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A Power Management System for Planned & Unplanned Grid Electricity Outages

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***Abstract*—To deal with frequent planned and unplanned grid power outages, local energy systems are becoming popular idea. These systems are equipped with storage devices and different distributed generations (DGs) such as diesel generators. Efficient and reliable operation of local power systems is complex since power outages are stochastic events, and also local energy suppliers have different operation costs, constraints, and efficiency characteristics. A power management system (PMS), consisting of two control layers is developed in this paper to address aforementioned complex operation. To validate the proposed method, energy system of a base transceiver station (BTS) in India is simulated. It composed of batteries, diesel generator, real BTS load data, and a utility connection. In addition, the real historical outage data from India has been utilized to simulate outage events.**

I. INTRODUCTION

The power generation shortage is a serious problem for developing countries and affects power quality (voltage and frequency fluctuations). In order to assure the quality of power and keep voltage and frequency within their acceptable range, power outages are frequently forced and occurred to customers everyday. For instance, different states in India such as Delhi, Bihar, etc. endure recurrent power-cuts and load shedding programs. Larger and more critical consumers such as communication towers employ the idea of local energy systems to handle the interruptions caused by power outages. In addition to grid connection, they include distributed generations (DGs) such as diesel generators, and storage devices such as battery units to supply their load. Storage unit and DGs could supply the demand when grid power is not available or whenever they could save some energy costs. However, an intelligent power management system (PMS) should be developed to consider the stochasticity of outage event, efficiency characteristics of some DG units such as diesel generators, and other operational constraints. This management system has two targets. First, it should operate available energy sources in a way that achieves minimum operation cost for local energy system. Second, it should be robust and reliable to supply the load during random outage events without any interruption.

Previous efforts try to solve different aspects of this problem. There are methods to address energy management of islanded hybrid systems. In [1], a real-time controller was developed that uses a storage unit and a dispatchable source to compensate the mismatch power between demand and renewable generation. To select a source at each time instance, it compares their cost of operation. Wies *et al.* in [2] assign a priority to every device available in energy network. For example, renewable sources have highest priority, storage units are the second option, and last is diesel. Katiraei and Iravani in [3] designed a method to manage distributed generations within a microgrids based on voltage and frequency droop characteristics. Their solution stabilizes the voltage and frequency, and ensures the quality of the power to end users in real time. Regarding the second target, we could not find any existing approach in literature to deal with grid electricity outage for local energy systems.

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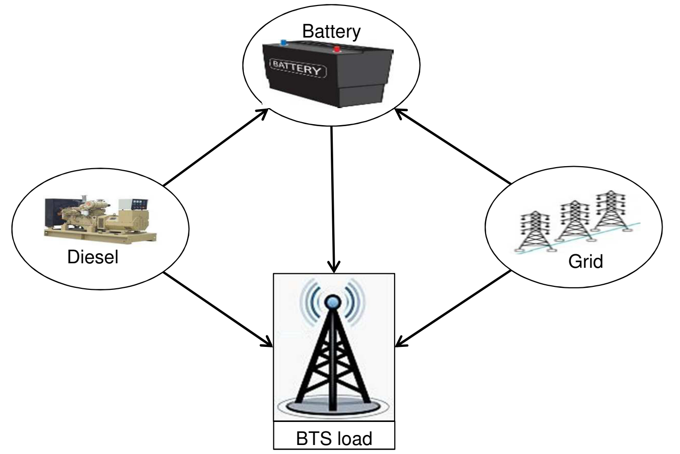

Fig. 1: Energy system model

As the discussion above and also other research studies such as [4]–[6] attest, there is need to develop a PMS that efficiently operates the devices, supply the demand both in grid-connected and outage times, and is able to control the devices in real time. In this paper, we propose a power management system that includes two control layers, real-time controller and outage scheduler. The rest of this paper is organized as follows: Section II explains the local energy system and its modeling. PMS structure is introduced in Section III. Outage scheduler is discussed in section IV. The real-time controller and its modules are defined in section V. Section VI presents the simulation studies. Finally, Section VII concludes the paper.

II. ENERGY SYSTEM MODELING

The energy system is modeled as a directed graph based on the energy system of a typical base transceiver station (BTS). As shown in Fig. 1, in this system, battery units and diesel generator are traditionally used as backup power sources to

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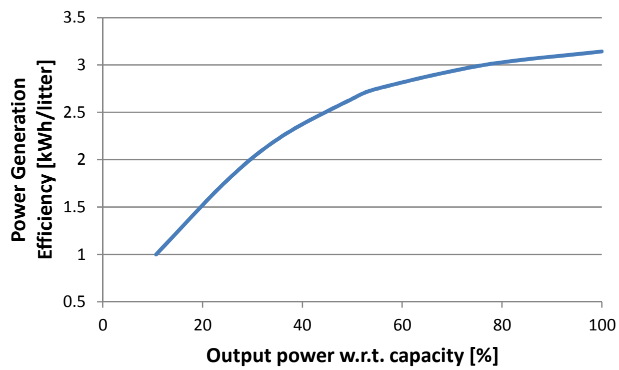

Fig. 2: Diesel efficiency characteristic curve

supply the BTS load whenever grid power is not available. In Fig. 1, the node on the right represents the grid connection. when it is available, grid is able to both charge the battery and supply the load. The node on top introduces the battery set. Battery can be charged by grid in grid-connected times, and by the diesel during outage times. It can also supply the load (be discharged) during the outages or in general whenever it is economically beneficial. Battery state of charge (SOC) dynamically changes based on the following difference equation:

$$soc(t+1) = soc(t) - \alpha P_{batt}(t) \quad (1)$$

in which $soc(t)$ is battery SoC in ampere-hour (Ah) at time t. α is a coefficient that changes kW unit into Ah, and also includes sampling time term. $P_{batt}(t)$ is the battery output power at time t. Negative value for $P_{batt}(t)$ means battery is charged, and positive value is discharging power. Battery SOC could vary in its allowable operational range recommended by battery manufacturer. This constraint is expressed as follows:

$$soc^{min} \leq soc(t) \leq soc^{max} \quad (2)$$

soc^{min} is minimum SOC or maximum depth of discharge (DOD). soc^{max} is maximum SOC or minimum DOD. Similarly, battery power is also restricted by its rated power, P_{batt}^{max}.

$$|P_{batt}(t)| \leq P_{batt}^{max} \quad (3)$$

The node on the left in Fig. 1 represents the diesel generator. The diesel generator operation is affected by its efficiency characteristic. Fig. 2 explains for higher values of power, diesel asset consumes less fuel per kWh of generation. It means the diesel price is cheaper for higher levels of generation.

$$diesel\ price[\$/kWh] \propto 1/P_{dies} \quad (4)$$

In addition, diesel output power ($P_{dies}(t)$ $[kW]$) is bounded by its rated power:

$$0 \leq P_{dies}(t) \leq P_{diesel}^{max} \quad (5)$$

Finally, the bottom node in Fig. 1 is the energy system load. Total power provided by energy sources (grid, battery and diesel) should balance the system load, $L(t)$, at each time instance.

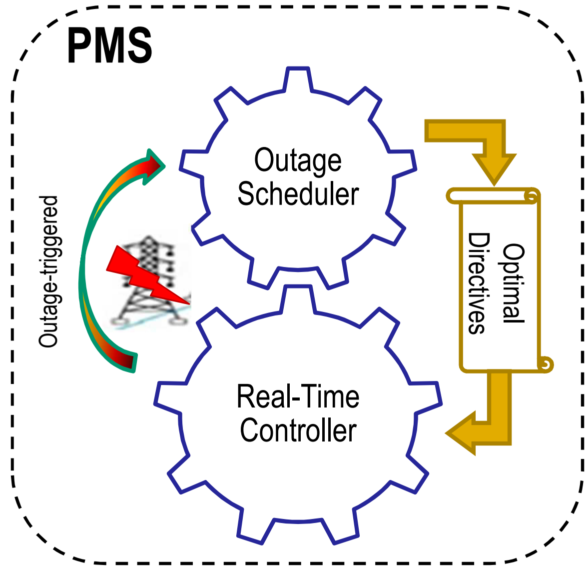

Fig. 3: Tiered PMS structure

$$P_{grid}(t) + P_{dies}(t) + P_{batt}(t) = L(t) \quad (6)$$

III. POWER MANAGEMENT SYSTEM STRUCTURE

Based on the discussion provided in introduction section, PMS objectives are:

- efficient and economic operation of the devices,
- Uninterrupted supply to the load during both grid-connected and outage times,
- Implementation of minute-by-minute control.

We use a tiered structure for the proposed PMS to address these targets. This structure includes real-time controller and outage scheduler. Fig. 3 explains the structure of PMS. As it can be inferred from its name, real-time controller operates the devices in a minute basis at real time of operation. When the system is connected to the power network, grid has the priority to supply the load since its tariff rate is cheaper than diesel generator fuel cost. It also charges the battery unit if it is not fully charged. When the outage occurs, there are two sources to supply the load, battery and diesel. In order to economically manage these sources and maximize the diesel efficiency, real-time controller triggers the outage scheduler. Using its forecasting tool, the scheduler first predicts the occurred outage duration (it is a deterministic input in the case of planned outages). For the predicted time window, it solves an economic dispatch problem in which the objective is diesel fuel cost minimization. Based on optimal solution for dispatch problem, outage scheduler calculates the level of diesel generation during outage event, and passes this value as long term optimal directive to real-time controller. Using the outage scheduler optimal directive, real-time controller economically manages diesel generator and battery unit to supply the load during outage event. The details and formulation of outage scheduler and real-time controller will be explained in next sections.

IV. OUTAGE SCHEDULER

To optimize energy system performance, PMS goal is minimizing the total energy cost at the presence of outage events. As explained in previous section, this goal is a straightforward task for real-time controller during grid-connected times since grid is always the cheapest power source. However, to achieve this goal during outage times, battery and diesel should be operated in a way that maximizes the diesel efficiency. To this purpose, an economic dispatch (ED) problem is formed by outage scheduler for outage time window. The objective of ED problem is minimizing the diesel operational cost during the occurred outage as follows (The battery operation cost equals to zero since the charging cost is already included in diesel power costs. For a more detailed battery cost model which considers battery life cost as well, readers can refer to [7]):

$$J := \sum_{t=0}^{T} C_{dies}(P_{dies}(t), U_{dies}(t)) \tag{7}$$

in which $C_{dies}(.)$ is diesel operational cost that is a function of its output power ($P_{dies}(t)$) and its commitment ($U_{dies}(t)$) at time t. Also, T is outage time duration. For planned outages, this value is known through local utility company. For unplanned outages, T is an uncertain parameter. To determine the value of T, outage scheduler performs a statistical analysis on historical outage data and creates the histogram for outage duration frequency. Based on outage histogram, it selects the value of T so that an outage duration with highest number of historical occurrences has the highest chance to be chosen. Note that the outage histogram is dynamically updated as PMS experiences more outage events. The constraints for ED problem are devices' operational limitations introduced in equations (1) – (6). To handle the constraints (1) and (2), ED problem also measures battery SOC at the start of outage (extent of charging from grid before outage event). The ED optimization problem is summarized as follows:

$$\begin{gathered}
\min J := \sum_{t=0}^{T} C_{dies}(P_{dies}(t), U_{dies}(t)) \\
subject\ to: \\
soc(t+1) = soc(t) - \alpha P_{batt}(t) \\
soc^{min} \leq soc(t) \leq soc^{max} \\
|P_{batt}(t)| \leq P_{batt}^{max} \\
0 \leq P_{dies}(t) \leq P_{diesel}^{max} \\
P_{grid}(t) + P_{dies}(t) + P_{batt}(t) = L(t)
\end{gathered}$$

The solution of ED problem (P_{ED}^*, in matrix (8)) determines the optimal schedule of battery (P_{batt}^*) and diesel generator (P_{dies}^*, U_{dies}^*) during forecasted outage time horizon, T.

$$P_{ED}^* = \begin{pmatrix} P_{batt}^*(1) & P_{batt}^*(2) & \cdots & P_{batt}^*(T) \\ P_{dies}^*(1) & P_{dies}^*(2) & \cdots & P_{dies}^*(T) \\ U_{dies}^*(1) & U_{dies}^*(2) & \cdots & U_{dies}^*(T) \end{pmatrix} \tag{8}$$

A. Outage Scheduler Optimal Directive

Due to the possible forecasting error in outage duration prediction, the implementation of this schedule in real time of operation is not feasible and threatens system reliability. Hence, in order to maximize the performance optimality and guarantee the real time operation reliability, this schedule is analyzed by PMS and its important information is passed to real-time controller as optimal directive.

Analyzing ED results shows that outage scheduler charges the battery by diesel power whenever diesel has to be used to supply the load. By doing this it increases the diesel output power to increase its efficiency (reducing its operation cost), Fig. 2. In addition, battery is charged to a level that it could be completely discharged by the end of outage event. It means outage scheduler does not keep any expensive diesel power in the battery at the end of outage to minimize system operation cost.

To transfer the optimal behavior of outage scheduler to real-time controller, total generation of diesel generator (E_{dies}^{opt}) during outage is calculated based on ED optimal result, P_{ED}^*.

$$E_{dies}^{opt} = \sum_{t=0}^{T} P_{dies}(t) \Delta t \tag{9}$$

Δt is the sampling time. ***Optimal diesel generation*** (E_{dies}^{opt}) is passed to real-time controller as outage scheduler optimal directive. Using this information, real-time controller can achieve the same optimality in performance as outage scheduler if predicted outage duration is the same as occurred outage duration in real time.

V. REAL-TIME CONTROLLER

Real-time controller (RTC) manages the devices in real time of operation (in a minute-by-minute basis) during grid-connected and outage times. To reliably and economically operating the system, it uses the following algorithm:

- *Gird is connected:*
  Grid supplies the load and charges the battery up to its soc^{max}.
- *Gird is NOT connected (outage occurred):*
  First RTC triggers the outage scheduler to prepare ***Optimal diesel generation*** (E_{dies}^{opt}). It also starts supporting the load by battery until it reaches soc^{min} (diesel is idle). When battery is fully discharged, diesel starts supplying the load and fully charging the battery or until diesel reaches the E_{dies}^{opt}. By then, diesel is stopped and battery is discharged to supply the load. When diesel reaches E_{dies}^{opt} and RTC still needs to utilize the diesel due to outage duration prediction error, diesel does not fully charge the battery and battery is discharged anytime that is has some power to support the load.
- *When outage is finished:*
  RTC measures the occurred outage duration. Outage database is updated based on measured value. Outage duration PDF is updated accordingly to improve future predictions.

VI. SIMULATION STUDY

The performance of developed PMS is studied in this section. To this purpose, we employ the model of a typical BTS energy system in India, Fig. 1. For grid power, the electricity rate is flat ($\$0.10/kWh$). The battery unit type is Lithium-ion and its specifications include:

- Capacity : 6.6 kWh
- soc^{max} : 100%
- soc^{min} : 10%
- Rated power: 6.6 kW

Battery initial SOC for starting the operation is its soc^{min}. Diesel generator capacity is 15 kW and its efficiency characteristic is as Fig. 2. Based on diesel capacity and efficiency, its cost curve in $[\$/h]$ can be obtained as Fig. 4. Note that for calculating diesel costs we ignore the fixed costs of running the generator. This cost curve can be nicely approximated by

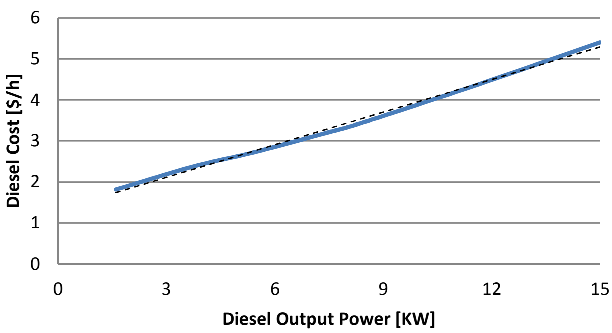

Fig. 4: Diesel cost curve $[\$/h]$

the following linear cost function (dashed line in Fig. 4):

$$Cost_{dies}^{[\$/h]}(t) = C_{dies}^{[\$/kWh]}(t) \times P_{dies}(t) + b \times U_{dies}(t)$$
$$= 0.2651 \times P_{diesel}(t) + 1.3152 \times U_{diesel}(t)$$

According to BTS load profiles that are almost constant too, load value is selected to be 1.5 kW all the time. It should be noted that a variable load profile does not affect PMS performance and can be easily integrated. Grid power outages are simulated based on typical real outage events in India as well. Finally, sampling time in one minute.

To evaluate PMS performance, we compare its results with a baseline management scenario and an ideal management scenario. In baseline management scenario, the energy management system performance is identical to that of proposed PMS in grid-connected times. However, during outage time when diesel generator supplies the load, it needs to fully charge the battery as well. In ideal management scenario, it is assumed that outage scheduler in PMS can accurately predict the outage duration.

The simulation results of each management scenario for a day in which the energy system experiences 8 unplanned grid power outages are as follows:

A. Baseline Management System

Fig. 5 shows the results for baseline management scenario. As it can be seen during all outages except outage number 4,

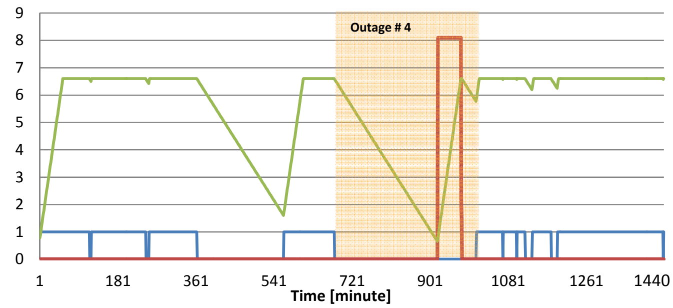

Fig. 5: Baseline management results: blue is outage signal (1 means grid-connected time, 0 means outage time), green is SOC $[kWh]$, red is diesel generation $[kW]$.

battery power is enough to support the load and diesel stand idle. During outage number 4, battery first supplies the load until it reaches its soc^{min}. Then, diesel starts supplying the load and charges the battery. When battery is fully charged, it support the load until the end of outage. It can be observed that at the end of this outage there remains expensive excess diesel charge in the battery that increases baseline cost of operation.

B. Ideal Management System

Fig. 6 illustrates the results for ideal management scenario.

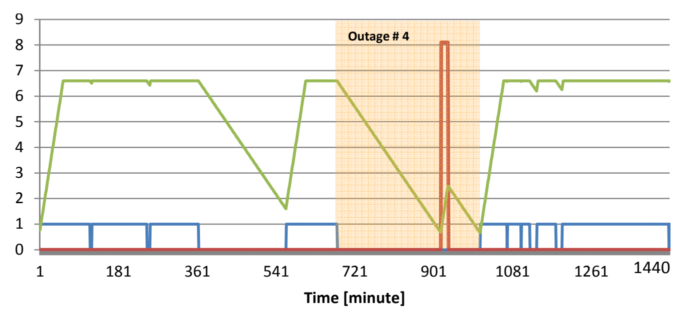

Fig. 6: Ideal management results: blue is outage signal (1 means grid-connected time, 0 means outage time), green is SOC $[kWh]$, red is diesel generation $[kW]$.

As it can be seen, since outage scheduler knows the exact value of duration for each outage, it prepares best possible optimal directives for real-time controller. In this case, it only determines 134.10 kWh as E_{dies}^{opt} for outage number 4. For the rest of outages it advices 0 kWh as E_{dies}^{opt} since battery energy is enough to supply the load. Following this directive by real-time controller, battery is charged by diesel up to the level that could be completely discharged (up to soc^{min}) at the end of outage event.

C. Proposed PMS

Fig. 7 shows the results for proposed power management system (PMS).

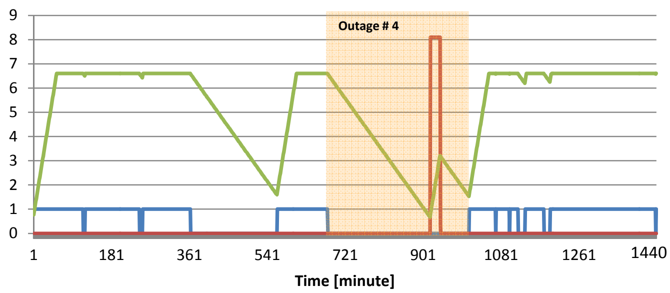

Fig. 7: PMS results: blue is outage signal, green is SOC $[kWh]$, red is diesel generation $[kW]$.

The optimal directive, E_{dies}^{opt}, for outage number 4 provided by outage scheduler is $186.6\ kWh$. This value is higher than ideal optimal directive, $134.10\ kWh$ that is due to prediction errors. So, there remains some diesel charge in battery at the end of this outage. However, this excess charge is still lower (70%) than baseline case. The table below compares the daily operation costs (grid and diesel costs) of management scenarios.

TABLE I: Daily operation cost

	baseline	ideal	PMS
Daily cost [$]	$6.63	$4.93	$5.23

According to table I, although PMS operation cost is 6% higher than ideal cost in which outage duration is a deterministic parameter, it creates 21% savings in compare to baseline approach.

VII. CONCLUSION

In this paper, we presented a novel power management system (PMS) to operate a local energy system. The developed PMS includes two modules, real-time controller and outage scheduler. To minimize daily operational costs at the presence of grid power outages, outage scheduler calculates the optimal diesel generation as optimal directive for real-time controller. The real-time controller manages the devices in real time of operation and considers the optimal directive. PMS performance was evaluated via a simulation study on a BTS energy system model. Simulation results demonstrate the proposed approach ability to efficiently employ the diesel power and decrease the daily operational cost by 21% in compare the baseline approach. Authors are currently working on adding a more advanced forecasting module to improve the performance of outage scheduler.

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