Hidden Costs of Power Cuts and Battery Backups

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ABSTRACT

Many developing countries suffer from intense electricity deficits. For instance, the Indian electricity sector, despite having the world's fifth largest installed capacity, suffers from severe energy and peak power shortages. In February 2013, these shortages were 8.4% (7.5 GWh) and 7.9% (12.3 GW) respectively. To manage these deficits, many Indian electricity suppliers induce several hours of power cuts per day that impact a large number of their customers. Many customers use lead-acid battery backups with inverters and/or diesel generators to power their essential loads during those power cuts. The battery backups exacerbate the deficits by wasting energy in losses (conversion and storage) and by increasing the load (by immediately charging the batteries) when the grid is available. The customers also end up incurring additional costs due to aforementioned losses and due to limited lifetimes of batteries and inverters. In this paper, we discuss the issues with power cuts and backups in detail and illustrate their impact through measurements and simulation results.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous; D.2.8 [**Software Engineering**]: Metrics—*complexity measures, performance measures*

General Terms

Electricity storage, inverters, battery backups, uninterrupted power supply, UPS, losses, power grids

Keywords

Electricity storage; inverters; battery backups; losses; power grids

1. INTRODUCTION

Many developing countries suffer from intense electricity deficits. For instance, the Indian electricity sector, despite having the world's fifth largest installed capacity [7], suffers from severe energy and peak power shortages. In February 2013, these shortages[1] were 8.4% (7.5 GWh) and 7.9% (12.3 GW) respectively [7]. Specific regions could suffer from larger shortages. For example, Tamil Nadu, a southern Indian state, reported 18.4% (1.2 GWh) and 13.5% (1.5 GW) energy and peak power shortages for the month of February 2013 [7]. In fact, India has long struggled with electricity deficit and as a consequence, millions of consumers have been suffering with inadequate power supply [31, 35].

To manage the deficits, many Indian electricity suppliers induce several hours of power cuts per day that affect large percentage of their customers. Many of those customers use a backup power source (such as a Diesel Generator (DG) and/or an inverter with a battery) to power their essential loads (such as lights and fans) during those power cuts [37]. Diesel generators do not depend on grid for their operations. However, they require periodic fuel refills and can generate fumes. Moreover, due to local fuel prices, electricity generated by them could be expensive. In India, cost of one kWh generated by a DG can be three times more expensive than a kWh bought from a electricity retailer [38]. This price difference could get much larger as the diesel subsidies are being gradually removed [10].

Inverter backups charge their batteries when there is mains supply and power the loads using the batteries when there is a power cut. Compared to DGs, the inverter backups can be simpler (no fuel refills) and cleaner (no fumes) to operate. But, they aggravate the power deficits by wasting energy in losses (conversion and storage) and by increasing the load (by charging the batteries) on the power grids whenever the mains supply is available. The customers also end up incurring additional costs due to aforementioned losses and due to limited lifetimes of inverters and batteries [37].

While inverter backups are used by residential consumers and small offices, Uninterruptible Power Supplies (UPS) are commonly used as power backups in commercial environments [37]. Inverter backups and UPS contain the same set of components, and they are similar except for the changeover (from mains to battery or vice versa) delay: the former takes about 500 milliseconds to a second and the latter takes only about 20 milliseconds[2]. UPS are typically used to protect computers, data centers, telecommunication equipment or other electrical equipment where an unexpected power

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[1] The shortages include the load from battery backups as well. Load-specific consumption details are not available.

[2] There is also a special kind of UPS called the online UPS where the batteries are always connected to the inverter, so that no power transfer switches are necessary.

disruption could cause serious business disruption or data loss. Some consumers, especially the commercial ones, use a combination of DGs and battery backups to handle power cuts.

The cumulative impact of battery backups on grids and consumers could be aggravated as more Indian consumers are able to afford inverters due to their increased purchasing power. Initially, they were used to fulfill only primary demands, such as powering a few fans and lights; however, now they are also being used to run desktops, air conditioners and the many other household appliances during power cuts. More importantly, the Indian power inverter market is expected to grow until 2016-17 [13]. This growth can aggravate supply-demand gap unless the inverters are lossless. Moreover, there exists a potential for economic disparity with the higher-income groups being able to afford backups with higher capacity and worsening the demand-supply gap increasing the frequency of power cuts in economically backward areas.

Since the impact of these inverter backups can increase non-linearly with the number of inverters in use, it is important to have a framework for analyzing their impact. Using detailed measurements and models of inverter backups, we analyze their impact on electricity suppliers and consumers. We also demonstrate the large-scale effects using a multi-agent simulation with load/generation profiles, multiple levels of inverter penetration, different battery capacities, duration of power cuts, etc.

The rest of the paper is organized as follows: Section 2 presents the technical details of inverters and batteries. An approach for quantifying the impact of battery backups is presented in Section 3. Simulation setup and results are presented in Section 4. Section 5 reviews the relevant existing body of work and finally, section 6 concludes with a discussion about future work.

2. BACKGROUND

2.1 Inverters

Figure 1 presents a simplified block diagram of a single-phase inverter. An inverter, using the charge stored in the attached battery, can give constant AC voltage (either 220V AC or 110V AC depending on the line voltage of the particular country) at its output socket when the AC mains power supply is not available. Inverters meant to handle power cuts usually have a built-in charger and the focus of this paper is on such inverters.

The inverter functioning can be explained under two situations [8]:

1. *When the AC mains power supply is available:* the AC mains sensor will sense the availability of mains supply and will activate a relay that will directly pass the line supply to the output socket so that the loads can be driven by the mains. The line supply is also connected to the battery charging section where it is converted to a DC voltage (usually, 12V DC or 24V DC) for charging the attached battery.
2. *When the AC mains power supply is not available:* the AC mains sensor will sense the unavailability of mains supply and cutoff the output socket from mains. Simultaneously, it will activate relays that connect the change-over section to inverter section where DC to AC conversion takes place. There are multiple realizations of inverter circuitry based on cost considerations. Simple designs use an oscillator to generate the mains cycle with a push-pull transistor circuitry connected to a transformer while more sophisticated ones employ a Pulse Width Modulation (PWM) based approach using digital signal processors driving a full bridge with filters at the output for precise sine wave generation and control.

The majority of inverters used in India produce quasi sine-wave outputs. These inverters produce a distinct sound when fans are operated and consumers are able to easily distinguish between mains and inverter operation. However, decreasing cost of computing and processors is making the quasi sine wave inverters obsolete and they are gradually being replaced with their pure sine wave counterparts.

Manufacturers of residential inverters (500V, 600VA, 800VA and 1000VA) are under constant pressure to decrease prices and this comes at the cost of performance and flexibility. Ease of use dictates that users need not bother with settings after the installation. Efficiency is often compromised since the user is not aware of the operating costs and benefits. Further, in order to decrease cost of the overall solution which includes the battery cost (the most significant contributor to cost), inverter charging current is optimized for a narrow range of battery capacities. As a result, using a higher-capacity battery would not be beneficial because charging it will take more time and may not get fully charged, if there are frequent power cuts.

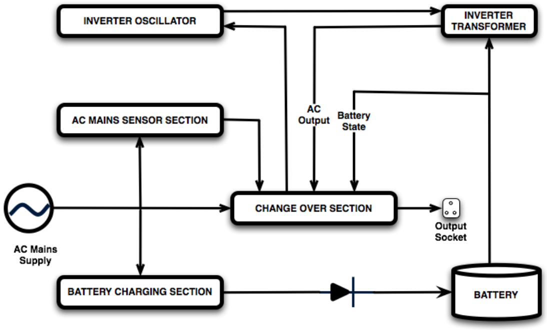

Figure 1: Simplified block diagram of a single-phase inverter

2.2 Batteries

Lead-Acid batteries are commonly used with inverters. The technology is affordable, proven and easy to manufacture, despite poor volumetric efficiency and relatively low depth of discharge. Most residential inverter systems use a single battery, even though it is not uncommon for multiple batteries (usually connected together in series) being used in installations that require high capacity backups.

Lead Acid batteries are characterized by voltage and capacity. The capacity of a battery is usually specified for of 20-hour[3] discharge cycle. Discharging the battery faster (at a higher current) will reduce available capacity. For instance, the Panasonic LC-XA12100P has 100Ah capacity when discharged in 20 hours and 55Ah capacity, when discharged in an hour [27]. This relationship between discharge rate and available capacity is given by well known Peukert's Law [20] which relates battery capacity to discharge rate:

$$C_p = I^k.t \quad (1)$$

where C_p is the amp-hour capacity at 1 A discharge rate, I

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[3] Known as C20 rating which means the battery is designed to provide 1/20th of the stated Ah capacity for 20 hours.

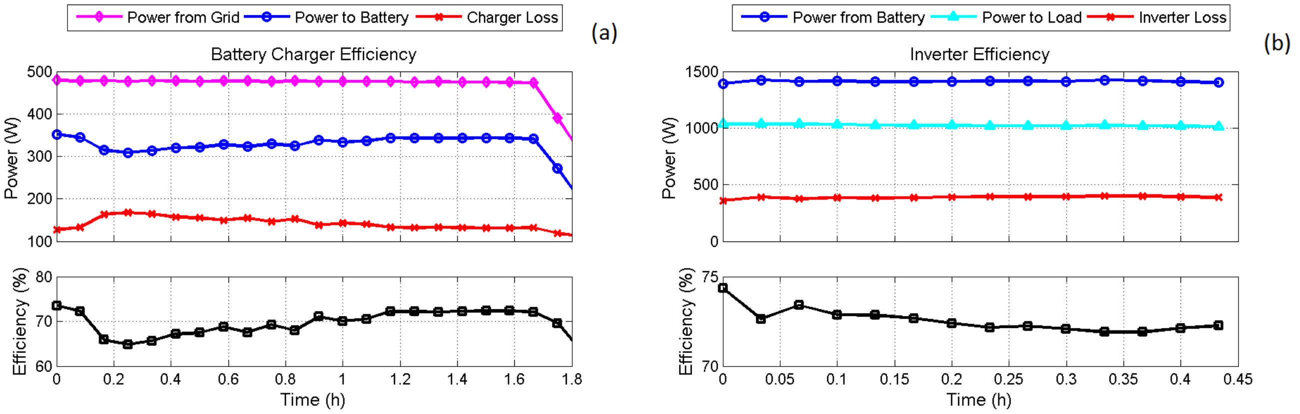

Figure 2: (a) Losses incurred by an inverter during charging, (b) Losses incurred by an inverter during discharging (powering a single-coil 1040W room heater.)

is the discharge current in Amperes, t is the discharge time in hours and k is the Peukert coefficient (typically 1.1 to 1.3).

Another important factor that must be considered is the depth of discharge as it has a non-linear effect on the life of batteries. For example, the Industrial Energy IEL 12150 battery, when discharged 30% (depth of discharge) of its capacity every time, can withstand 1200 cycles; whereas, at a depth of discharge of 50%, the life of battery falls by more than half to about 450 cycles [26].

3. IMPACT ANALYSIS

The negative impact of battery backups can be analyzed in terms of various direct costs incurred by electricity suppliers and consumers. These costs are interconnected in complex ways. For example, if the schedule of power cut is known in advance, consumers can preplan and complete their activities before or after those hours. However, from the point of view of suppliers, this may not be beneficial since the energy consumption is not reduced as much as it time shifted. As a result, unscheduled power cuts would be more beneficial for the suppliers and less convenient for the consumers; on the other hand, scheduled power cuts would be more convenient to the consumers and less effective for the suppliers.

In the following sections, each of the costs is explained in detail and is expressed as mathematical expressions. Since the parameters of the equations arise from the interplay of various socioeconomic and technological factors, it may not be straightforward to obtain their values. Nevertheless, these equations can be used to get a perspective of the costs using estimated (for instance, from data collected through well-designed customer surveys) parameter values.

3.1 Impact on the Electricity Supplier

3.1.1 Energy Loss

Every unit of electricity that passes through a battery backup suffers various losses. To illustrate these losses, we measured the charging and discharging losses of a 1400 VA inverter (Numeric Digital HPH 1400) with a 150 Ah battery (Amaron). As illustrated in Figure 2, the rectification and inversion efficiencies are about 70%.

As a result, an electricity supplier must provide additional energy to compensate for such losses.

$$LE = \sum_{i=1}^{N} e_i\left(\frac{1-\eta_i}{\eta_i}\right) \tag{2}$$

where LE is the total loss incurred by the supplier during a power cut, N is the total number of inverters, e_i is the energy served by the i^{th} inverter and η_i is the total efficiency from mains to load through the inverter.

The total efficiency η_i can be expressed as:

$$\eta_i = \eta_r \eta_c (1 - l_s) \tag{3}$$

where η_r is the efficiency of rectification process (AC to DC conversion) used for charging the battery, η_c is the efficiency of inversion process (DC to AC) used while powering the loads from batteries, and l_s is the electrochemical loss (in percentage) incurred in charge-discharge cycles.

Typically in developing countries, the volume of inverters sold is highest in the sub-1kVA range. These inverters are used for powering a few lights, fans and a TV. For such inverters, η_r and η_c are around 80%, and l_s is around 10%. It is important to note the efficiency depends on the delay between charging and discharging. If this delay is significant (in the order of months), batteries could leak the charge and the efficiency could reduce.

Since the inverters are usually neither monitored nor metered, it may not be possible to get the exact inverter specific data, therefore equation (2) can be rewritten as the following to estimate the energy lost during a power cut:

$$LE = E \times \frac{\delta}{100} \times \frac{IF_a}{100} \times \frac{IP}{100} \times \left(\frac{1-\eta_a}{\eta_a}\right) \tag{4}$$

where E is the baseline energy demand during the power cut time, δ is the % energy deficit with respect to the baseline demand, IF_a is the % consumer load that is served by inverters, averaged over all consumers with the inverters, IP is the % inverter penetration, and η_a is the inverter efficiency from mains to load through the inverter, averaged over inverter efficiencies η_i (defined in (3)) for all the consumers.

In addition to the above mentioned losses, energy is also lost in the form of tare losses [6] in operating the inverters even when they are not serving any load. These tare losses can accumulate to significant energy wastage when there are a large number of inverters without appropriate loss control mechanisms.

3.1.2 *Rebound Effect*

Since the battery chargers do not follow any managed charging schedules, they could start recharging the batteries as soon as the mains supply becomes available. Such simultaneous charging from multiple backups could impose additional load on the grid. The additional load from battery chargers and deferred loads on the grid during the hours that follow a power cut can be expressed as:

$$AE = \frac{E \times \frac{\delta}{100} \times \frac{IF_a}{100} \times \frac{IP}{100}}{\eta_c \eta_r (1 - l_s)} + E_d \tag{5}$$

where E, δ, IF_a and IP are same as defined in equation (4) and E_d is the total amount of deferred energy consumption from other time-shiftable loads such as washing machines, dish washers,etc.

There are a few important factors to consider about this rebound effect:

Scheduling power cuts - If the power cut ended just before the peak hours, the backups will aggravate the peak load by charging during the peak hours. Moreover, the distribution infrastructure that is already operating close to its capacity will be further taxed by this additional load. On the other hand, if the power was cut during the peak hours, the backups could alleviate peak loads. However, the power must be cut through the peak hours to avoid any rebounding during those hours or additional load must be cut to handle deferred consumption, if the power can't be cut for the entire duration of peak hours. It must be noted that these battery backups could be beneficial if there is an overall energy surplus but there is a power shortage during peak hours.

Differential energy prices - Since the price of electricity in bulk markets[4] varies with time, the economic impact of rebound effect must be carefully considered. Without power cuts, consumers would have used even their non-essential loads during those hours and cost of supplying power for those loads could have been high (it is possible that powering the secondary loads may not have been an option due to deficits). But, that cost savings must be carefully compared with additional costs incurred when the rebound happens. This cost difference can be expressed as follows:

$$NB = \sum_{i=1}^{n} OE_i \times p_{t1} - \sum_{j=1}^{m} AE_j \times p_{t2} \tag{6}$$

where NB is the net benefit to the utility company, OE_i is the baseline energy demand i.e. the original energy (for both primary and secondary loads) that would have been consumed if there were no power cuts at the i^{th} time slot, AE_j is the rebounded energy consumption as defined in (5) at the j^{th} time slot. p_t1 and p_t2 are price per kWh of energy during the power cut and rebound hours respectively. n and m are the total number of hours of power cut and hours of rebound respectively.

3.1.3 *Peak-to-Average Ratio of Inverter Current Consumption*

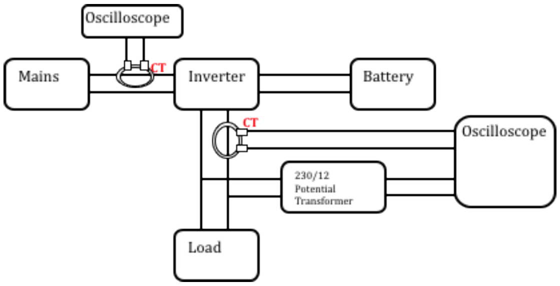

Figure 3: Setup for measuring the charge/discharge characteristics of a single-phase inverter (Numeric HPS1000, 1kVA inverter) with a battery (Amaron Tubular 150AH, 12V).

Most inverters employ switched mode charging since it offers better efficiency than linear charging. Switched mode charging results in a non-sinusoidal current waveform with high peak to average current. The high peak to average ratio implies that the apparent power requirement is high and this places high instantaneous demand on the electrical infrastructure. To illustrate this behavior, we studied an inverter using the measurement setup presented in Figure 3 to measure the charging/discharging characteristics and the corresponding inefficiencies. As shown in Figure 4, peak current (2.52A) and peak-to-average ratio (3.6) for the current can be quite high. When multiple inverters start charging immediately after a power cut, the cumulative current drawn from the grid can be quite high.

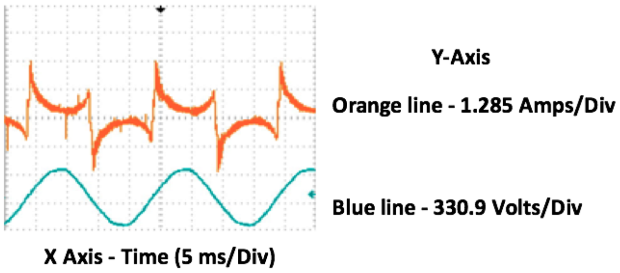

Figure 4: High peak-to-average inverter charging current. (Blue line represents supply voltage and the orange line is the charging current.)

3.2 Impact on the Consumers

3.2.1 *Higher Electricity Cost*

Consumers end up paying higher price per unit of power due to the conversion and storage losses. The additional cost incurred by the consumer i, AC_i, during a power cut can be expressed as:

$$AC_i = E_i \times IF_i \times p_u \times \left[\frac{1}{\eta_c \eta_r (1 - l_s)} - 1 \right] \tag{7}$$

where E_i is the original electricity demand of the i^{th} consumer during the power cut, IF_i is *Inverter load factor* - the fraction of original demand (E_i) served by the inverter i and p_u is the price for one unit of electricity.

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[4] Indian bulk power markets use time-varying Availability Based Tariff (ABT)[4] as the electricity pricing mechanism.

3.2.2 Inconvenience Cost

The inconvenience cost experienced by consumers due to the power cuts depends upon various factors. It varies for every consumer and depends upon the factors like time of day and type of appliances affected due to power cut etc. We model the inconvenience cost by using the categorization of appliances and utility functions suggested in [22].

Let $q_{i,a}(t)$ is the power demanded by i^{th} consumer at time slot t for an appliance $a \in A_i$, where A_i is the set of appliances used by consumer i. Let $q_{i,a}$ denote the vector of power demands over all possible time slots. Let $U_{i,a}(q_{i,a})$ is a utility function that provides the utility obtained by user i for consuming electricity as $q_{i,a}$.

Due to the power cuts, the consumption vector is altered depending upon whether the appliance a can run on inverter or not. Let $q_{i,a}^{cut}$ denotes the new consumption vector obtained due to the power cuts in a given day. The total inconvenience cost, IC_i, incurred by consumer i can be computed as:

$$IC_i = \sum_{a \in A_i} U_{i,a}(q_{i,a}) - U_{i,a}(q_{i,a}^{cut}) \tag{8}$$

where the utility functions $U_{i,a}(q_{i,a})$ vary depending upon the appliance types - temperature controlling appliances (like AC, Refrigerator), deferrable appliances (like washing machine, dish washer etc.), essential loads (like lighting) and interactive appliances (like TV, entertainment devices)- and could be used as suggested in [22].

3.2.3 Battery Life

In general, the battery life (the number of charge/discharge cycles) reduces with the increase in Depth of Discharge (DoD). The DoD in turn depends on the duration of power cuts and load levels during those hours. The depth of discharge during a power cut for consumer i can be approximated as:

$$DOD_i = \left(\frac{D \times w_i}{v_i \times A_i}\right) \tag{9}$$

where D is duration of the power cut in hours, w_i is the amount of power supplied by i^{th} inverter during that power cut, A_i is the total capacity of the battery in ampere hours, and v_i is the nominal voltage of the battery in volts.

Since deep discharges can reduce the life of batteries, inverters prevent deep discharges by shutting down the inverter at a pre-determined voltage. The open terminal voltage as a reference for the State of Charge (SoC) is reliable only if many factors (such as battery age, ambient temperature, etc) are considered and if the battery is allowed to rest for a few hours before the measurement [5].

After sustained use, the lead plates eventually weaken and are no longer able to store energy [33]. Used lead-acid batteries (ULABs) are either discarded or recycled. Because of the toxic materials within these used batteries, the Basel Convention has included ULABs on its list of materials classified as hazardous waste [2]. However, since the environmental protection laws in developing countries are not strict, these batteries usually do not get disposed properly. Unregulated recycling industries and informal methods of extracting lead can cause high levels of environmental contamination.

3.2.4 Available Capacity

As explained above, the available capacity of a battery is determined by the charging and discharging rates. Typically, in backup systems, batteries are sized such that they can be fully recharged in five hours. This ensures the batteries would be fully recharged, if two consecutive power cuts are separated by a gap of at least five hours.

Inverter systems have an asymmetrical charge-discharge characteristic. Discharge currents can be very high and sometimes can be more than 10 times the charge current. Moreover, since the battery voltage (12 V/ 24 V) can be much smaller (1/20th or 1/10th) than the line voltage (230 V) required by loads, the discharge current must be correspondingly larger (20 times or 10 times) than the actual current drawn by the loads to maintain the same power rating (VA). Further, while charge currents are constant, discharge currents vary dynamically depending on load conditions.

The available capacity as a function of discharge current can be computed using Peukert's Law. However, this model doesn't include the recovery effect (when discharged intermittently, batteries can recover during idle periods) [20], an important feature of backup systems where batteries get charged and discharged to various depths as per the availability of mains supply and the energy requirement of loads. The Kinetic Battery Model (KiBaM) model [24] is more accurate since it accounts for (a) decrease in capacity with increasing charge or discharge rates, (b) recovery in charge, (c) increase of voltage with charging current and state of charge, and (d) decrease in voltage with discharging current and state of charge. The KiBaM uses a chemical kinetics process as its basis. In the model, as illustrated in Figure 5, the battery charge is distributed over two wells: the available-charge and the bound-charge wells. The available charge well supplies electrons directly to the load, whereas the bound-charge well supplies electrons only to the available-charge well. The rate at which charge flows between the wells depends on the difference in heights of the two wells, and on a parameter k. The parameter c gives the fraction of the total charge in the battery that is part of the available-charge well.

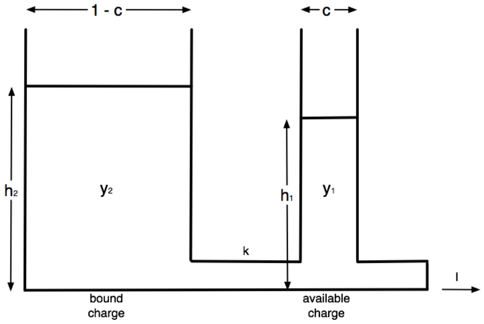

Figure 5: Two-well model used by KiBaM)

Computing Available Charge

The KiBaM model calculates available capacity as follows:

$$\begin{aligned} y_1 =& y_{1,0}.e^{-k't} + \frac{(y_0 k' c - I)(1 - e^{-k't})}{k'} \\ & - \frac{Ic(k't - 1 + e^{-k't})}{k'} \\ y_2 =& y_{2,0}.e^{-k't} + y_0(1-c)(1 - e^{-k't}) \\ & - \frac{I(1-c)(k't - 1 + e^{-k't})}{k'} \end{aligned} \tag{10}$$

where k' is defined as $k' = \frac{k}{c.(1-c)}$, and $y_{1,0}$ and $y_{2,0}$ are the amount of available and bound charge, respectively, at $t = 0$. And, $y_0 = y_{1,0} + y_{2,0}$.

Computing Terminal Voltage

The battery is modeled as a voltage source in series with an internal resistance. The level of the voltage varies with the depth of discharge. The voltage is given by:

$$V = E - IR_0 \tag{11}$$

where I is the discharge current and R_0 is the internal resistance. E is the internal voltage, which is given by:

$$E = E_0 + AX + \frac{CX}{D - X} \tag{12}$$

where E_0 is the internal battery voltage of the fully charged battery, A is a parameter reflecting the initial linear variation of the internal battery voltage with the state of charge, C and D are parameters reflecting the decrease of the battery voltage when the battery is progressively discharged, and X is the normalized charge removed from the battery. These parameters can be obtained from discharge data.

3.2.5 *Electrical Noise*

Most low-cost inverters are quasi sine wave (or modified sine wave) type inverters since they are cheaper to manufacture than the ones that supply pure sine wave voltage output. The output of the inverter (measured using the setup in Figure 3) is shown in Figure 6 and as shown, it only approximates sine wave output. During discharging, these inverters can have their capacities reduced when driving electronic loads since these loads demand current at the peak of the waveform. Since the waveform is more like a step, the current behavior is also more impulse-like generating higher harmonics. This can be a problem when powering sensitive electronic equipment or Hi-Fi audio. Although these quasi-sine wave inverters are being phased out by the large manufacturers, we have noticed that some of the cheap unbranded inverters still use this design.

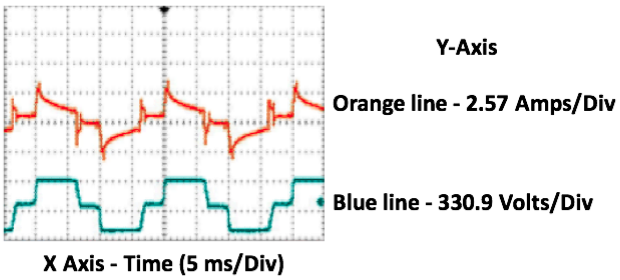

Figure 6: A quasi sine wave inverter powering a number of consumer electronics appliances. (Blue line represents the inverter output voltage and the orange line is the current drawn by the loads.)

4. SIMULATION RESULTS

In this section, we present the overall large-scale effects of the power cuts and battery backups observed in simulation. Firstly, using a multi-agent simulation system, we study the positive feedback effect of battery backups. Next, we analyze how the durations of power cuts and their frequency affect the battery life. Finally, we discuss the changes in grid stability as a function of inverter penetration using a power system simulator.

4.1 Feedback spiral of electricity deficit and battery backups

In this section, we discuss the positive feedback loop that exists between the energy deficit and battery backups. We study this aggregate effect using a multi-agent simulation.

4.1.1 *Simulation Setup*

Consumer segments: In simulation, we create a population of 1000 consumer agents and divide them uniformly into three consumer groups. Each group is assigned a set of configurable parameters: maximum total load, primary load, deferrable load, battery capacity and inverter/ battery efficiencies (rectification, inversion, and storage). The groups are assigned maximum total loads of 1 KW, 2 KW, and 3 KW. We categorize the consumer demand into three different categories: 1. Primary load - it includes the essential load like lighting, fans and some interactive appliances which can be run on inverter, 2. Deferrable load- it includes the loads like washing machine, water pumps etc. which can be time-shifted, 3.Non-deferrable secondary loads - it includes loads like air conditioner, refrigerator which are not time-shiftable and can be expensive to run on inverter. We assume primary loads to be 25% of total loads. The secondary load of a consumer is defined as difference of the respective total load and the primary load, and deferrable load is assumed to be 30% of secondary load.Based on the percentage of inverter penetration, a subset of consumer agents are assigned inverters with operating parameters that match the primary load requirements of the corresponding consumer agents.

Demand Modeling: The original consumer demand of electricity at every time step (1 minute) is computed using a parameter: time of use probability, that determines the amount of electricity a customer would be using at a specific time of the day. We use the residential demand pattern as a bimodal distribution with one peak occurring in the morning and the other in the evening as specified in [29]. At every time step, if there is no power cut for a given consumer, its original demand is added to the total load on the grid. If the consumer has an inverter and if the attached battery needs recharging, that charging requirement is added to the grid load. Similarly, if there are any deferred loads due to the previous power cuts, those are also added to the load served by the grid. This total demand that is the sum of original, charging and deferred loads is referred to as *actual demand*. In case of a power cut, if a consumer agent has an inverter with a sufficiently charged battery, that consumer's entire primary load would be served by the inverter.

Supply Capacity Modeling: The capacity of the electricity supplier at each hour is a configurable property. For generating different scenarios with different peak power deficits and energy deficits, different supply capacities are allocated to hours across a day.

Shortage calculation: The shortage for every hour is computed as the difference between total demand (Sum of original, charging and deferred loads. The latter two can be zero, if there were no recent power cuts.) and the available capacity at that hour.

Power cuts: The decision to cut power is determined based on the computed shortage for that hour. Based on the percentage of shortage, a subset of consumers are randomly (over uniform probability distribution) selected from each of the consumer groups. This ensures required power cut spread uniformly over different consumer groups.

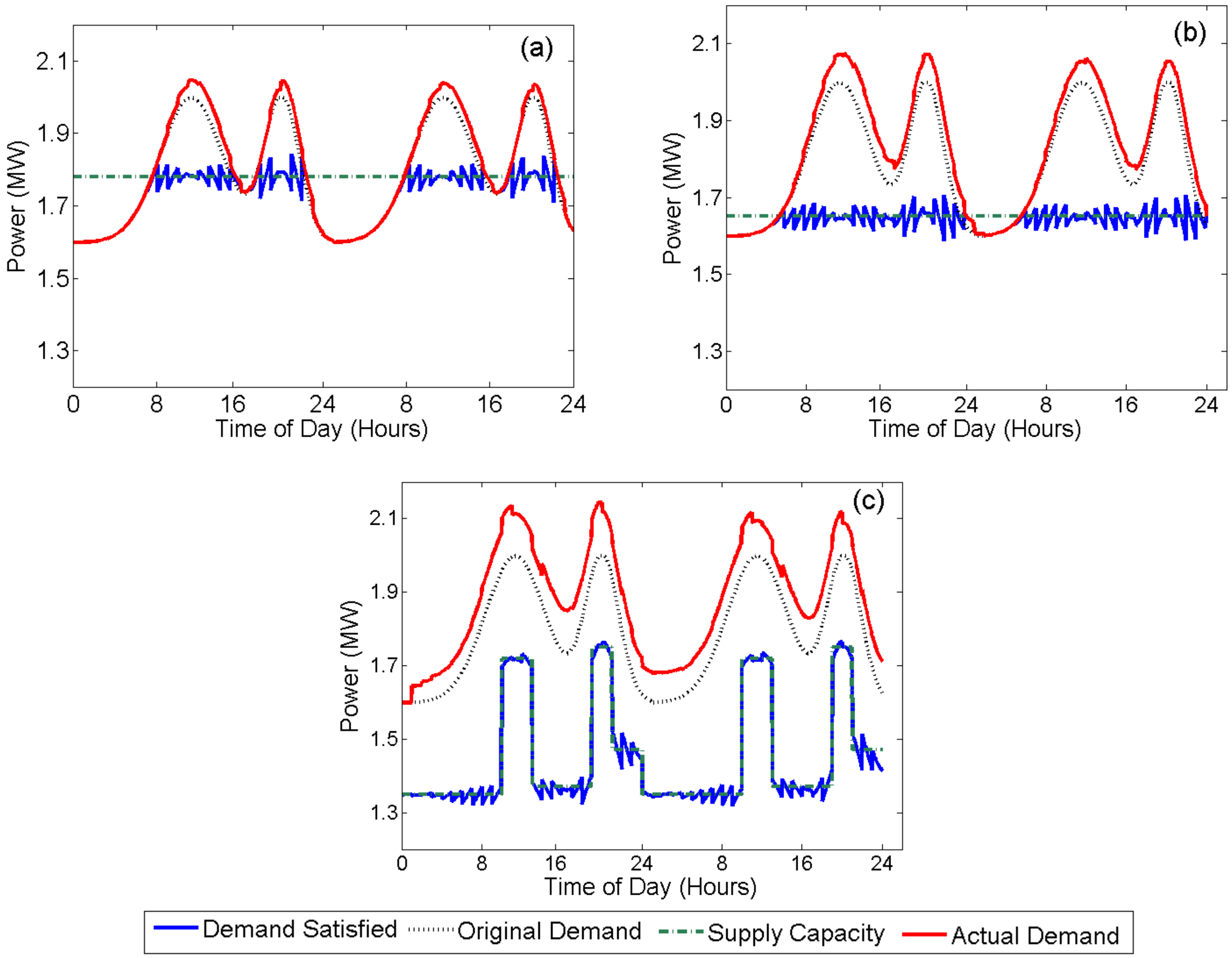

Figure 7: Multi-agent simulation of 1000 consumers with 20% inverter penetration for three different scenarios - (a)Scenario 1: No energy deficit, Peak power deficit - 10%, (b)Scenario 2: Energy deficit - 8%, Peak power deficit - 15%, (c)Scenario 3: Energy deficit - 18% Peak power deficit - 13% (Real-world Scenario of Feb, 2013 in Tamilnadu state, India [7])

Inverter	Scenario 1		Scenario 2		Scenario 3	
Penetration (%)	Avg. Power Cut Hours	Losses (%)	Avg. Power Cut Hours	Losses (%)	Avg. Power Cut Hours	Losses (%)
0	1.025	0	2.427	0	5.825	0
10	1.090	0.096	2.577	0.209	6.091	0.456
20	1.139	0.182	2.685	0.411	6.334	0.934
30	1.174	0.274	2.779	0.631	6.577	1.445
40	1.217	0.372	2.893	0.869	6.806	1.982

Table 1: The effect of different % inverter penetrations on average number of hours of power cut per consumer and energy deficit (due to inverter losses) considering three different scenarios.

Losses calculation: We take into consideration three types of losses: rectification loss, inversion loss, and storage loss. We calculate these losses using rectification, inversion and storage efficiencies that are usually around 80%, 80% and 90% respectively. For every unit of energy served by an inverter, effectively 1/.8 (=1.25) units will be drawn by inverter from battery. This leads to 25% of inversion loss. Similarly for every one unit of usable energy to be drawn from battery, 1/.9 (=1.11) units of energy will need to be stored. So, this amounts to total storage losses of .11*100/.8 = 13.75%. On top of these, there will be additional (.25*100)/(.8*0.9) =34.77% of rectification losses in for every unit of usable energy drawn, to effectively put back one unit of charge in the battery. These three losses together sum up to 76.52%.

4.1.2 Evaluation

To study the effect of power cuts and increasing inverter penetrations in different energy deficit scenarios, we run the simulation for multiple combinations of peak power deficit and energy deficit. For each scenario, we run the simulation for inverter penetration values of 0,10,20,30, and 40%.
We consider following scenarios:
Scenario 1: No energy deficit, Peak power deficit - 10%

Scenario 2: Energy deficit - 8%, Peak power deficit - 15%
Scenario 3: Energy deficit - 18% Peak power deficit - 13% (Real-world Scenario of Feb, 2013 in Tamil Nadu state, India [7]).

Figure 7 represents the supply and demand situation for a multi-agent simulation of 1000 consumers with 20% inverter penetration considering three aforementioned scenarios. The dotted black line represents original demand in the absence of power cuts, based on ToU probabilities. The green dotted line specifies the supply capacity. If the original demand is greater than the supply capacity at that time, the power cuts are initiated and the thick blue line shows the demand satisfied. As a consequence of prior power cuts, some of the deferrable loads and inverter charging loads get accumulated and add to the original demand. This actual demand is represented by the red line. Even for a moderate (20%) level of inverter penetration, for the scenarios with and energy deficits, Figure 7 shows that the accumulated demand (due to earlier power cuts) is significantly higher than the original demand. This aggravates deficit, causing additional power cuts.

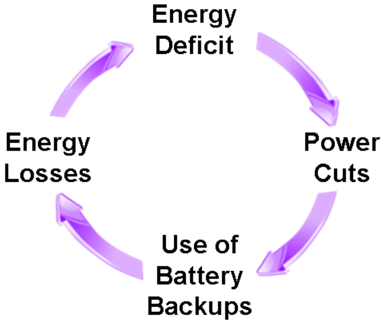

Figure 8: Feedback loop: energy deficit and battery backups

We further evaluate the effect of different inverter penetration values on this feedback loop by observing two parameters: *average power cut duration per consumer per day* and *% of energy losses with respect to the original demand.*

As shown in Table 1, the average power cut duration increases with increase in inverter penetration. This is primarily because of the unscheduled charging of inverters. When power comes back after a power cut, all the inverters start charging simultaneously, aggravating deficits leading to additional power cuts. Moreover, the energy losses increase drastically with every 10% increase in inverter penetration. Additionally, as shown in Table 1, impact of increased inverter penetration becomes more significant with increase in energy deficit. We found that in absence of energy deficit even at high levels of inverter penetrations, losses incurred are less than 0.4%, which may not be significant. Therefore, in absence of energy deficit even if peak power deficit exists, inverters can be used to alleviate peak loads. However, loss percentages go up to 2% when 18% energy deficit preexists. So, in the case of pre-existing energy deficit, increase in inverter penetrations adds to the deficit, leading to larger number of power cuts.

Increased duration of power cuts and energy losses together cause a spiral effect as shown in Figure 8. With the increase in average power cut duration, the load getting served by inverter increases. Increased inverter loads cause more energy losses. As supply capacity remains same, more losses results in greater energy deficit that leads to even more power cuts. This spiral effect becomes more prominent in presence of high energy deficit that exists in India, adding to the seriousness of the matter in the long run. Also, additional power cuts can potentially increase inverter penetration [13], thereby worsening this effect. An important social consequence could be the subset of population that can afford inverters may end up depriving energy for the others who cannot afford them.

4.2 Impact of power cuts on battery life

In this section we analyze how the duration of power cuts and the frequency (consequent interval between two power cuts) affect the life of batteries.

4.2.1 *Power cut duration and discharge current*

As explained above, a battery can go through a certain number of charge-discharge cycles (called cycle life) before it loses its capacity to store energy. The cycle life depends on the Depth of Discharge (DoD) per cycle. The DoD in turn depends on the duration of power cuts and/or the load levels during those power cuts. To illustrate this effect, we studied a model (KIBAM [24]) battery with 200 Ah capacity. As illustrated in Figure 9, we varied the duration of power cuts with three different constant (for the duration of power cuts) discharge currents. As shown, the cycle life decreases rapidly with the duration and/or the current levels.

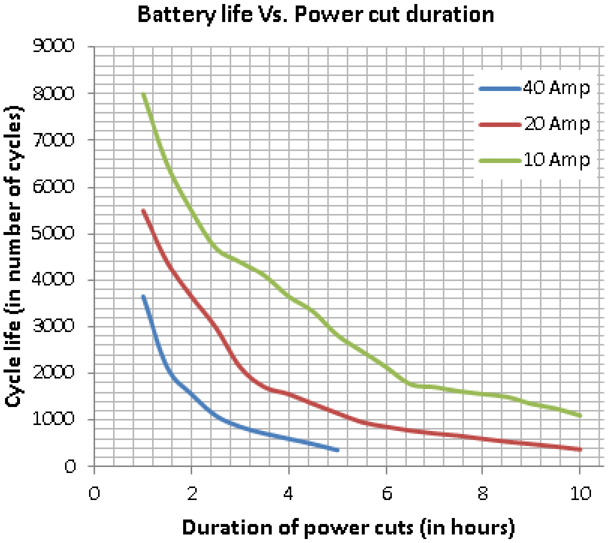

Figure 9: Relationship between duration of power cuts (with different discharge currents) and battery life.

4.2.2 *Recovery duration*

The time interval between two consecutive power cuts determines the amount of time a battery gets to recover and recharge itself. This recovery actually adds to the total available capacity [24]. To understand this effect, we studied a model (KIBAM [24]) battery with 100 Ah capacity and explored the impact of recovery duration with constant charge (20 Amps - corresponding to C/5) and discharge (40A[5] currents for different durations (50 - 70 mins) of power cuts. As illustrated in Figure 10, the battery life increases rapidly with increase in recovery duration and conversely, decreases with decrease in recovery interval.

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[5] As explained above, the AC current supplied to loads could be much smaller as the voltage needs to be stepped up to 230 V from the battery terminal voltage.

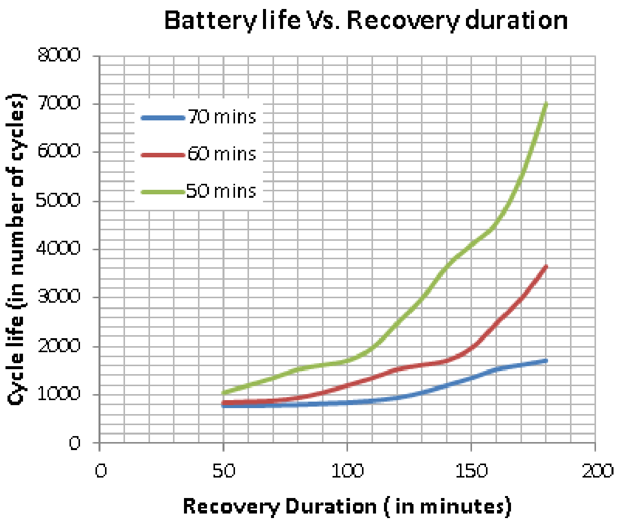

Figure 10: Relationship between recovery interval (with different power cut durations) and battery life

4.3 Impact of Inverters on the Grid Stability

Increase in inverter penetration leads to decreased voltage stability and frequency stability. The former happens due to reactive power shortage caused by battery charging systems that are not power factor corrected and the latter happens because of the supply-demand imbalance caused by aforementioned energy losses. In this section, we study these stability issues in simulation using a benchmark IEEE 300 bus system which is the largest openly available system [18]. This system includes 300 substations, 304 transmission lines, 199 load buses, 107 transformers and 69 generators. This system could be a good representative of Northern Region Electricity Broad (NREB, India) system having 390 buses. For simulation purpose, inverters were assumed to be placed at all the load buses. Inverter loads were assumed to be composed of two components: battery charging load and inverter losses. Battery charging load was assumed to be proportional to the overall load on that bus. We simulated four types of inverters having efficiency of 60%, 70%, 80%, and 90% respectively. Simulations were made for the worst case scenario when all the inverters get charged simultaneously just after when power got restored following a power cut.

Real and reactive power equations with inverter load are represented as follows:

$$\begin{aligned} P_k &= P_g - (P_d + P_{inv}) \qquad (13) \\ Q_k &= Q_g - (Q_d + Q_{inv}) \qquad (14) \end{aligned}$$

$$P_k = \sum_{j=1}^{N} |V_k||V_j| \left(G_{kj} cos(\theta_k - \theta_j) + B_{kj} sin(\theta_k - \theta_j) \right) \qquad (15)$$

$$Q_k = \sum_{j=1}^{N} |V_k||V_j| \left(G_{kj} sin(\theta_k - \theta_j) - B_{kj} cos(\theta_k - \theta_j) \right) \qquad (16)$$

where P_k and Q_k are active and reactive power injections, respectively at node k.
P_{inv} is inverter load, P_g and Q_g are active and reactive power injections, respectively. V and θ are voltage magnitude and voltage phase angle respectively. G_{kj} and B_{kj} are the conductance and susceptance, respectively for the line between nodes k and j.

These set of equations are solved iteratively using standard fast decoupled load flow method which calculates voltage stability, frequency stability and network losses in the system.

4.3.1 *Voltage instability*

In general voltage stability is determined from PV (Active power-Voltage) characteristics [36] of the system. At the ”knee” of the PV curve, voltage drops rapidly with an increase in MW transfer due to inverter penetration. After certain percentage of inverter penetration, voltage falls rapidly and finally, system becomes unstable. This effect is characterized using an index called voltage stability index (VSI) [30] as defined bellow:

$$V_{si} = \frac{\partial P_i / \partial \delta_i}{\sum_{j=1 j \neq i}^{n} B_{ij} V_j} \qquad (17)$$

Where, n is number of buses in the system, P_i is real power injection at bus i, V_i is magnitude of voltage at bus i, δ_j is phase angle of voltage at bus j and B_{ij} is element of network admittance matrix. During normal condition VSI value is close to 1 and with the increase in stress VSI value reduces and grid collapse occurs at VSI value of 0.5. Figure 11 illustrates how VSI changes as a function of penetration of inverter load and inverter efficiency.

Figure 11 shows that inverters with 60-90% efficiency, VSI gradually decreases until 20% penetration and beyond 20% VSI starts decreasing drastically and the grid becomes unstable at 25% penetration. This happens because of nonlinear effects caused by inverter penetration. Similarly, for inverters with 80-90 % efficiency, VSI gradually decreases until 25% of penetration and the grid becomes unstable at 30% of penetration. It shows that the grid can sustain higher level of inverter penetration, if inverters are efficient.

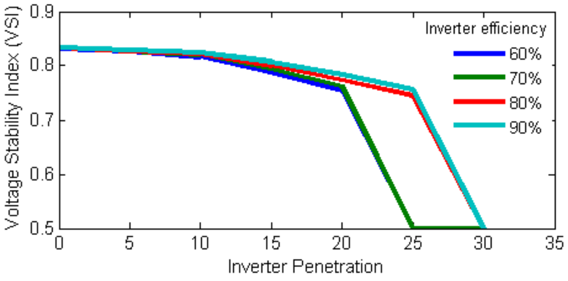

Figure 11: Voltage stability with penetration of inverters

4.3.2 *Frequency stability*

We also studied the effect of inverter penetration on grid frequency. As inverters create additional load on the grid, and generators can not increase their out put immediately, a power mismatch happens in the grid. This power mismatch is responsible for frequency dip in the system. Normally, for a 50Hz system, tolerable frequency range is between 49.5 Hz and 50.5 Hz.

Figure 12 shows how grid frequency changes with inverter penetration and inverter loss. Figure 12 shows system frequency gradually decreases until 15-20% of inverter penetration and thereafter frequency dips very fast. This happens because initially generators meet the extra load using stored kinetic energy in the flywheel and beyond certain point generators fall short of sufficient kinetic energy and frequency dips very sharply. Simulation results show that the grid can safely sustain only 21-27% of inverter penetration depending on inverter efficiency.

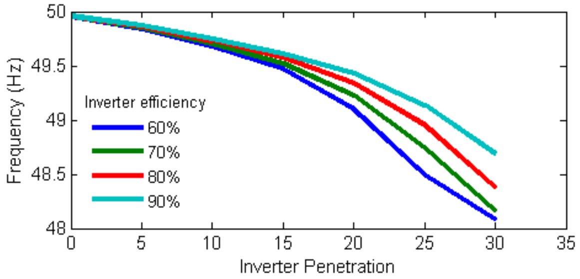

Figure 12: Frequency stability with penetration of inverters

4.3.3 Network loss

We also studied how network loss varies with inverter penetration. This is an important aspect because inverter penetration can magnify this loss considerably. As network loss is proportional to $I^2 \times R$, cumulative network loss highly depends on peak to average current. As discussed in previous section, inverter penetration increases peak to average ratio which effectively increases loss in the network. Figure 13 presents how network loss varies with inverter penetration. It can be seen from the figure that beyond 15% penetration, network loss increases almost exponentially.

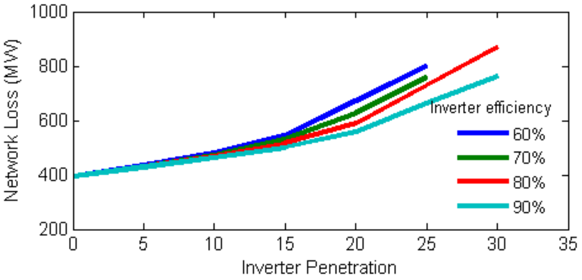

Figure 13: Network loss with penetration of inverters

5. RELATED WORK

Since ability to accommodate all types of distributed storage options and renewable energy sources is one of main characteristics of smart grid [23], there has been a great interest in understanding the impact of various energy storage technologies on the power grid. The existing body of work can be broadly classified into four categories: understanding the impact of power cuts, Vehicle to Grid (V2G), understanding the impacts of Electric Vehicles (EVs) on the power grids and grid-wide storage systems.

5.1 Impact of Power Cuts

Fisher-Vanden [12] present the impact of power cuts on the productivity of industrial consumers and on the environment in the context of developing countries like China. Wartsila corporation conducted a study that examines the severity of power outages in these cities and the different ways consumers deal with these outages. The study quantifies the costs incurred by consumers who invest in power back-up mechanisms - both initial as well as operating costs [37].

Our focus is different: we study the systemic effects of power cuts and of battery backups.

5.2 Vehicle-to-grid (V2G)

Vehicle-to-grid (V2G) describes a system in which plug-in electric vehicles communicate with the electricity supplier to provide demand response services by either injecting some of the energy stored in their batteries into the grid or by throttling their charging rate. Kempton et al [21] present systems and processes required for implementing V2G. Tomic et al [32] discuss how battery-electric vehicles can provide regulation services to a specific electricity market and evaluated the economic potential of two utility-owned fleets of battery-electric vehicles to provide regulation services in four US regional markets.

The focus of V2G literature is different from ours in the following ways: their main objective is to analyze how V2G power could be sold to high-value, short-duration power markets such as regulation, spinning reserves and peak load when there is an explicit request for such services from the grid operator. On the other hand, we focus on uncoordinated inverter backups that recharge themselves whenever they require and whenever the mains supply is available.

5.3 Grid-wide Energy Storage

Future electrical grids are expected to include significant dedicated energy storage elements at different locations: they may be installed at generating stations to smoothen variations in the intermittent sources, in the transmission networks to even out peak transmission loads, or at substations and feeders in distribution networks to absorb variations in electrical loads [11, 19]. Ardakanian et al [1] study the effect of storage on the loading of neighborhood pole-top transformers. Using the techniques developed for sizing buffers and communication links in communication networks, the authors compute the potential gains from transformer upgrade deferral due to the addition of storage.

Similar to V2G storage, the charging and discharging of these dedicated storage elements will be coordinated by electricity suppliers. As a result, these grid-wide storage technologies will not introduce the unintended consequences like the inertia backups.

5.4 Impact of Electric Vehicles

Several researchers have analyzed the impacts of electric-drive vehicles (such as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs)) charging on the power grids. Putrus et al [28] analyze the impact of EVs on power distribution networks using a typical distribution network that is serving a demand profile that usually occurs in Europe. Clement et al [9] analyze the potential impact of PHEVs on the Belgian distribution networks. Hadley et al [16] analyze the potential impacts of PHEVs on electricity demand, supply, generation structure, prices, and associated emission levels in 2020 and 2030 in 13 regions specified by the North American Electric Reliability Corporation (NERC). Hadley et al [15] conduct an analysis of what the grid impact may be in 2018 with one million PHEVs added to a region of the USA that includes South Carolina, North Carolina, and much of Virginia.

Impact of electric vehicles is primarily dependent on the local driving patterns. On the other hand, the impact of inverter backups is mainly a function of grid deficit and involves a positive feedback loop. In other words, more consumers invest in inverters when the power cuts increase; power cuts become more frequent and/or longer with increase in energy and power deficits; the inverters worsen the energy deficit through conversion losses and power deficit by charging whenever the mains supply is available. Moreover, as the number of power cuts increase, these backups will be forced into a higher number of charge/discharge cycles despite their limited durability and higher cost per kWh of electric energy. As a result, the consumers also stand to lose.

To summarize, the existing body of work has not analyzed the impact of power cuts and battery backups in detail as presented in this paper.

6. DISCUSSIONS AND FUTURE WORK

The developing countries such as India are likely to struggle with power shortages for the next several years unless electricity generation (central or distributed) capacity is increased drastically to match the exploding demand [17]. The power deficit could worsen when electricity grid is expanded to the unserved communities in these countries [6]. As a result, power cuts and battery backups will continue to be an integral part of these geographies. The impact analysis presented in this paper could be used to assess the various costs incurred by the society and electricity suppliers in these situations. It is important to note that many of these costs will remain relevant even if high-efficiency ($> 95\%$) inverters and low-loss ($< 5\%$) batteries become available because rebound effects experienced by the suppliers and inconvenience costs to consumers cannot be eliminated by those advancements.

The costs incurred by the different stake holders could increase exponentially with the duration of power cuts and the number of backups employed. Given that, when the inverter penetration becomes significant, the impact analysis could be used as a basis for designing solutions and setting policy mandates. A few specific recommendations could be:

- Electricity suppliers could manage the charging schedules of batteries through centralized technologies such as Demand Response programs [34] or through decentralized technologies such as nPlugs that can sense the grid conditions locally without any explicit communication from the suppliers[14].

- Electricity suppliers could introduce time-of-use pricing mechanisms to discourage consumers from charging the batteries during peak hours. Without such a differential pricing structure, the consumers and inverter manufacturers have no economic incentives for maintaining grid-friendly charging schedules.

- Consumers can demand more details about and controls over charging/discharging schedules of their battery backup so that they can optimize its operational characteristics. For instance, a small LCD display could provide various details such as state of charge, average discharging rates, etc; and a control user interface (even simple buttons and knobs) could be provided so that the consumers can control charging schedules, maximum discharge rates, etc.

- Government agencies such as BEE [3] could enforce strict efficiency standards for inverters and batteries.

- Governments, instead of attempting to curb the use of inverters [25], can mandate that a certain percentage of every inverter's capacity must supplied by renewable energy sources at the site.

We are considering several future extensions to our work. Firstly, we plan to study a much larger number of backup system configurations: inverters (capacities, conversion efficiencies, etc), chargers (charging rates, charging patterns, etc) and batteries (capacity, charge/discharge characteristics, etc). Secondly, while measuring the inconvenience cost of consumers, we are attempting to include richer models of electrical appliances such as the one proposed by Li et al [22]. Thirdly, do a cost-benefit analysis between a government providing subsidies to encourage local energy generation and incurring various costs in such backups. Finally, we are hoping to establish a framework for optimizing the charging/discharging schedules for a given level of inverter penetration and power/energy deficits. However, optimizing for a large number of inverters with different load characteristics may not be straightforward since the optimizer would require fine-grained real-time performance characteristics of the backup systems. Moreover, these characteristics could change with ambient temperature, number of charge/discharge cycles, power quality, etc.

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