daily peaks and energy purchase from the utility grid. In order to implement the proposed methodology a completely customer driven home energy management algorithm is proposed and the robustness of the same is tested on a residential consumer, considering a 24 load curve. The simulation studies for the projected methodology are performed in MATLAB.**

Index Terms- Home energy management; High solar power penetration; AC Electric springs; Residential consumers

I. INTRODUCTION

Due to the increase in concern over changing climatic conditions there is a steep increase in the installation of renewable energy sources in the system [1]. Due to the reduction in capital cost of renewable energy sources (especially solar panels), the installation of solar panels on roof tops of residential buildings is picking up momentum in most of the south Asian and African countries [2]. The installation of solar panels on roof tops reduces the energy bills paid by the consumers to the utility and also reduces the stress on the utility during morning and evening peaks occurring on the system. The economic benefits of installing standalone roof top solar PV systems in countries like India has been presented in [3]. Along with installation of solar panels, there is a necessity to schedule the house hold appliances in an effective way so as to achieve better reduction in electricity bills paid by the residential consumers to the utility. A multi objective quadratic programming based residential scheduling in the presence of solar panels, energy storage devices and building loads has been presented in [4]. In the work proposed in [4] the authors used machine learning algorithms to accurately predict the requirements of the users and also to maximize the energy savings to the possible extent. The authors in [5] presented a mixed linear programming approach for energy management suitable for residential consumers. The approach presented in [5] is predominantly flexible to operate the residence on standalone mode which is defined as net zero energy mode in the manuscript. Based on the required comfort levels the authors in [6] proposed a home energy management (HEM) model using fuzzy logic approach. The developed model is tested on a residential complex by considering a summer and winter load curve. Further, the authors in [7] proposed a HEM system by considering a set of rules. The authors in [7] presented a methodology which considers the output from the solar PV systems as a backup source and operates the entire home based on the cost of electricity price either on grid dependent or battery support mode. Unlike most of the works presented in literature the authors in [8] presented a different DSM methodology which schedules the non-critical loads in the presence of rooftop solar panels considering the effect of voltage rise. The algorithm suggested in [8] has been successful in reducing in the peak to average ratio for an aggregated load demand and also demonstrated its capability in regulating the voltage rise problem. A model predictive control strategy for effective management of residential load in the presence of solar modules in presented in [9]. The methodology presented in [9] tries to maximize the utilization rate of the solar cells and the suggested technique improves the utilization factor of solar cells by 87.54 %. Similarly, different energy management strategies for residential consumers in the presence of roof top solar PVs have been proposed in [10], [11] & [12]. Apart from the works presented in [1] – [12], a new smart technology namely AC electric spring has been introduced to the field of Electrical Engineering [13]. The AC electric spring is an input control device which is used for a variety of purposes such as, reduction in battery storage requirements for future micro grids [14], regulation of voltage and frequency [15], enhancement of power system stability [16], reduction of main grid dependence of future micro grids [17], neutral current mitigation [18] and for reduction of power imbalance in 3 phase systems [19].

By looking at the literature available on home energy management systems in the presence of solar panels [1] – [12] and AC electric springs [13] – [19] it is clear that AC electric springs were used for different set of applications in power systems but not used for energy management of residential users, having roof top solar power generation. The work presented in this article tries to re-shape the existing load pattern of a residence consisting of higher penetration of heating loads using AC electric springs in the presence of roof top solar panels. Installation of solar panels on the roof tops reduces the cost of electricity bills paid to the utility and in this work an attempt is made to estimate the further savings in electricity bills paid by the consumers due to the installation of AC electric springs (ES). Along with reduction in the energy bills paid by the consumers, springs also complement the efforts of the solar modules in reducing the daily peaks occurring on the system. Springs achieve the above said benefits by operating the non-critical loads (NCL) in power saving modes instead of curtailing them completely. Further, springs are also capable of supplying (or) consuming reactive power based on the requirement. As suggested in [8] due to the incorporation of solar panels there may be a problem of voltage rise and this problem can be effectively solved to a certain extent by operating the springs in real power suppression and reactive power consumption mode, which is an unique feature. This reactive power handling capability of springs really helps the utility in dealing with over voltage problems caused due to the penetration of solar power. During under voltages caused due to peak loading occurring on the system, springs will be useful in reducing the peaks by operating the non-critical loads in power saving mode and are also capable of providing reactive support to the system to deal with the under voltages.

II. CONCEPT OF AC ELECTRIC SPRING

AC electric spring is a power electronic interface which consists of 4 MOSFETs and other passive elements as shown in Fig.1. The connection diagram for the same is as shown in Fig. 1, ES is an input control device which can be treated as a virtual energy storage unit. As shown in Fig.1. ES is connected in series to the non-critical loads, which are nothing but constant impedance loads (R) and this entire combination appears in parallel to the critical loads. Critical loads in this work are assumed to be voltage sensitive loads, where in there is a necessity to supply constant voltage to them and also the power consumption of the critical loads is always held constant. The work presented in this article tries to operate the NC loads in power saving modes as per the inputs provided by the consumer/s. Further, ES is also capable of supplying (or) consuming reactive from the system.

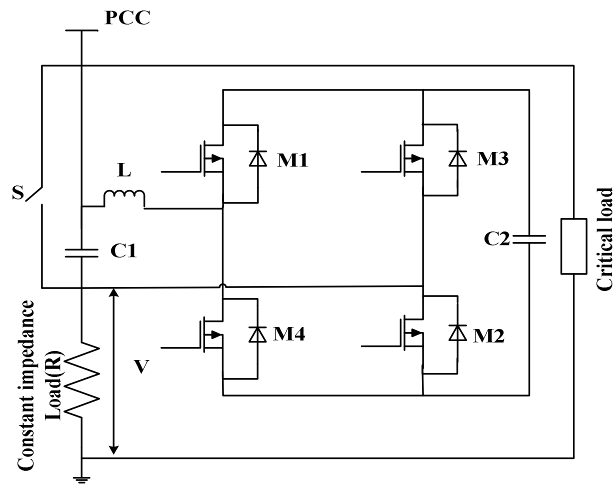


Fig.1. Architecture of ES [13] & [20]

The operation of ES is as follows. During normal operating conditions i.e. whenever there is no necessity to operate NC loads in power saving mode the switch ‘S’ is kept closed and therefore both the Critical and NC loads will operate in parallel which means the voltage supplied to both the set of loads will be the same. Whenever, there is a necessity to operate constant impedance loads in power saving mode the switch ‘S’ is opened and the DC capacitor ‘C2’ is allowed to charge through the anti-parallel diodes present across the power electronic switches(M1, M2, M3 & M4) and further the charged capacitor is discharged through the MOSFETs by maintaining an appropriate firing angle. This charging/discharging of ‘C2’ through ‘C1’ makes it possible to always maintain a finite amount of voltage across ‘C1’. The voltage appearing across ‘C1’ can be controlled by varying the firing angle applied to the MOSFETs. It is because of this action the voltage appearing across ‘R’ is not simply the voltage appearing at the PCC, it is the difference in the voltage across ‘C1’ and the PCC. Therefore, it can be said that the voltage appearing across R will be lesser than the voltage at the PCC which results in reduced real power consumption of the NC load. In this way the real power consumption of the NC loads can be reduced during the operation of spring. Further, ES is also capable of supplying/consuming reactive power and this is completely based on the phase angle between the current flowing through ‘R’ and voltage appearing across ‘C1’. The detailed explanation about the same can be inferred from [21].

The real power consumption of the NC load (P_{nc}) during normal operating conditions, i.e. whenever ‘S’ is closed is as follows

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

During operation of spring the voltage appearing across ‘R’ is the difference between the voltage appearing across the filter capacitor (V_a) and PCC. Hence, (1) can be re-written as follows

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

Where V_{pcc} is the voltage at the PCC, as shown in Fig.1

Hence by looking at (1) and (2) it can be understood that the power consumption during the operation of ES is lesser when compared to its absence and the same is as follows

$$P_{nc}^{ES} \leq P_{nc} \quad (3)$$

Similarly the reactive power supplied/consumed by the ES can be written as follows

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

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

Where Q is the reactive power capability of ES, I is the AC current flowing through the ES. As the NC load and spring are connected in series the current flowing through the ES and spring are the same and hence ‘I’ in (4) can be substituted with the ratio of voltage appearing across NCL and its own resistance ‘R’ as shown in (5).

III. PROBLEM FORMULATION AND METHODOLOGY

The objective of this work is to provide further support to the roof top solar installations in conserving power drawn from the utility gird and this achieved by operating springs. Along with the power conservation from the utility grid springs are also capable of reducing the electricity bills paid by the consumers, reduce the power rampage and regulate the reactive power as per the requirement. The power balance equation for a residence consisting of roof top solar panels, main grid interconnection point in the presence of critical and NC loads for a 24 load curve can be written as follows

$$\sum_{k=1}^{24} P_u(k) + \sum_{k=1}^{24} P_s(k) = \sum_{k=1}^{24} P_c(k) + \sum_{k=1}^{24} P_{nc}(k) \quad (6)$$

Where P_u is the power supplied by the utility grid, P_s is the power supplied by the roof top solar panels, P_c is the power consumption of the critical loads and P_{nc} is the power consumed by the NC loads

As the focus of this work is to minimize the power consumption from the utility grid in the presence of solar panels (6) can be re-written as follows

$$Min. \sum_{k=1}^{24} P_u(k) = \sum_{k=1}^{24} P_c(k) + \sum_{k=1}^{24} P_{nc}(k) - \sum_{k=1}^{24} P_s(k) \quad (7)$$

From (7) it can be understood that in order to reduce the power served by the utility grid the only possible option is to operate the NC loads in power saving mode by adjusting the voltage supplied to them. From (1), (2) & (3) it can be understood that springs are capable of suppressing the power consumption of the NC loads and hence minimization stated in (7) can be achieved. The above mentioned objectives are achieved by implementing a certain control strategy. In this work a completely user friendly energy management algorithm has been proposed.

The proposed algorithm is completely user dependent and works solely based on the inputs given by the consumer/s. In the proposed algorithm the user has freedom to choose the required percentage savings. It has to be understood that the quantum of power savings is decided based on the requirement. As the savings in power is dependent on the value of voltage supplied to the NC loads, in this case the maximum permitted deviation of the voltage level is held at 18 % from its base value. Therefore, the maximum quantum of savings in any particular hour can be calculated by making an estimate of power consumption of the NC loads, when they are operated at the lowest permitted voltage level. The choice of the customer is taken into account because, for operating the heating/resistive loads in power saving the users have to sacrifice their comfort levels.

Pseudo code

Step 1:- Start the process

Step 2:- Read the hourly estimated solar power output and the load data for the day

Step 3:- Estimate the hourly power required from the utility grid

Step 4:- Read the hourly NC load data

Step 5:- Estimate the hourly quantum of power and electricity bill that can be saved, if ES is pressed into action

Step 6:- Communicate the estimate to the consumer

Step 7:- Of the total saving quantum available request the consumer to provide the required hourly savings on percentage basis

Step 8:- Read the hourly percentage saving in the power specified by the consumer; k=1

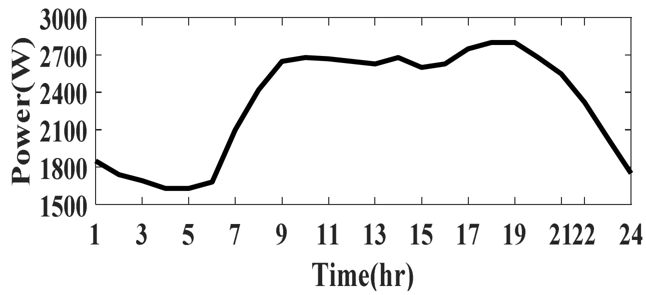
Step 9:- If the NC loads are operational, Plan them as per the power savings specified for the k^{th} hour by altering the voltage supplied to them using springs; else go to step 10

Step 10:- Is k=24? ; Yes go to step 2; else k=k+1, go to step 9

IV. RESULTS AND DISCUSSIONS

The performance of the proposed algorithm is tested on a residence consisting of solar arrays, higher penetration of heating/resistive loads and a main grid connection point. The residence is assumed to be located at Vellore, India and it is expected to have a peak load of 2.8 kW and based on the peak load on the system, hourly load data is estimated as per the methodology suggested in [22]. The estimated load data is the combination of both the critical and NC loads and is as shown in Fig. 2. The share of heating (NC) loads considered for this work is assumed accordingly and the pattern of the same can be found in Fig.6. In this course of work all the loads present in the residence are supposed to operate at a rated AC voltage of 220 volt, 1 phase and at an operating frequency of 50 Hz.

Further, the rating of the roof top solar PV is considered based on the peak load of the residence. In this case as the peak load of the residence is assumed to be 2.8 kW a 3 kW rated solar panel is assumed to be installed on the roof top. The solar output of one day winter day for a location namely Vellore located in the South Indian state of Tamil Nadu has been considered. The output of a 3 kW solar panel for the location mentioned is presented in Fig. 3.The data for the same is obtained from [23]. Although, the residence is assumed to be at Vellore the cost at which the energy is purchased by the consumers in Vellore, India is not dynamic and the consumers enjoy flat rate tariff throughout the day. Therefore, in order to test the robustness of the proposed strategy in dynamic pricing environment the cost of energy is estimated based on the methodology suggested in [24] and the same is presented in Fig.4.



.Fig. 2 Load profile of the residence

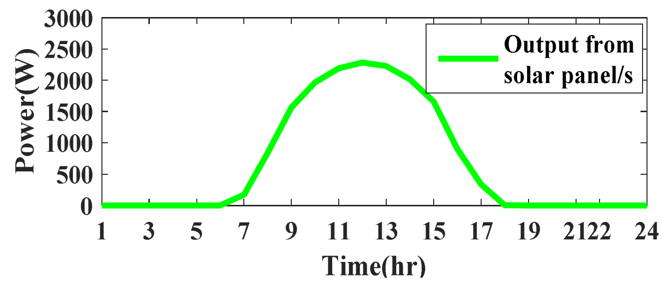


Fig.3. Power output pattern from the solar cells

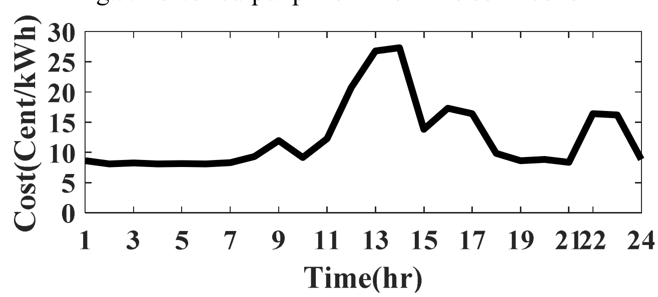


Fig.4 Cost of main grid energy

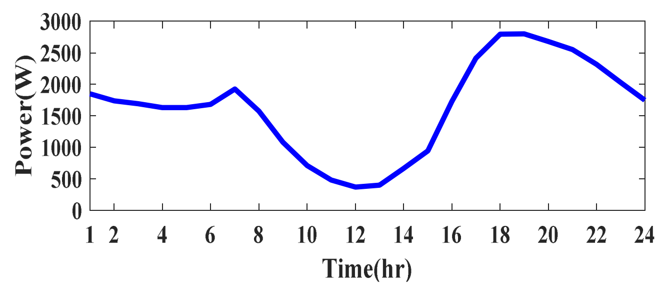


Fig. 5 Power requirement from the utility grid

Due to the presence of roof top solar panels the requirement for power from the main grid reduces and is as shown in Fig. 5. The objectives of this proposed strategy is to further reduce

the power consumption from the utility by pressing springs into action based on the inputs given by the consumer.
As discussed earlier the savings in the power drawn from the utility grid can only be reduced by operating the non-critical loads in power saving mode. The required power saving can be achieved by adjusting the voltage supplied to the NC loads. In this case as the minimum permissible value of voltage which can be applied to the NC load is about 180 volt, which is 18 % from its base value. Therefore, it can be said that a power savings of 100 %(maximum possible savings) is achieved if the NC loads are supplied with 180 volt. In order to estimate the maximum possible power savings for a day it is assumed that the consumer gives consent to save 100 % of the available quantum. The pattern of the power consumed by NC loads during 100 % & 0 % saving mode is shown in Fig.6.

From Fig.6 it can be observed that the power consumed by NC loads can be reduced by pressing springs into action. Because of the reduction in the power consumption of the NC loads the total power consumed of the residence reduces. This reduction in power consumption is as shown in Fig. 7 and the same can be compared with the actual load profile presented in Fig. 2. Further Fig. 7 also depicts the reactive power capability curve of the ES. The reactive power capability curve is a measure of spring's capability to supply or consume reactive power. The spring is made to consume reactive power if there is a voltage rise due to the penetration of solar power and the springs can be made to supply reactive power during under voltage conditions which may occur during evening peaks in the absence of solar power.

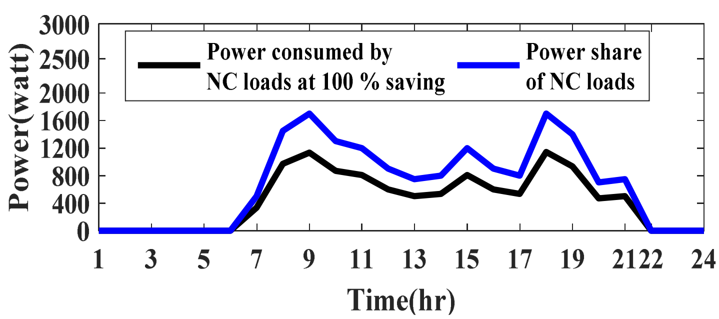


Fig. 6.Power consumption of the NC loads

It is because of the action of spring the total power consumption is reduced and therefore the power drawn from the main grid further decreases than the one shown in Fig. 5 and the same is depicted in Fig. 8.

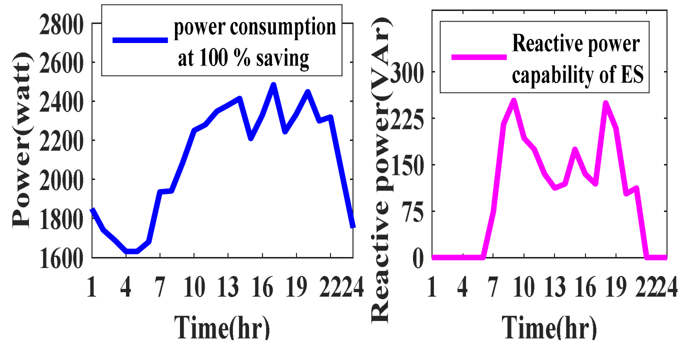


Fig. 7 Real power of the residence and reactive power capability curve of ES

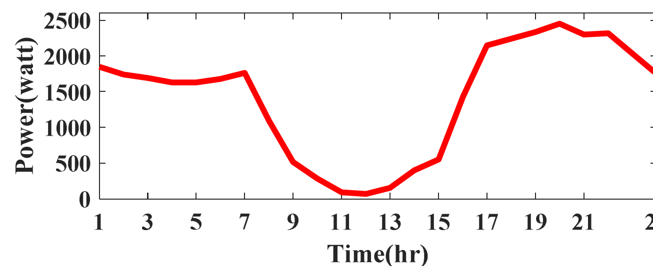


Fig. 8 Power served by main grid in the presence of solar power and ES

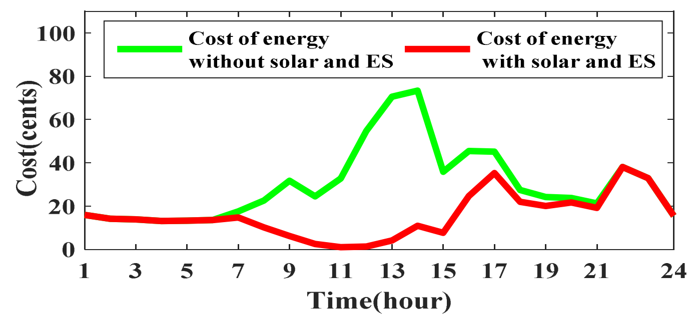


Fig. 9 Cost of energy purchased from main grid

Going little further the cost of energy which has to be purchased from the main grid also reduces due to the power supplied by the solar panel/s and the action of ES and the same is presented in Fig. 9. It has to be understood that the savings in the cost shown is under the assumption that the consumer has accepted to save 100 % of the available power. Therefore, it should be noted that the achieved value of cost cutting is the maximum permissible value for the considered residence under the given circumstances. The rate of savings will be different if the consumer specifies some other savings percentage. The total per day electricity bill paid by the consumer in the absence of both solar arrays and ES is about 722 cents. In the presence of solar power and ES the per day electricity bill paid by the consumer is around 373 cents.

Hence it can be concluded that there is a savings of about 48 %, which is quite interesting. The peak load on the considered system occurs at 18th & 19th hours of the day. During this time the power consumption is almost around 2.8 kW and during this time of the day the contribution of solar power is almost negligible and hence the burden to reduce the peak completely falls on ES. Further, as the consumer's preference is to completely save the available power and therefore the power consumption by pressing springs into action is 2.24 & 2.33 kW respectively for 18th and 19th hours of the day. Hence it can be said the percentage peak reduction for the presented hours is about 20 % and 16 % respectively.

V. CONCLUSION

The work presented in this article proposed a new customer driven home energy management algorithm using electric springs. The proposed algorithm is completely user friendly and has been successful in achieving the said objectives. Also, the results obtained in this work show cause that the presented algorithm achieves considerable savings in the power purchased from the main grid in the presence of solar power penetration which results in cost cutting. Further, in this work the reactive power capability curve of ES is only show caused but no emphasis is made on calculating the actual level of reactive power that has to supplied or consumed by springs, which can be treated as future scope of this work. Also, there is a necessity to study the performance of the proposed strategy on a large scale systems consisting of more than one residential consumer.

ACKNOWLEDGMENT

S Hari Charan Cherukuri is a recipient of Senior Research Fellowship (SRF) from the Council of Scientific and Industrial Research (CSIR), Ministry of Science and Technology, Government of India under the file no. 09/844(0039)/2016 EMR-I. The author would like to sincerely thank the CSIR, for awarding the fellowship.

REFERENCES

[1] Chapter 10, Solar Energy, Australian Energy Resources Assessment report. 2010

[2] Frontier Power Market Outlook – Micro-grids on the horizon, Bloomberg New Energy Finance, Q2 2017

[3] Shukla, A.K., Sudhakar, K. and Baredar, P, "Design, simulation and economic analysis of standalone roof top solar PV system in India", *Solar Energy*, vol. 136, pp.437- 449, 2016.

[4] Jin, X., Baker, K., Christensen, D. and Isley, S., "Foresee: A user-centric home energy management system for energy efficiency and demand response", *Applied Energy*, vol. 205, pp.1583-1595, 2017.

[5] Hemmati, R. and Saboori, H., "Stochastic optimal battery storage sizing and scheduling in home energy management systems equipped with solar photovoltaic panels", *Energy and Buildings*, vol. 152, pp.290-300, 2017.

[6] Chekired, F., Mahrane, A., Samara, Z., Chikh, M., Guenounou, A. and Meflah, A., "Fuzzy logic energy management for a photovoltaic solar home", *Procedia Engineering*, vol. 134, pp.723-730, 2017.

[7] Shakeri, M., Shayestegan, M., Reza, S.S., Yahya, I., Bais, B., Akhtaruzzaman, M., Sopian, K. and Amin, N., "Implementation of a novel home energy management system (HEMS) architecture with solar photovoltaic system as supplementary source", *Renewable Energy*, vol. 125, pp.108-120, 2018.

[8] Yao, E., Samadi, P., Wong, V.W. and Schober, R., "Residential demand side management under high penetration of rooftop photovoltaic units", *IEEE Trans. Smart Grid*, vol. 7, no.3, pp.1597-1608, 2016.

[9] Oliveira, D., Rodrigues, E.M., Godina, R., Mendes, T.D., Catalão, J.P. and Pouresmaeil, E., "Enhancing home appliances energy optimization with solar power integration", *International Conference on Computer as a Tool (EUROCON 2015)*, pp. 1-6, 2015.

[10] Mahmoudi, N., Shafie-khah, M., Saha, T.K. and Catalão, J.P., "Customer-driven demand response model for facilitating roof-top PV and wind power integration", *IET Renewable Power Gen.*, vol. 11, no. 9, pp.1200-1210, 2017.

[11] Nassereddine, M., Rizk, J., Hellany, A., Nagrial, M., Elrafhi, A., Obeid, Z. and Hajar, K., "Electrical energy management for advance smart home systems: Introduction", 3rd *IEEE International Conference on Renewable Energies for Developing Countries (REDEC- 2016)*, pp. 1-6, 2016.

[12] Soltowski, B., Strachan, S., Anaya-Lara, O., Frame, D. and Dolan, M., "Using smart power management control to maximize energy utilization and reliability within a microgrid of interconnected solar home systems", *7th Annual IEEE Global Humanitarian Technologies Conference (GHTC 2017)*, pp. 1-7, 2017.

[13] Hui, S.Y.R., Lee, C.K. and Wu, F.F., "Electric springs— A new smart grid technology", *IEEE Trans. Smart Grid*, vol. 3, no.3, pp. 1552-1561, 2012.

[14] Lee, C.K. and Hui, S.Y.R., "Reduction of energy storage requirements in future smart grid using electric springs", *IEEE Trans. Smart Grid*, vol. 4, no.3, pp. 1282-1288, 2013.

[15] Chen, X., Hou, Y., Tan, S.C., Lee, C.K. and Hui, S.Y.R., "Mitigating voltage and frequency fluctuation in microgrids using electric springs", *IEEE Trans. Smart Grid*, vol. 6, no.2, pp.508-515, 2015.

[16] Soni, J. and Panda, S.K., "Electric spring for voltage and power stability and power factor correction", *IEEE Trans. Industry Applications*, vol. 53, no.4, pp.3871-3879, 2017.

[17] Cherukuri, S.H.C. and Saravanan, B., "A novel energy management algorithm for reduction of main grid dependence in future smart grids using electric springs", *Sustainable Energy Technologies and Assessments*, vol. 21, pp. 1-12, 2017.

[18] Krishnanand, K.R., Hasani, S.M.F., Soni, J. and Panda, S.K., "Neutral current mitigation using controlled electric springs connected to microgrids within built environment", *IEEE Energy Conversion Congress and Exposition (ECCE - 2014)*, pp. 2947-2951, 2014.

[19] Yan, S., Tan, S.C., Lee, C.K., Chaudhuri, B. and Hui, S.R., "Electric springs for reducing power imbalance in three-phase power systems", *IEEE Trans. on Power Electronics*, vol. 30, no.7, pp.3601-3609, 2015.

[20] Cherukuri, S.H.C. and Saravanan, B., "An overview of selected topics in smart grids", *Front. Energy*, vol. 10, no.4, pp.441-458, 2016.

[21] Chaudhuri, N.R., Lee, C.K., Chaudhuri, B. and Hui, S.R., "Dynamic modeling of electric springs", *IEEE Trans. Smart Grid*, vol. 5, no.5, pp.2450-2458, 2014.

[22] Grigg, C., Wong, P., Albrecht, P., Allan, R., Bhavaraju, M., Billinton, R., Chen, Q., Fong, C., Haddad, S., Kuruganty, S. and Li, W., "The IEEE reliability test system-1996. A report prepared by the reliability test system task force of the application of probability methods subcommittee", *IEEE Trans. power systems*, vol. 14, no. 3, pp.1010-1020, 1999.

[23] https://www.renewables.ninja

[24] Logenthiran, T., Srinivasan, D. and Shun, T.Z., "Demand side management in smart grid using heuristic optimization", *IEEE Trans. smart grid*, vol. 3, no.3, pp.1244-1252, 2012.