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Analysis of load shedding strategies for battery management in PV-based rural off-grids

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***Abstract*— Off-grid solutions based on PV-diesel hybrid systems with battery backup during night are operationally ready to provide communities with electricity services, particularly in rural areas. However, lack of efficient energy management strategies to balance supply and demand results in frequent outages especially during night and increase the diesel fuel consumption, thus leading to a fiasco. This paper analyses how energy from the batteries in the hybrid system can be managed during the night and efficiently distributed among the loads such that the critical loads like hospitals and telecom towers get maximum energy security.**

***Index Terms*—Battery Management, Demand side Management, Load Shedding, Rural Electrification.**

I. Introduction

About 1.2 billion people in the world have no access to electricity [1] and 46% of the people are living in rural areas where grid extension is financially ambitious because of high installation costs [2]. Since, majority of them live in the rural areas of Asia and Africa which lies in the solar belt region, PV-diesel hybrid power system (HPS) have enormous potential in electrifying these areas by decentralized generation. In PV-based off-grid systems for rural electrification, batteries play a vital role in storing the solar energy and delivering it to the load during the night. Batteries contribute to a major amount of investment and therefore, should be sized optimally. With increasing demand and rising fuel prices, the system thrives for further expansion. However, in many cases, without sufficient revenue to pay for additional installations, critical services like hospitals and telecom towers experience frequent power cuts during energy shortage, e.g., on cloudy days [1].

This puts forth the need for energy management protocols like Demand side Management (DSM) in an off-grid system. DSM is planning, implementation and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape [3]. Various DSM protocols like load shifting, peak shaving and tariff based DSM have been implemented in developed countries to reduce the burden on the system. However, these protocols need the participation of the consumers to achieve it efficiently [4] [5]. Due to the lack of knowledge penetration, achieving these protocols seem a major challenge in current rural grids. Moreover, individual household loads are contributed only by few lights and mobile phone chargers [1] which provides no room for shifting loads. Installing Compact Fluorescent Lamps (CFL) may reduce overall load curve which might achieve DSM through 'Energy Efficiency', however fails to keep the system running when there is an energy shortage.

This paper proposes priority based classification of consumers and load shed them optimally with the use of smart meters during energy shortage. Various load shedding strategies have been discussed and compared to manage the energy stored in the battery. A rural electrification scenario in a village of Burundi with 670 households has been considered for analysis.

II. Topology

Various topologies and sizing approaches of hybrid systems for rural electrification and its associated advantages and limitations have been discussed in [2] and [6]. A centralized AC-coupled HPS is preferred in most of the rural electrification projects where its components are connected to a common AC-bus [7]. The PV panels and the batteries are connected to the AC-bus via dc-ac inverters. The loads are considered as a single unit which taps electricity from the AC-bus.

The limitation of the existing topology is that all loads from basic household loads to critical hospital loads are considered as one equivalent and not distinguished. When an energy deficiency is experienced, the system is burdened as it does not have control over the loads. When the demand is much greater than the supply, the system has to shut down completely.

A. Proposed Modification

This paper proposes classification of loads into groups based on priority with respect to consumers' ability to pay, their importance and required energy security as shown in Fig. 1. The objective of this modification is to ensure maximum energy security to high priority load groups like hospitals during energy shortage, i.e., during cloudy days.

B. *Load Curve*

The load curve is estimated by a survey conducted in a village of 670 households in a village in Burundi. In this paper, the loads are classified into 5 groups based on priority. Group1 includes critical loads in hospitals and telecom towers while group5 includes households which consume less energy and cannot afford paying huge electricity bills.

Fig. 2 shows the load split between groups. The majority of the system load curve as well as the peak is contributed by group5 which consists of large number of households which use only lighting loads during the evening. Group3 and 4 represents small scale industries, schools, offices and group2 are non-critical loads in hospitals and telecom towers.

C. *Role of smart meters*

An important addition to the proposed topology is the inclusion of smart meters at the consumer end. The smart meters are pre-programmed with respect to the groups. Smart meters are able to disconnect or reconnect users based on the command from the central system. The smart meters also send periodic energy consumption data of customers to the utility from which a reference load curve is formed which is used by the load shedding strategies discussed in this paper.

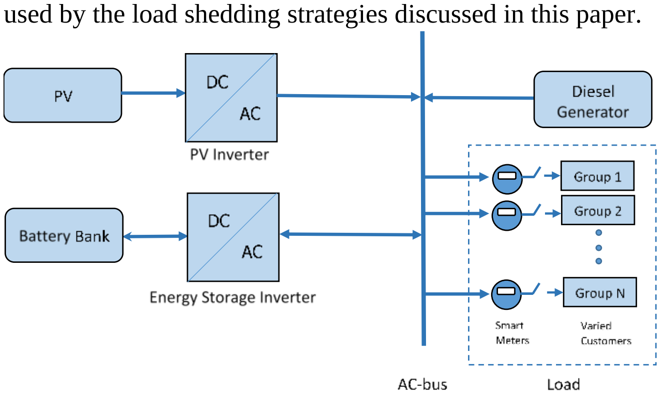

Fig. 1 Proposed topology

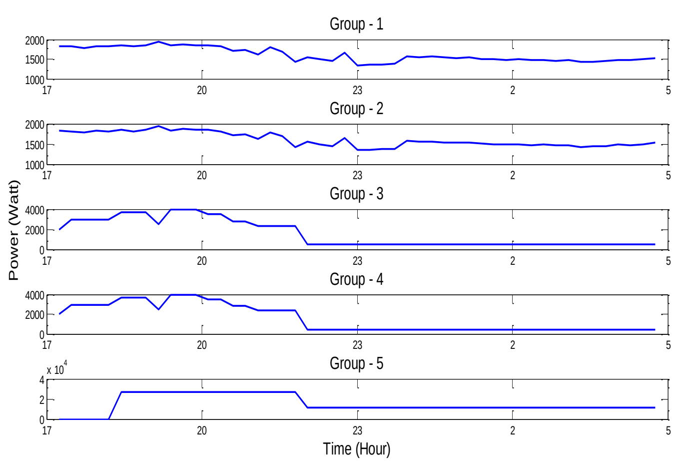

Fig. 2 Load curve for different groups

III. LOAD SHEDDING STRATEGIES

Load shedding is done only on the basis of priority of load groups. Five load shedding strategies (LSS) have been discussed in this paper. Diesel generator is operated when the batteries are not able to supply group1 loads after load shedding of other groups. During low insolation days, the batteries are not fully charged. The batteries are assumed to have a SoC (State of Charge) of 40% of their battery capacity indicating energy shortage. This is based on the SoC of the battery charged by the day of lowest insolation in a year. The LSS operate during the night from 5 PM to 5 AM when solar energy is not available and are executed in the proposed topology to obtain the system performance characteristics. The terms used by the strategies are represented in Table 1.

A. *Load shedding based on defined SoC set points (LSS1)*

Each group is assigned a SoC cut-off point. When the battery SoC falls below the cut-off points, the smart meters are informed to load shed that particular group. The LSS1 provides a simple solution of load shedding groups according to priority. Defining cut-off points may depend upon factors like energy security for the group, frequency of low insolation days and group's ability to pay. Fig. 3 shows the procedure of load shedding based on SoC set points.

Table 2 contains the fixed SoC set points for each group used for the simulation. The set points are fixed at regular intervals such that, there is a gradual load shedding of groups. However, if maximum energy has to be allocated for group1, then pre-defined set points of groups can be fixed one after another.

Table 1 List of variables used

Variable	Definition
Pload	Total load seen by system at time t
n	Customer group (n ranges from 1 to N, where 1 and N are most and least priority groups respectively)
Pload_n (t)	Individual load data of a group at time t
Pbatt (t)	Battery Power at time t
SoC (t)	State of Charge of the battery at time t
cutoff_n	SoC cut-off point for group n
SoC_sunset	SoC at sunset
t_end	End time
ref (t)	Energy required from time t to t_end
Pload_average	Daily Load average
Sload_n (t)	Scheduled load value of group n at time t

Table 2 Assumed pre-defined set points for LSS1

Load Group	**Cut-off Points in % of battery capacity**
Group 5	24%
Group 4	21%
Group 3	17%
Group 2	14%

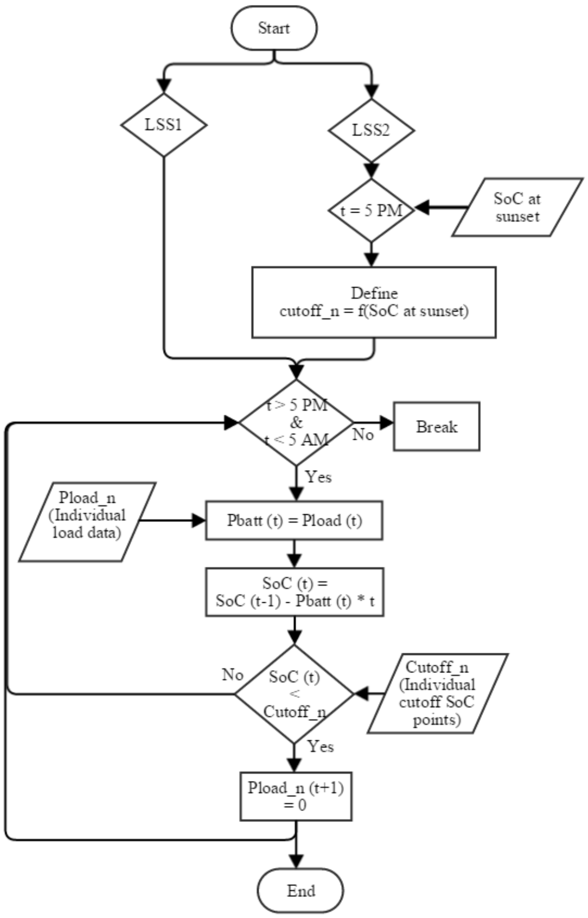

Fig. 3 Flowchart for LSS1 & LSS2

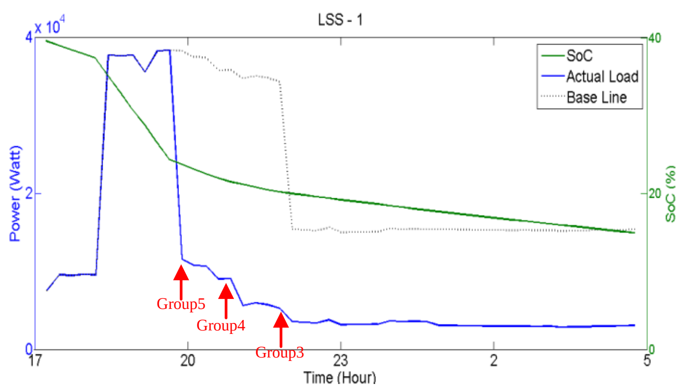

Fig. 4 System response for LSS1

The load shedding of groups at different time intervals is denoted by the red arrows in Fig. 4. The base line represents the actual trend in system load curve without load shedding. The groups are load shed when their SoC set points are reached. Group 2 and Group 1 remain switched on as the battery SoC is above the groups' assigned set points.

B. Load shedding based on solar profile (LSS2)

This strategy performs load shedding depending on the solar insolation on that day. A parameter which indicates the solar yield on the particular day is SoC of the batteries at sunset. A sunny day would have charged the batteries to full whereas on a rainy or a cloudy day, the output from the PV panels are not enough to charge the battery to 100%. Based on the solar profile, the SoC set points for each group are determined. The flowchart shown in Fig. 3 displays the methodology of load shedding based on SoC set points. The cut-off points are updated only once at sunset. Load shedding of groups is done when the SoC of the batteries reaches the corresponding set point. Table 3 shows cut-off points for different scenarios of sunny and cloudy days. During a sunny day, the SoC set points are set such a way that maximum energy is sold, whereas, maximum energy security is given to group 1 during a cloudy day. The system response on a cloudy day to LSS2 is shown in Fig. 5. Different groups are load shed according to their respective cut-off points as indicated.

C. Peak Shaving during energy shortage (LSS3)

Peak shaving is one of the main protocols of demand side management which is executed to reduce the burden of the system during peak hours. In rural areas, the peak is contributed only by lighting loads and majority of the people from group5. The algorithm for executing peak shaving is mentioned in Fig. 6.

Load characteristics after peak shaving protocols is shown in Fig. 7. The peak contributing group is load shed when energy shortage is detected. When the peak is averted, all the load shed groups are re-connected. However, in the simulation, the system encounters a shutdown as the batteries are discharged to its critical SoC and the diesel generator has to be switched on to supply high priority groups.

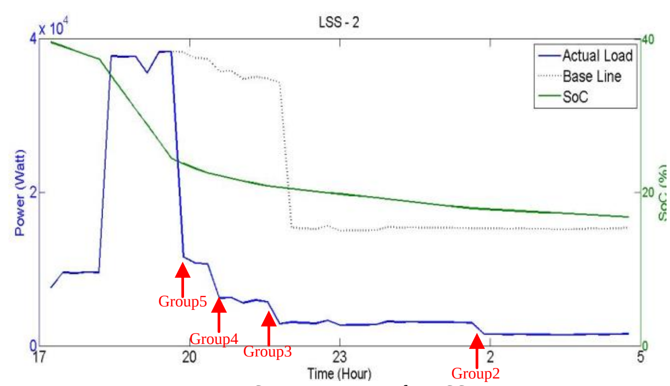

Fig. 5 System response for LSS2

Table 3 Set points for LSS2

Load Group	**Cut-off Points in % of battery capacity**	
	SoC at sunset = 100%	**SoC at sunset = 40%**
Group 5	18%	25%
Group 4	16%	23%
Group 3	14%	21%
Group 2	12%	18%

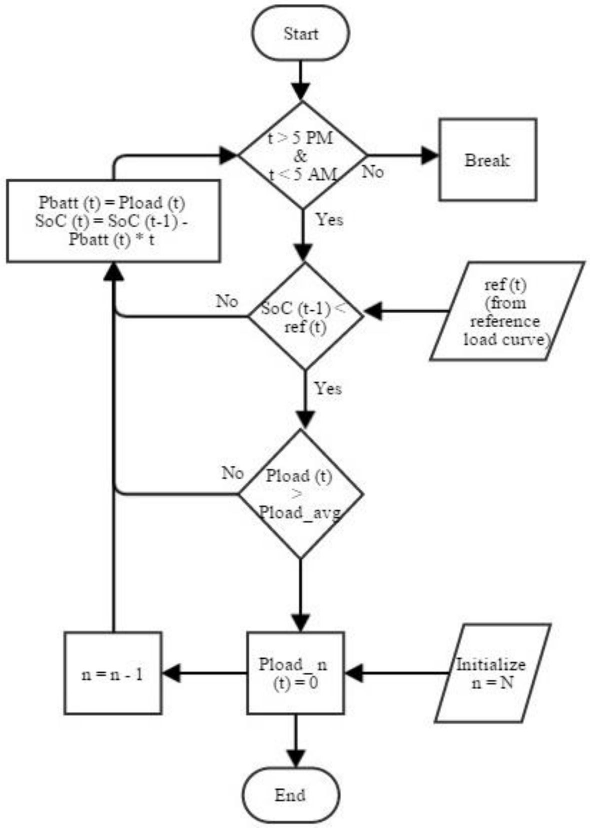

Fig. 6 Flowchart for LSS3

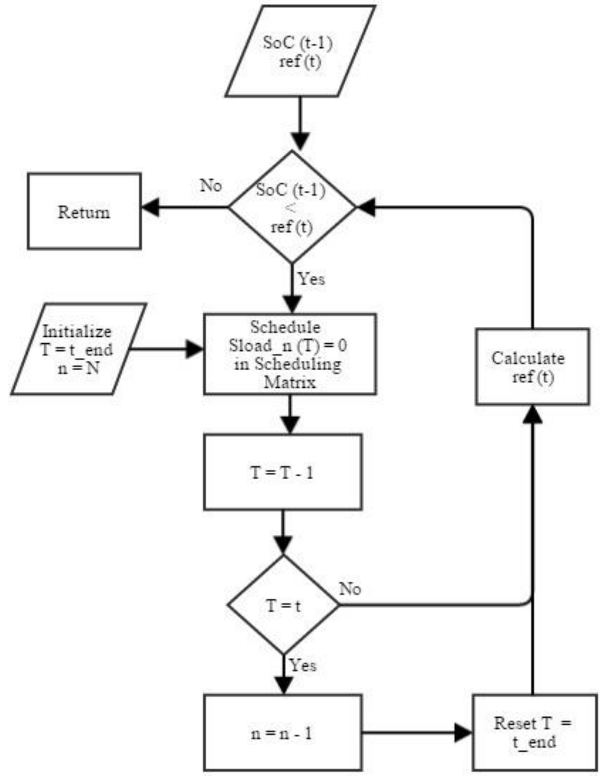

Fig. 8 Flowchart for scheduling unit

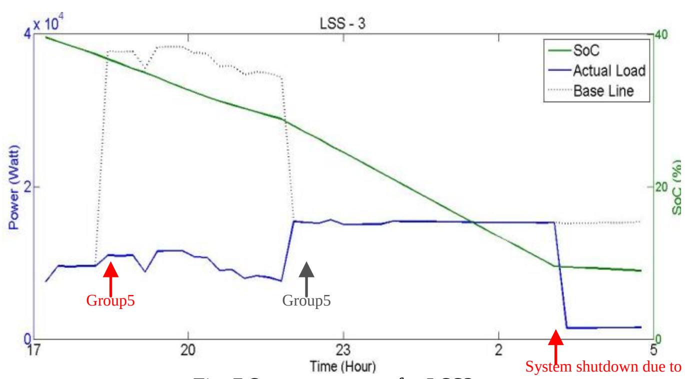

Fig. 7 System response for LSS3

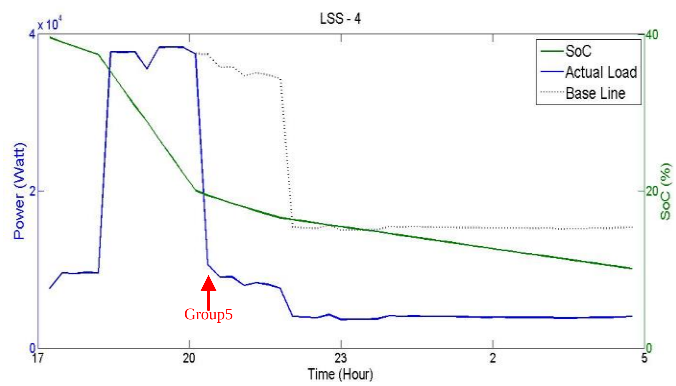

Fig. 9 System response for LSS4

D. *Load shedding by scheduling (LSS4)*

LSS4 uses the scheduling unit which computes and schedules load shedding points every sampling period. The process of scheduling unit is shown in Fig. 8. The unit compares the SoC of the battery every sampling period with the energy required from the reference load curve. Depending on the mismatch, the load shedding points are scheduled.

At every sampling period, if the unit predicts balance between energy required and energy available, no load shedding is scheduled for the remaining period. The algorithm uses the scheduling matrix from the scheduling unit to execute the load shedding as represented in Fig. 10. The scheduling unit tries to compensate the energy shortage by load shedding low priority groups for maximum time. Loads except that of group 5 are not load shed as shown in Fig. 9.

E. *Load shedding by scheduling with load limitation (LSS5)*

LSS5 includes a load limitation feature for each group in addtion to the scheduling unit. Each group is allocated a load limitation point, which in this case, is the SoC set point. The SoC set points can be assigned similar to LSS1 or LSS2. In this paper, a pre-defined set point feature with scheduling unit is considered as shown in Fig. 10. Similar to LSS4, the scheduling unit schedules load shedding points based on energy deficiency. When the scheduling unit predicts that the SoC will drop below the pre-defined set point, the corresponding group is scheduled to load shed from that point till sun rise as shown in Fig. 11. With the load limiting feature, the high priority loads are ensured defnite amount of energy during energy shortage.

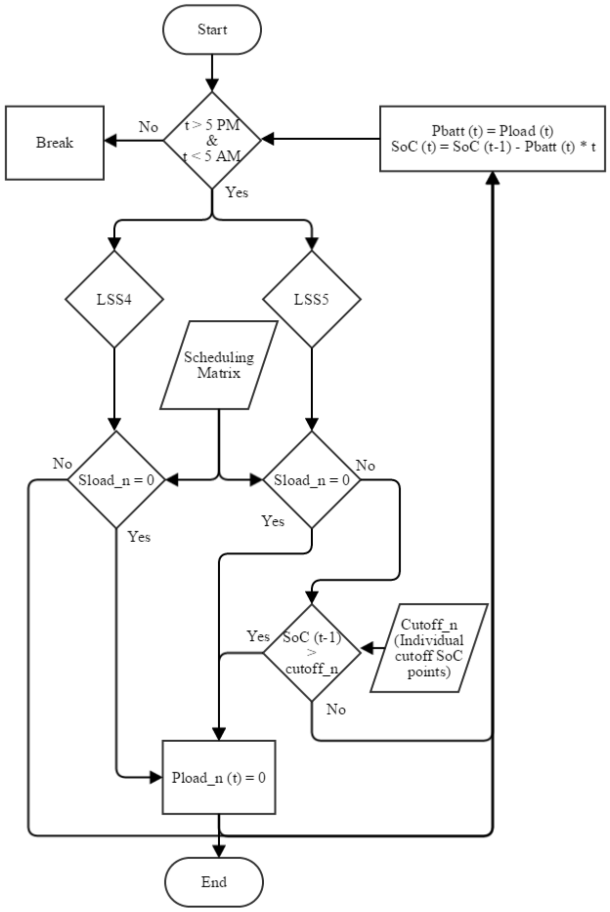

Fig. 10 Flowchart for LSS4 & LSS5

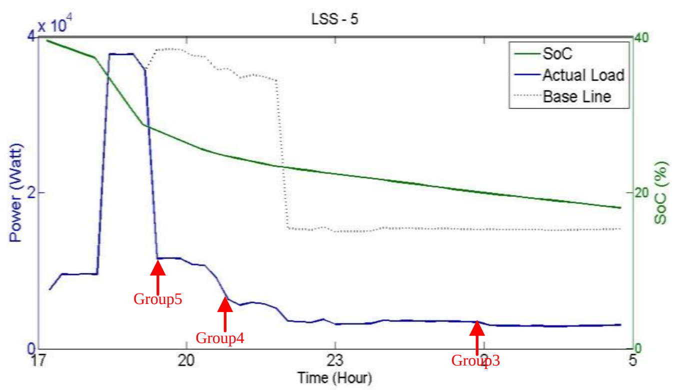

Fig. 11 System response for LSS5

IV. Multi-Criteria Analysis

A multi-criteria analysis is performed to compare and evaluate the load shedding strategies according to a particular location. In this analysis, annual simulation of different load shedding strategies is performed with the proposed topology and the results are discussed.

A. *Diesel fuel consumption*

In the existing centralized HPS, the diesel generators are switched ON to feed all the loads during low insolation days which would consume around 2500 liter per year for the considered load curve. However, with proposed load shedding strategies, diesel generators are switched on only when the batteries are not able to feed group 1 loads after load shedding of other groups. Annual simulation reveals that the load shedding strategies according to priority reduce or even eliminate the diesel fuel consumption. The fuel consumption for different load shedding strategies for a year is shown in Fig. 12.

B. *Hours of load shedding*

It is important that the groups are load shed for minimum number of hours. Fig. 13 shows the load shedding hours for each group by each strategy in a year. LSS4 seems to have less number of load shedding hours for high priority groups while LSS3 performs the best for low priority groups.

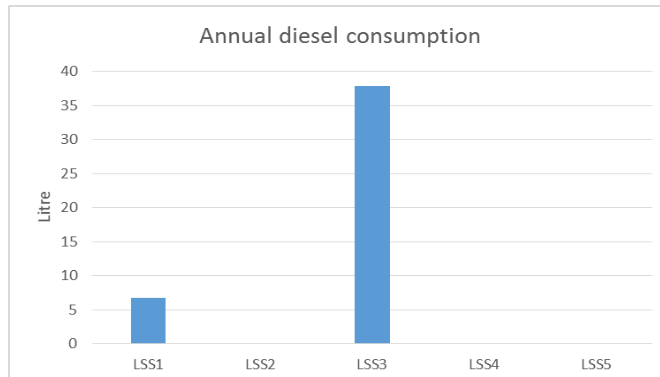

Fig. 12 Annual fuel consumption by different strategies

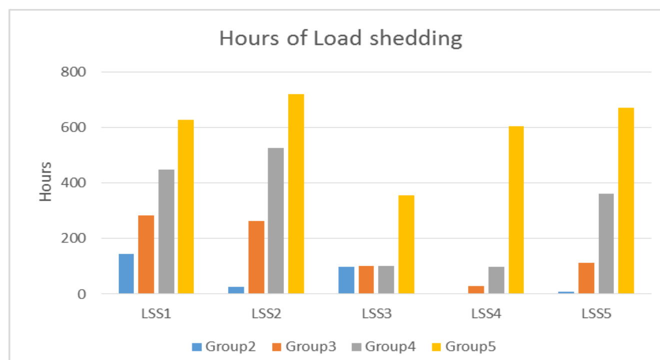

Fig. 13 Hours of load shedding per group per year

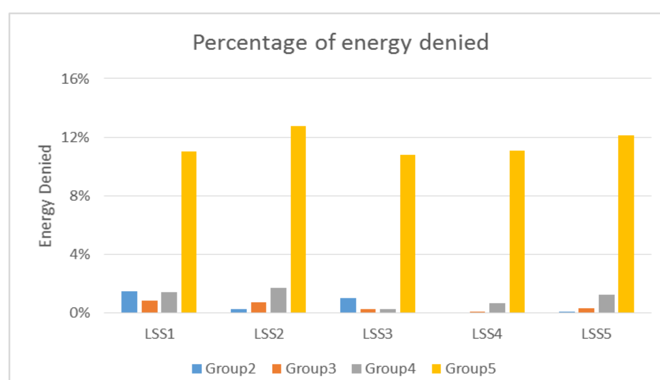

Fig. 14 Amount of energy denied per group per year

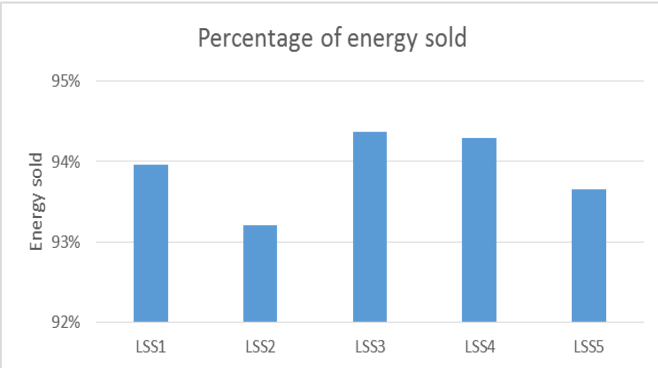

Fig. 15 Energy sold per year

C. Energy denied per group

This section compares the energy not delivered per group by different strategies for a year due to load shedding. The number of load shedding hours and energy denied need not be proportionate as seen in the comparison between LSS3 and LSS4 in group5. LSS3 has less load shedding hours. However due to peak shaving, large amount of energy has been denied to the group as shown in Fig. 14.

D. Total energy sold

Cash flow is an important requirement in a rural electrification project. It plays a major role for covering operational and maintenance costs and also provides revenue for future expansion. This paper assumes the revenue is directly proportional to the amount of energy sold and does not include different tariffs for different priority groups. Fig. 15 shows the total energy sold by different strategies.

The analysis shows that LSS4 performs efficient balancing when compared to other LSS with minimum disadvantages and therefore is tested for its robustness in sensitivity analysis.

V. Sensitivity Analysis

One of the main platform for efficient working of the algorithm is the reference curve which is obtained from the data collected from the smart meters. To test the robustness of the chosen algorithm, a mismatch is introduced between the reference and actual load. From Fig. 16, it can be seen that the LSS4 algorithm, load shed groups to ensure energy to critical users and tries to keep up with the mismatch. The system is able to accommodate disparity within 30% from the reference. However, in this case, due to large deviation from the reference, the system fails its purpose at the end of the period. This imposes the need for smart meters to keep the system updated.

Rise in demand after electrification is inevitable. Usually, the system is oversized to accommodate this demand. However, it struggles during low energy days and calls for back up to ensure power supply to critical loads. The LSS4 is tested for a flat increase by 30% from Fig. 9 and its performance is shown in Fig. 17. The LSS4 algorithm load sheds the low priority group5 earlier by an hour when compared to the previous scenario as it senses that the energy available in batteries will not be sufficient to feed all the loads for the given period.

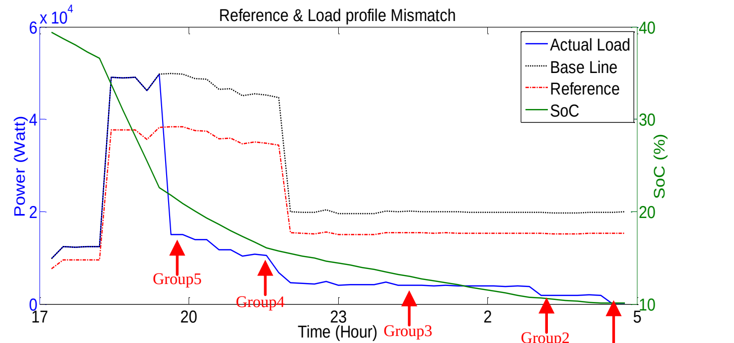

Fig. 16 System response during reference & load mismatch

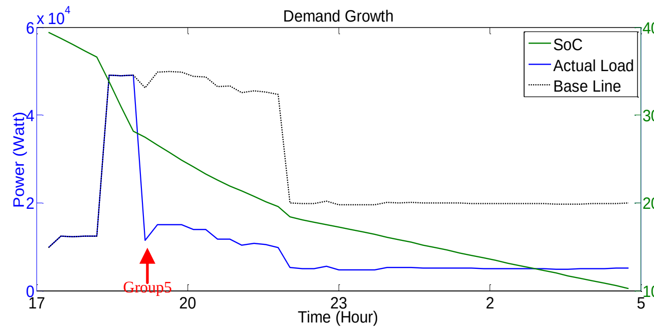

Fig. 17 System response after demand growth

VI. Conclusion

The proposed topology of classifying loads based on priority creates a platform for executing demand side management protocols in rural grids. Different methodologies of allocating the available energy from the battery to different groups during energy shortage by load shedding are discussed. With load shedding strategies, the need for diesel generator in the off-grid system is eliminated making the system environment friendly. LSS4 proves that the load shedding hours is minimum for high priority groups and competitive with LSS3 for low priority groups. The sensitivity analysis also verifies that LSS4 can accommodate load changes by accommodating the expected growth in demand. Therefore, this paper concludes that LSS4 is the best strategy for the rural electrification scenario in Burundi.

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