i13DR: A Distributed Real-Time Demand Response Infrastructure for Integrating Renewable Energy Resources

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ABSTRACT

With the ongoing integration of Renewable Energy Sources (RES), the complexity of power grids is increasing. Due to the fluctuating nature of RES, ensuring the reliability of power grids can be challenging. One possible approach for addressing these challenges is Demand Response (DR) which is described as matching the demand for electrical energy according to the changes and the availability of supply. However, implementing a DR system to monitor and control a broad set of electrical appliances in real-time introduces several new complications including ensuring reliability and financial feasibility of the system. In this work, we address these issues by designing and implementing a distributed real-time DR infrastructure for laptops, which estimates and controls the power consumption of a network of connected laptops in response to the fast irregular changes of RES. The result of our field experiments confirms that our system successfully schedules and executes rapid and effective DR events. However, the accuracy of estimated power consumption of all participating laptops is relatively low, directly caused by our software-based approach.

KEYWORDS

Smart Grid, demand response, demand side management (DSM), load management, power modelling

1 INTRODUCTION

Reduction of greenhouse gasses is one of the significant concerns of the global community, where the continuous development of Renewable Energy Sources (RES) plays a crucial role. However, integration of RES into existing transmission and distribution grids is challenging. One main issue is the fluctuating nature of RES which increases the complexity and vibrancy of the power grids [6]. One approach for addressing these issues is Demand Response (DR), where the demand for the electrical energy is matched with the available supply [3, 5]. Participation of a large number of electric appliances on the demand-side plays a crucial role in the implementation of a robust DR infrastructure. However, managing a large number of distributed devices requires a sophisticated and resilient system. This complexity increases with the integration of immediate fluctuating RES. One other challenge is providing the demand-side participants with attractive incentives to join the DR system. The participants are required to initially pay for enabling their appliances with power measurement and control devices, as well as communication systems. This initial cost discourages several potential participants, especially for residential consumers who might not receive a significant financial gain from participating in the DR events [1].

In this work, we propose a design and implementation of a distributed responsive DR infrastructure for balancing the power consumption of a network of laptops with the intermittent supplies of RES in real-time. The primary reason for selecting laptops as our target appliances are the extensive prevalence of laptops in the everyday use. Furthermore, we use the resources of laptops to offer an entirely software-oriented approach for performing DR tasks and events, including monitoring, estimating, and controlling the power consumption of laptops and interacting with the utilities, which dramatically reduces the initial cost for demand-side participants to zero cents.

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2 RELATED WORK

Several studies confirm DR as a useful solution for addressing the issues of integrating the fluctuating RES to the distribution grid [2, 4, 7]. In [2], authors offer an approach for optimizing integration of RES to the grid by using energy management systems and offering real-time pricing, where the simulation study yields real results for matching the demand with available RES. In [4, 7], the authors offer a scheduling and optimization approaches for maximizing the benefits of DR in the presence of volatile RES and reducing the electricity cost. Their simulation study also confirms DR as a good candidate for integrating RES to the grid. We extend the previous works by implementing a real-world DR infrastructure where different optimization and scheduling can be realized through field experiments.

3 DESIGN AND IMPLEMENTATION OF I13DR

The proposed i13DR design consists of two major parts, a demand-side manager application, which we call *i13DM*, and a bundle of server-side applications that manage the DR system, that we refer to as *i13DRP*, as Figure 1 shows. We design and develop i13DM to encapsulate the fundamental functionalities for performing DR events efficiently, including the features for measuring and limiting the power consumption of laptops, and communicating with i13DRP. i13DM is distributed as a cross-platform Windows and Ubuntu applications. On the sever sides, i13DRP consists of two primary subsystems, the DR provider, and the real-time database. The DR provider is responsible for managing the laptops and communicating with RES for inquiring the availability of supply. Furthermore, i13DRP performs the scheduling and executing the DR events with

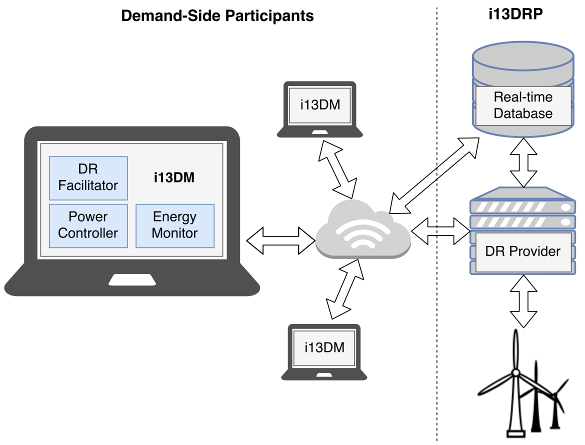

Figure 1: Overview of i13DR infrastructure design.

the cooperation of real-time database. The real-time database persists the DR related data and can distribute the data in real-time.

For performing the DR related activities, i13DR relies on two primary datasets of *Location Profiles* and *Power Profiles* of laptops which the i13DMs provide and continuously update. Location profile provides the i13DRP with an approximate location of the laptop during the week. Power profile of each i13DM provides an estimate of laptops' power consumption in standard mode and power save mode during a week. We define the power save mode as the time when the i13DM activates the load control mechanism on the laptop to reduce the power consumption which we achieve by taking advantage of the power saving functionalities of the OS. We require, managing the profiles because we assume people follow a weekly routine, e.g., the laptops are located five days a week at the users' works. Thereby, we can create context-aware DR events depending on the requirements of the grid in different locations. Furthermore, we use regression models to estimate power consumption of laptops in real-time based on the reading of system metrics of the laptops. These regression models are trained on a System Under Test (SUT) beforehand, and we deploy them on the participating laptops. Furthermore, the source code is open-source and freely available[1].

4 SOFTWARE DEMONSTRATION AND EVALUATION

To demonstrate the i13DR DR scheduling abilities, we offer a scheduling mock-up component for i13DRP where the administrator can schedule and manage multiple DR events and monitor the participating laptops. Because we do not connect i13DR to any RES supplies, the mock-up component simulates the behavior of a wind turbine integrated with the local power grid. For planning a DR event, the administrator first determines the position of the wind turbine. Afterward, the administrator specifies the expected reduction of wind turbine's electrical output in watts. Once the administrator provides all the required inputs, i13DRP starts the scheduling procedure. First, i13DRP queries all the currently online laptops to find the laptops located within a 1000 meters radius of the provided location of the wind turbine. Next, for each retrieved laptop, i13DRP fetches the power consumption profiles from 20 minutes before the start time of the DR event up to the start time. Then, i13DRP accumulates the reported difference of the real power consumption in normal power mode and power save mode to have an estimate of the amount of power one specific laptop can contribute to power reduction. Finally, i13DRP creates a schedule which immediately starts and lasts as defined by the administrator. When all the schedules are created, i13DRP submits the schedules to the real-time database to be downloaded by i13DM on the selected laptops. Afterward, the i13DMs fetch the new schedule and activate and deactivate the power control according to the new timetable. Moreover, the i13DMs send a status code announcing that they either joined or left the DR event, which can be observed by the administrator.

To evaluate the performance of the system, we used the scheduling mock-up to conduct five DR events with three fully charged laptops which were connected to power meters. The evaluation of our experimental events verifies that our system successfully schedules and executes DR events. Furthermore, we construct power models for estimating the power consumption for laptops with min/max accuracy up to 95% on Ubuntu and 85% on Windows on the SUT. However, the accuracy of the estimation of demand load reduction is about 67% indicating rather low reliability. The main reason for the low accuracy is our entire software-based approach which sacrifices high accuracy for the sake of eliminating initial DR costs.

5 CONCLUSIONS

In this paper, we offer a design and an implementation of DR infrastructure for integrating the fluctuating RES into the grid. Furthermore, our approach offers no initial cost for demand-side participants which are laptops, and our system can be used as a testbed for researching different scheduling and optimizations approaches.

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