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Fault Tolerant Power Balancing Strategy in an Isolated Microgrid via Optimization

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Abstract: The increasing penetration of renewable energy generation (REG) in the microgrid paradigm has brought with it larger uncertainty in the scheduled generation. This along with the inevitable variation between actual load and forecasted load has further accentuated the issue of real-time power balancing. With the advent of smart loads and meters supported by advanced communication technologies, several new possibilities for demand side management have opened up. In this paper, a real time optimization strategy for load side energy management system (EMS) and for power balance is proposed. The proposed strategy achieves power balance by optimizing load reduction. The objective is to ascertain uninterrupted power to critical loads and reduce non-critical loads depending on the priorities for various loads. To further enhance the flexibility of the system, the addition of a battery to the management model is also discussed. The proposed algorithm also makes the system tolerant to possible generator failures if battery is added to the system. The effectiveness of the proposed online power balancing strategy via optimization is demonstrated through various simulation case studies.

Keywords: Microgrid, Optimization problems, load control, load modelling, Energy management systems, Energy storage.

1. INTRODUCTION

The increasing incidence of distributed generation and active distributed networks along with the dire need to promote clean energy has been some of the motivating factors for the microgrid concept. Microgrids are essentially low voltage networks composed of loads and distributed generators, including one or more renewable energy sources. Microgrids may operate in isolated mode or in grid-connected mode. An increasing number of microgrid proposals have been targeting remote communities and non-integrated areas in developing countries and geographical islands (Kyriakarakosa et al. 2011, Driesen and Farid, 2008). These isolated grids form autonomous microgrids that supply electricity and in some cases heat and hot water to residential and commercial consumers (Xu Li Zhong, et al. 2013). One of the main concerns for these microgrids is stability of the microgrid and one key requirement for stable microgrid operation is power balancing. Unlike a grid-connected system, power balancing in an isolated microgrid is a challenging task. Furthermore penetration of renewable energy sources in microgrids poses additional challenges due to stochastic and intermittent nature of renewable sources. While the power balancing becomes very difficult in presence of these uncertainties, power balance must be achieved for stable microgrid operation.

Although there have been many offline load-scheduling algorithms and strategies proposed (Gan et al. 2013, O'Brien and Rajgopal 2013), this particular aspect of online power balancing in isolated microgrids has not been addressed adequately and satisfactorily. One most commonly employed solution, to maintain power balance, is to use energy storage (ES) devices, such as batteries. Various applications of ES devices have been looked into (Ibrahim and Perron 2007, Nigim and Reiser 2009). Storage equipment also plays a big role in the integration of renewable energy generation (REG). As shown by Faias et al. (2008), and Qian et al. (2009) ES acts as an energy buffer by compensating inherent variations in REG; thereby reducing voltage fluctuations and improving power quality. Xu et al. (2011) also employed an ES system (in a dc microgrid) for automatic power balancing by a PI controller for dc voltage control. They also discussed separate load curtailment policies in case the power balancing was not achieved due to insufficient power. Thus, ES systems are used to mitigate power fluctuation and to regulate voltage and frequency. However battery life reduces drastically if they are not maintained properly (e.g. excessive charging or discharging can reduce battery life). Thus, along with power balance, battery management must also be taken care of.

Another commonly used approach for power balancing is to ramp up or down the generation units (Ahn and Moon, 2009). However the generators are usually lugged down by their larger time constants (Kirby, 2003). Therefore direct load control, which responds to the requests of the operator instantaneously, is preferable. Such a use of load as a system service can also circumvent the use of fast ramping but inefficient generators. In many cases an unforeseen increase in electrical demand causes the operator to bring increasingly inefficient generation online. Under such circumstances, it is possible that the supply side generation costs will be greater than the retail price. The use of direct load control, under pre-agreed terms and conditions, can help alleviate such problems. However the only reason why direct load control is not employed is lack of load models and reliable control

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strategies (Callaway, 2011). Earlier it has also been shown that the use of these controllable loads, to provide system services, can also reduce the overall grid emissions (Strbac 2008). In (Subramanian et al. 2012), the controllable load is modelled in such a way that they can be scheduled to meet the REG. Short et al. (2007) proposed dynamic demand control (DDC) to control the statuses of appliances based on the monitored grid frequency. It essentially showcased a compromise between the needs of an appliance (e.g. refrigerator) and the grid. All these approaches seem to address discrete problems and there is no reliable and comprehensive online power balancing strategy available.

In this paper a power balancing approach based on optimization is proposed. In the proposed approach, loads are treated as system service and focus is on the prioritization and advanced control of load in conjunction with a controlled use of an energy storage device. The objective of this paper is to develop novel load side operation and control methods for isolated microgrid systems. Various opportunities to use load control schemes for power balance are also discussed. The proposed strategy is preferable over conventional generator based approaches (Callaway, 2011). Another aspect that must be taken into consideration is a large penetration of REG and rather realistic variations between forecasted load and actual load resulting in larger power imbalances compared to conventional power grids. This paper presents the whole energy balancing issue as a real-time optimization problem, which runs every few minutes. The proposed algorithm also provides failure tolerance against failure of small generator unit by optimally utilizing ES resources. The effectiveness of the proposed algorithm is demonstrated through various realistic case studies.

An overview of the system is presented in Section 2. The principles of the proposed optimization approach are discussed in Section 3. Section 4 showcases three case studies. A brief concluding remark is included in section 5.

2. SYSTEM OVERVIEW

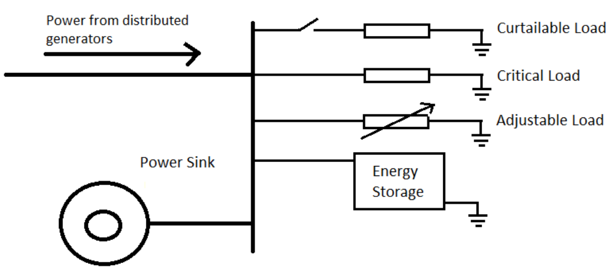

Fig.1. Load classification and general layout

A microgrid is an interconnection of i) various loads, domestic or commercial, ii) low-voltage distributed energy sources, such as micro-turbines, fuel cells, wind turbines, photovoltaic arrays and iii) energy storage devices, such as batteries. It is proposed to categorize loads into three broad categories, namely high priority sensitive/ critical loads, curtailable loads and lower priority adjustable loads. These loads may be fed via separate feeders to facilitate load control.

2.1 Critical Loads

The critical loads include the power supply to hospitals, banks, indoor lighting etc. The critical loads of the microgrid are prioritized above all other loads. The local power supply and ES systems should ensure that the critical loads are met at any cost. Since they hold the highest priority these loads are catered to even at the expense of the other classes of loads.

2.2 Curtailable Loads

The curtailable loads are prioritized just below the critical loads. As mentioned earlier, these loads are fed from separate feeders. Curtailable load control is analogous to on-off control. These loads can either be connected or disconnected for a particular time interval. From optimization algorithm perspective, curtailable loads add as many binary variables as the loads themselves. Such large number of binary variables result in combinatorial explosion and such optimization problems are hard to solve. One may consider simplifying the problem by lumping all the curtailable loads as a single entity. However, such simplification is not considered in this paper. Furthermore these arms have been provided with their own priorities (penalties for disconnection) in the objective function formulation. These priorities include energy constrained loads, i.e. they will fail to provide their primary-end use function if they do not receive sufficient amount of energy. Loads such as refrigerators, escalators in shopping complexes and segments of street lighting can be included in the curtailable loads section.

2.3 Adjustable Loads

The adjustable loads include clusters of low priority loads whose curtailment lead only to a compromise in the quality of comfort experienced by the end user. These include classes of loads, which are highly responsive to operator requests. Heating and cooling loads like water heaters and air-conditioners can be categorized into adjustable loads. To further elucidate the operation of these loads, let us take the example of a central air conditioning system in a building that is subjected to this scheme. Power usage of the system is a minimum when ambient temperature is to be maintained. Maintaining temperatures other than ambient temperature requires more power. The larger the difference between ambient temperature and set point the more power is required. Any compromise in desired set point can result in power savings. A mere change in the set points of these devices can be seen as a means of load control.

The practicality of dispatching these prioritized loads depends much on how they are modelled. Various priority loads discussed above can be further elucidated through a couple of examples. First let us consider an example of street lighting. While modelling the street lighting load we can have one in every three street lights belong to critical load. The other two can belong to two different sets of curtailable loads. Since one in every three street lights belong to a critical load we can ensure that even in case of large disturbances, the streets will still be lit to a certain extent. Next, consider modelling air conditioners for large buildings. The power required to maintain the temperature of a centrally air conditioned office building at 25 °C will be much less compared to the power required to maintain the temperature at 21 °C. Additional power required to lower the temperature of the building to 21 °C for end user comfort can be treated as an adjustable load which can be compromised (given low priority) to maintain power balance. The same ideas can be extended to the operation of heating loads such as water heaters. Thus in case studies presented later, the air conditioners and water heaters have been considered as purely adjustable loads.

Since control of these loads is fast, the attainment of power balance depends solely on the speed of the algorithm and the speed of the communication network. And with recent advancements in communication technology and with availability of options ranging from broadband internet connections to advanced metering infrastructure, it may seem that the only impediment to reliable utilization of loads as system services is the development of necessary load models and control strategies (Callaway, 2011).

2.4 Energy Storage

Having an ES system (i.e. battery) gives the added advantage of leveraging stored energy to maintain power balance and to minimize the curtailment of priority loads. Further, batteries can also help achieve failure tolerance against failure of a small generation unit. Batteries provide opportunity for the operator to store energy when it is in excess and use the stored energy to compensate for increased load demand or decreased energy generation. As stated earlier, excessive discharging or charging of a battery can adversely affect battery health. Therefore, certain constraints on charging and discharging rate, as well as on the maximum and minimum energy level of the ES have been modelled. The details of which are given in Table 1. The battery power is considered positive when it is charging and it is negative when it is discharging.

Table 1. Energy System Specifications

$P_{bat\text{-}max}$	$P_{bat\text{-}min}$	E_{max}	E_{min}
20kW	-20kW	100kWh	25kWh

2.5 Power Sink

The Power sink is seen as an energy dump. It is where all the excess energy that is generated is dumped. Since this is a wasteful practise, the proposed strategy will minimize the use of the power sink. However in the case of system operation without energy storage, it becomes imperative to use this provision to maintain power balance and mitigate over-voltages.

3. THE PROPOSED POWER BALANCING STRATEGY

This section of the paper will focus on the formulation of the optimization problem that will govern the proposed failure tolerant load balancing system. At the heart of the proposed strategy is an online optimization module. Two separate optimization problems have been constructed for cases with and without the use of ES. The objective function formulation of the load management system without ES is presented in the next subsection.

3.1 Problem formulation (without ES)

The objective function formulation of the EMS for real time power balancing for each instant without the use of battery is discussed in this section. The decision variables used here include $P_{adj}(k)$ which is the total adjustable load aggregate available for reduction at the time instant k, $P_{cur}(i,k)$ is the value of the curtailable load i at the time instant k. $P_{crit}(k)$ is the value of demanded critical load at time instant k. $P_{sink}(k)$ gives the value of power dissipated in the dump.

The objective function then can be formulated as follows:

$$\min_{\substack{\{f,u(i,k)\\ P_{sink}(k)\}}} \alpha f P_{adj}(k) + \sum_{i=1}^{N} \beta(i)\left(1-u(i,k)\right)P_{cur}(k) + \gamma P_{sink}(k) \quad (1)$$

Subject to:

$$0 \le f \le 1 \quad (2)$$

$$\begin{aligned}&(1-f)P_{adj}(k) + P_{crit}(k) + P_{sink}(k) + \\ &\sum_{i=1}^{N} u(i,k)P_{cur}(i,k) = P_{gen}(k)\end{aligned} \quad (3)$$

Where α, β and γ are the priority values of the adjustable, curtailable loads and the sink respectively. The number of distinct curtailable load sets is N. The f denotes a fraction of the adjustable load that should be curtailed for power balancing and naturally it varies from 0 to 1. In the proposed formulation, curtailable loads have higher priority compared to adjustable loads. In addition it is preferable to minimize usage of power sink. Thus, the priority values should follow the following inequality: $\gamma > \beta > \alpha$. As a consequence, the wasteful use of P_{sink} is discouraged and the lower priority adjustable loads are controlled before disconnecting the curtailable loads.

3.2 Problem formulation (with ES)

The problem formulation in this case is as follows :

$$\begin{aligned}\min_{\substack{\{f,u(i,k)\\ P_{sink}(k),E(k)\}}} &\alpha f P_{adj}(k) + \sum_{i=1}^{N} \beta(i)\left(1-u(i,k)\right)P_{cur}(i,k) \\ &+\gamma P_{sink}(k) + \delta\left|E(k)-E_0\right|\end{aligned} \quad (4)$$

subject to:

$$0 \le f \le 1 \quad (5)$$

$$E(k) = E(k-1) + 0.25 P_{bat}(k) \quad (6)$$

$$E_{\min} \le E(k) \le E_{\max} \quad (7)$$

$$P_{bat\_\min} \le P_{bat}(k) \le P_{bat\_\max} \quad (8)$$

$$\begin{aligned}&(1-f)P_{adj}(k) + P_{crit}(k) + P_{sink}(k) + \\ &\sum_{i=1}^{N} u(i,k)P_{cur}(i,k) + P_{bat}(k) = P_{gen}(k)\end{aligned} \quad (9)$$

Where δ is the priority value and E_0 is the desired value for battery energy level. The objective function has been formulated in such a manner that the battery energy level strives to return to this optimal energy value. The proposed formulation gives flexibility to decide relative importance of battery energy level and various loads. In this paper, it is recommended that battery energy level should be given slightly higher priority than adjustable loads, while it should be given lower priority than curtailable loads. This would imply the priorities would follow the inequality: $\gamma > \beta > \delta > \alpha$. As a consequence the battery will try to attain its optimal energy value even at the expense of the adjustable load, while curtailable loads are provided for even if battery energy level deviate from its desired value. However the choice of these weights are completely flexible and they may be chosen differently for a given application.

3.3 Failure Tolerance (with ES)

The proposed power balancing optimization formulation can allow an operator to continue providing for critical loads even if one of the distributed generators fail. This loss of generation is made up by energy stored in battery, adjustable loads and if necessary, curtailable loads. Thus the microgrid can become failure tolerant and a complete black out can be avoided. The objective function formulation need not change in the event of a failure and the decision to curtail or adjust loads will be taken by the proposed algorithm based on the available power generation capacity at any given instance ($P_{gen}(k)$).

4. CASE STUDY

Various simulations were performed to demonstrate effectiveness and failure tolerance capabilities of the proposed power balancing strategy. Due to brevity here three case studies are presented: i) system operation without ES, ii) system operation with ES and iii) system operation under failure. The simulations were carried out using a desktop computer having Intel core i3 (3rd generation) 3.1 GHz processor and 4GB RAM. Lindoglobal solver in the GAMS environment was used for solving the proposed optimization problem. The optimization was performed every 15 minutes however; this duration can be easily reduced, as the average time taken by the solver was 0.15 seconds only.

In the case studies all adjustable loads are lumped to a single adjustable load whose value can be varied from full load to zero. Three distinct curtailable loads with varying priorities are considered. The priorities refer to the penalty faced by the operator for compromising the end use performance of the load. In all three case studies the load demand curves shown in Fig. 2 are dealt with. The simulations are carried out for a period of 24 hours, which is divided into 96 intervals of 15 minutes. Fig.3 shows the variable generation curve over 96 time intervals. The same generation profile will be followed in the first two cases. In the third case study, due to faulty generator some generation capacity is considered lost.

4.1 System Operation without ES

In this mode of operation the optimization module dictates the levels of various loads without the provision of any standby energy. Here the loads are adjusted and curtailed according to their priorities. The priorities of the curtailable loads increase from 1 to 3, i.e. curtailable load 1 have lower priority compared to load 2 and load 3. In all the cases catering for the critical load is imperative and no compromise can be made. The catered profiles of the curtailable loads are shown in Fig.4.a. As can be seen from the figure, during the significant portion of interval 45-57 the curtailable loads could not be catered. Fig.4.b shows the adjusted values of the adjustable loads and the power dumped.

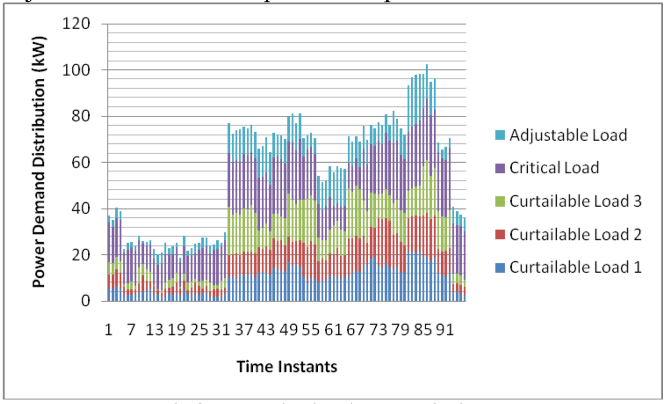

Fig.2. Load distribution over *24 hours*

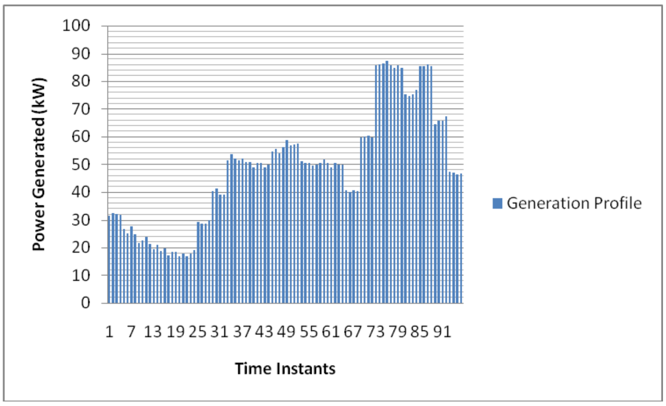

Fig.3. Generation Curve over 24 hour

4.2 System Operation with ES

Next performance of the proposed power-balancing algorithm for a system with ES is considered. In this operation the optimization module dictates the levels of various loads with the provision of a standby energy source. The catered profiles of the curtailable loads under this scheme are shown in Fig.5.a. In this case, due to ES system some of the curtailable loads are catered during interval 45-57. Fig.5.b shows the adjusted values of the adjustable loads and the power dumped. In this particular case the wasteful dissipation of power in the power sink has been completely avoided. Instead this power is being stored in the ES system for later use. As is clearly seen from Fig.5.a and Fig.5.b, the inclusion of an ES has resulted in increased availability of the higher priority curtailable loads. At the same time this has resulted in the deterioration of adjustable load profile. This is expected because adjustable loads have least priority values.

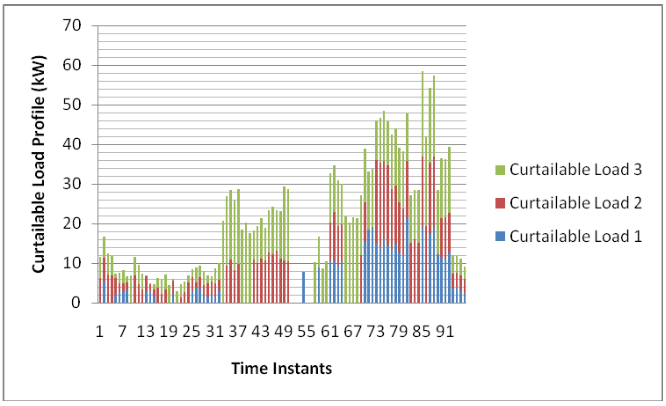

Fig. 4.a Curtailable Load Profile for case 1

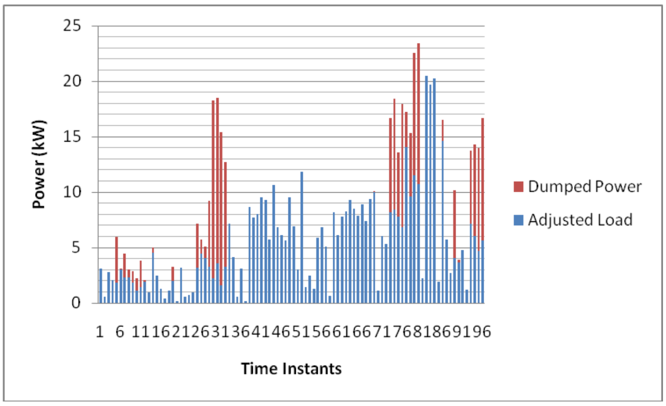

Fig. 4.b Catered Adjustable Load and Dumped Power for case 1

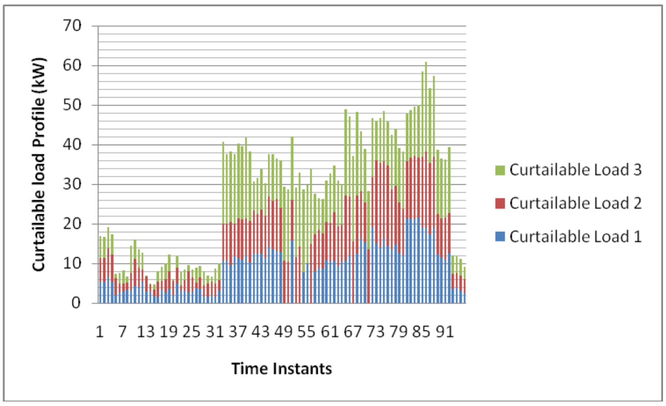

Fig. 5.a Curtailable Load Profiles for case 2

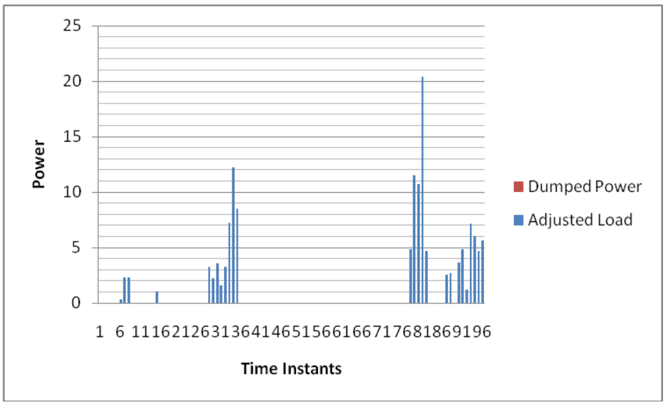

Fig. 5.b Catered Adjustable Load and Dumped Power for case 2

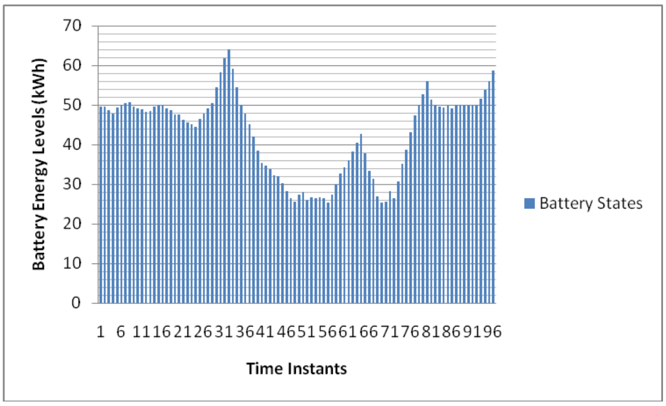

Fig 5.c Battery Energy States for case 2

4.3 System Operation with ES under large Failure

In the third case study, we are considering a large disturbance in the system (an outage of a generation unit) leading to a large dip in power generated for about 2.5 hours. Similar simulations were run for this condition. The following are the figures relevant to this case study.

The real time power generation profile is shown in Fig.6.a. Although the generation is less than critical load demand at instant 51, the system managed to cater to the critical load thanks to the battery support. It is seen that the proposed algorithm provides tolerance to major failure until the failure could be rectified and required maintenance could be performed.

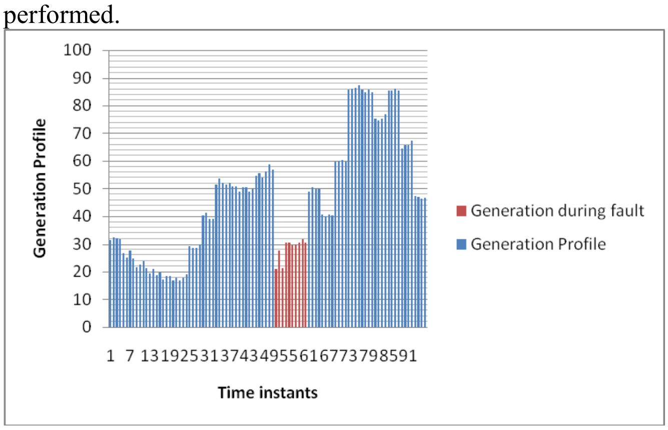

Fig. 6.a Generation Curve with Large disturbance between time instants 51 and 60 for case 3

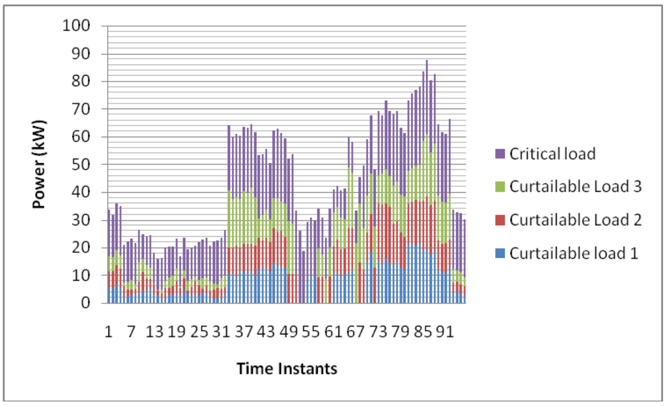

Fig. 6.b Power allotment to Critical and Curtailable Loads for case 3

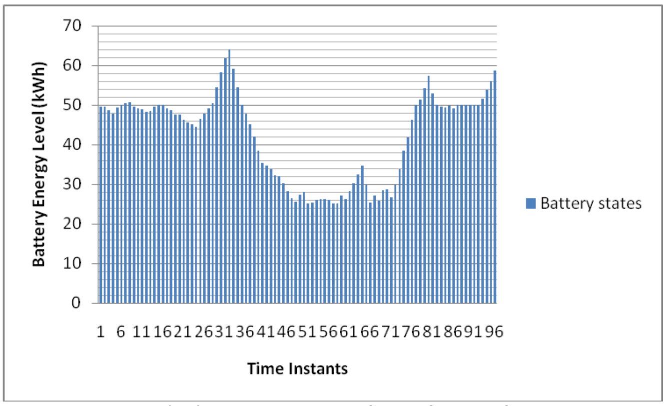

Fig 6.c Battery Energy States for case 3

From Fig.6.b it is also observed that although Curtailable Load 3 ranks higher in priority in comparison to Curtailable Load 1 & 2, power has not been allotted to it during intervals 51 to 60 simply because its demand is much larger (during the interval) than that of 1&2 which is also beyond the limited capacity of the system during the concerned intervals. Fig.6.c shows the Energy levels of the battery during online load balancing performed over a day.

5. CONCLUSIONS

In this paper an optimization approach for online power balancing in microgrid is proposed. The proposed approach is fault tolerant and can handle a generator failure for a limited time period. The duration of continued operation under failure is determined by stored energy in the battery. The proposed approach thus provides new avenues for providing spinning reserves. Further the proposed power balancing approach can help reduce any impact on end user based on the set priorities.

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