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Enabling electricity access in developing countries: A probabilistic weather driven house based approach

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HIGHLIGHTS

- Alternative optimized solution to power interruption problem due to power generation shortage.
- A probabilistic weather driven house based approach to enable electricity access in developing countries.
- Effect of residential houses growth on enabling electricity access.
- Conservative voltage reduction effect on enabling electricity access.
- Power distribution utility's economic benefit maximization.

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ABSTRACT

Meeting the growing electricity demand in many developing countries is a major challenge as there is a shortage in power generation. This paper proposes a novel strategy for mitigating the effect of weather intermittency on the scheduling power interruption of residential houses. The proposed method involves optimal scheduling strategy for the electricity supply of these houses in a distribution grid and weather temperature prediction using a probability paper plot is deployed. Data training is achieved through the Monte-Carlo Simulation, and the prediction model is validated through error analysis. Using this method, novel power interruption schedules, based on maximizing houses' accessibility to electricity and considering consumers' fairness of accessing electricity services on hourly basis, have been designed. The design considers two optimization problems, scheduling electricity supply and validating the schedule in the power distribution grid by ensuring no violations of grid operational requirements. Moreover, a sensitivity analysis has been conducted to investigate the effect of scaling up the demand from the house context on enabling electricity access to such houses. The effect of conservative voltage reduction schemes on energy consumption reduction has also been explored. The studied results demonstrate the effectiveness of the proposed method in enabling electricity access of new regions accommodated in the grid by up to 47.6% which increases the profit of the power utility from residential electricity bill payments.

1. Introduction

Developing countries are facing the challenge of meeting electricity demand because of two reasons; firstly the growth in electrification rate and household energy consumption, and secondly, the unofficial electricity supply of many houses [1–3]. The situation in Maharashtra, a state in India provides a prime example of this challenge, where the electricity demand is expected to grow from 106.643 TW h in 2007 to 167 TW h by 2017. Moreover, the peak load is expected to reach 28347.752 MW in Maharashtra by 2017 [4]. Similarly, the electricity demand was 697.961 TW h across India in 2007. Such a demand is expected to reach 1392 TW h by 2017[4]. Loads forecasts are considered to be inaccurate in many developing countries since these forecasts ignore the reduction in poverty where for the first time, typically low income communities are now able to purchase appliances [5–7].

In many developing countries, the generation capacity falls below the total connected loads. In Maharashtra [8], the electric power demand exceeded the available power generation where the deficiency gap varied between 17.7% and 23.7% between 2005 and 2007. This power generation deficiency still remains a problem restricting the development of these countries as the work in [9] indicates that the energy demand is growing at a rate

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that is coupled with the economic growth resulting in constraints affecting social and economic development. The problems caused by such a deficiency are severe as noticed in [10]. Ref. [11] showed that power cannot be supplied for durations that can reach 12 h daily in many regions [12]. The negative gap between the generation and the demand had led to a situation where 34.5% of Indian's population lives without electricity [5,13,14]. On the other hand, Pakistan consumers of electricity encounter power cuts up to 20 h daily [15] as the shortfall in electricity is 4500 MW [16]. Consequently, approaches to minimize the severity of the problem has been addressed in practice or discussed in literature from the customer perspective and the power distribution utility perspective.

From the customers' practical perspective, approaches have included restricting the feeder's loads in specific areas to a percentage of the actual value by preventing electricity theft and utilizing efficient home devices as main actions to supervise the demand and prevent transformer breakdown [2,11]. However, not all consumers can afford the costs of replacing their current devices with more efficient devices.

With population growth, there is a demand to connect new regions to the grid. The current approaches practically applied by the power distribution utility to minimize the severity of the power generation shortage problem are to leave this new area un-electrified [5,13], supply 10% of the households in the village so that the village is recognized to be an electrified area as in [2,17,18] or to follow a power interruption scheme [2,19]. The latter is represented by a cycling power cuts' schedule over the grid's zones for specific times that do not overlap, and is a method of minimizing the total load connected to the grid and avoiding grid blackout [2,20]. The power cuts' schedule is a critical issue in in India where it can vary between 10 and 12 h daily in many regions [21]. The cycling power interruption has been experienced also in Korea in 2011 due to a peak demand causing economic losses [22]. Solutions to this problem could be building power plants or a smart grid technology based on charging residential energy storage systems (ESS) from electric vehicles [22]. The first option raises concerns on limited resources, environmental impact and capital costs [22]; while the second option is not suitable for poor developing countries as such a technology is not yet deployed. Moreover, the power interruption during peak load hours was studied through a fuzzy system approach in [23] neglecting studying results at the grid operational level that is accounted for in this work.

A demand response approach reflecting the roles of the utility and the customers in minimizing the power interruption at no incentive had been applied in the past in India in the form of the Akshay Prakash Yojana program [24]. Nevertheless of its effectiveness in reducing electricity peak demand, it was stopped due to the difficulty of long term supply of a guaranteed electricity subject to a demand reduction by 20% [24]. Another constraint on this program was its operation at the feeder's level rather than individual houses' level driven by the weather uncertainty discussed in this work. Also, the program would form a constraint on the other villages to take an advantage of it as governed by the perception of the first village in a similar concept to the cycling power cuts. This problem will be solved in this paper as such a constraint is not set. It is important to emphasize that regardless of the demand response option [24], the idea of demand side management is still a new topic for the Indian power sector [12].

Deciding the power interruption level in a short time planning horizon of few hours based on a solution of robust policies for studying possible feeder's failure or planned power outage was introduced in [25]. However, this type of study did not focus on a daily power generation deficiency style, did not consider the possibility of grid extension and its interference with any planned power outage, did not apply the long time planning horizon of power cuts due to a generation shortage and might not be applicable for consumers lacking the knowledge of weather driven devices' energy consumptions. Therefore, the effect of weather on scheduling power interruption and thus electricity supply will be studied in this paper.

An alternative approach to deal with the power generation deficiency in developing countries is to reduce the electricity demand of the distribution grid's feeders though the conservative voltage reduction method. This method had been discussed in literature in [26–29]. By conservative voltage reduction, it is possible to bring down the voltage levels on the system to a permissible levels to reduce the peak demand and save energy [26,27]. The advantages and disadvantages of the conservative voltage reduction were discussed in [28,29] along with the theoretical applications. Moreover, the techniques of quantifying the conservative voltage reduction and such reduction types were reviewed in [26]. In this paper, the concept of conservative voltage reduction will be applied to utilize the gap in the power reduction to accommodate more loads in a new context of individual houses' power interruption governed by the weather uncertainty.

The concept of power interruption was investigated in literature for other purposes rather than addressing the power generation shortage. In literature, it was introduced for the purpose of grid operational management such as increasing the grid's frequency stability through a cyber control [30] and ensuring the frequency when power generation/demand imbalance exists [31]. The power interruption due to an unfavorable reduction or an increase in the grid's reactive power was minimized in [32] through optimally allocating a static VAR compensator and a static synchronous compensator in the grid. The power interruption was also minimized in [33] by optimally allocating a series controller of the unified power flow controller in the grid for its protection. The power interruption was carried out in [34] to prevent the issue of voltage instability through swarm optimization methods with the use and the absence of a unified power flow controller. The power interruption was also applied for a micro-grid's power management as in [35] where the interruption compensation bid in a micro-grid with electric vehicles was studied. Plug in hybrid electric vehicles were also used in [36] to minimize the power interruption through a charging power control. The power interruption was also introduced in transmission and sub-transmission networks for transmission security under system expansion with wind penetration at low cost [37] and for studying the voltage during fault conditions and the reliability [38,39], respectively.

Planning the power interruption is subject to uncertainty in electricity generation and demand. The uncertainty of the feeding and consuming sides were discussed in [40–42]. From the demand side, a physical statistical method was presented in [43] to model and forecast it for various buildings; while [44] focused on forecasting the cooling energy demand of commercial buildings. From the power generation side, the weather uncertainty drives many generation sources and reflected on their allocation and sizing toward minimum grid losses [40–42]. Models for energy forecasting suitable for buildings with energy systems were established and verified in [45] without studying the impact of energy systems and demand variability on the grid operation. On the other hand, the weather temperature uncertainty is a factor affecting the consumers' perception to utilize electricity as it drives many appliances' operation. In [46], a day ahead scheduling of buildings' energy systems with PV and ESS was studied to minimize operational costs. Although generation and demand were forecasted in [46], the study did not schedule residential demand under the stochastic weather nature. An attempt to estimate energy sharing between buildings clustered based on energy demand was discussed in [47]. The study accounted for uncertainties in the indoor