Dynamic forecasting and adaptation for demand optimization in the smart grid

Dynamic Forecasting and Adaptation for Demand Optimization in the Smart Grid

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***Abstract*—The daily peaks and valleys in energy demand create inefficiencies and expense in the operation of the electricity grid. Valley periods force utilities to curtail renewable energy sources such as wind as their unpredictable nature makes it difficult to maintain line frequency across the network within target bounds. Peak periods require additional generators that remain dormant during other periods. Smoothing this demand cycle is one of the fundamental challenges of the Smart Grid, requiring flexibility and coordination between actors throughout the Grid. This paper describes the Smart Grid as a multi-layered system and proposes a cross-layered dynamic adaptation approach to facilitate this flexibility and coordination. This method uses a hierarchical taxonomy to identify appropriate adaptation actions in response to identified mismatches, supported by a run-time predictive statistical framework to predict mismatches, enabling timely adaptations to be triggered.**

***Keywords*-dynamic adaptation; cross-layer; prediction; demand optimization; Smart Grid;**

I. Introduction

Fluctuations between periods of high (peak) and low (valley) demand create numerous challenges and inefficiencies in the operation of power grids and pose a significant barrier to the effective incorporation of renewable energy sources such as wind. Meeting these challenges increases operations costs as redundant generators must be maintained to provide spinning reserves for peak periods and otherwise available generation must be constrained when demand is low. As a result, optimizing the electricity demand cycle has emerged as a significant goal for the Smart Grid, motivating research efforts in demand side management techniques such as demand and dispatch and load aggregation [1] [2] [3].

In this paper we propose a dynamic adaptation approach to facilitate cooperation and flexibility between actors in the Smart Grid enabling demand to be moved from peak times to fill valleys periods in the demand cycle, helping to create a more stable energy demand whilst better exploiting available wind energy. Our approach models the Smart Grid as a multi-layered system composed of distributed components and agents that interact across these layers. We propose a cross-layered adaptation approach using a hierarchal index of adaptation steps to be undertaken for identified mismatches in grid behavior or efficiency. To further increase efficiency, our approach is augmented with a predictive run-time statistical framework that can forecast future values for sensed information, enabling the identified adaptation steps to be undertaken pro-actively. The remainder of this paper is structured as follows. Section II details the context for this research and discusses the problem using Ireland's grid as an example. Next, Section III describes the proposed solution. Finally, Section IV briefly discusses some existing research in demand optimization in the Smart Grid.

II. Demand Fluctuation and Wind Power

Demand for electricity fluctuates greatly throughout the course of a day with a significant gulf between peak and valley periods. Utilities respond to these variations predominantly on the supply side, turning generators on or off to increase and decrease energy production in line with demand. This method requires some reserve capacity to be present in the system to cope with peaks in the demand cycle, which is provided by maintaining generators that lie dormant for much of the operational time of the Grid.

The cost of this redundancy requirement is compounded by the inefficiencies of turning machines on and off, which costs both time and money and increases the wear and tear on the physical components. Peak periods further impact the operation of the Grid as the increased demand causes generator devices to spin more slowly, making it difficult to maintain grid frequency within tight operating bounds. When demand reaches very high levels, load shedding may also be used, where certain consumers are disconnected from the Grid. These are typically industrial consumers, who possess local fossil fuel generators to satisfy their demand in the short term, resulting in an adverse environmental impact.

Incorporating renewable sources, such as wind, into the energy mix can help alleviate some of these issues, however they also creates additional challenges due to their intermittent nature. Traditionally, generators using non-renewable fuels such as coal, oil and gas provide predictable levels of electricity with a known ramp up time. Wind lacks this dependability as the level of energy produced depends entirely on the prevailing climate conditions, making it unsuitable as a reserve for peak periods. Additionally, unlike traditional generators, renewable energy sources will be distributed near the periphery of the Grid, resulting in energy loses if the energy produced is not required locally and must be transported elsewhere in the Grid.

However, valley periods present a greater obstacle to effectively incorporating wind energy as when overall demand drops a greater proportion of the overall requirement can be met with wind. As this penetration increases, the overall security of supply is threatened by the unpredictable nature of wind. This can force utilities to constrain wind production to maintain the security of supply, although it results in an otherwise available energy supply being unused.

Ireland's electricity network is particularly exposed to the challenges presented by demand fluctuations, and provides us with a real-world example of these limitations. The relative absence of significant big industry means that demand is predominantly driven by domestic and small business activities creating a drop of over 50% between maximum and minimum demand in the yearly cycle [4].

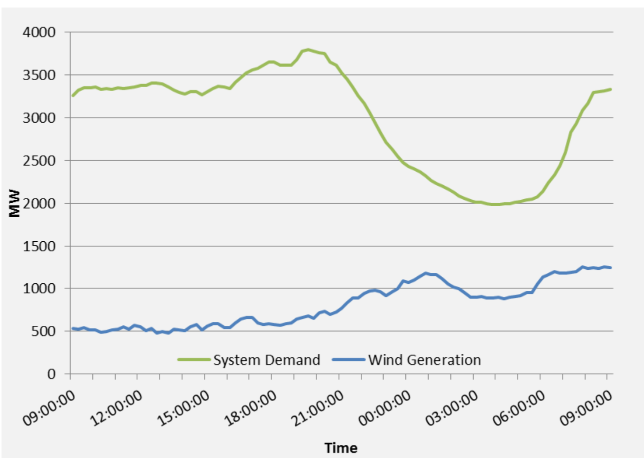

Figure 1. Example system demand and wind generation for Ireland's grid

Figure 1 contains a graph of the system demand and wind generation across Ireland's electricity grid over a 24 hour period in October 2011[1]. Peak demand occurs at approximately 8pm when domestic consumption increases as people arrive home from work and begin turning on their lights, heating and cookers creating a spike in electricity demand. During the night, demand drops by almost 50% into a valley as the majority of people are asleep, with the minimum demand occurring at approximately 3am.

Meanwhile, wind generation remains relatively constant throughout the day, but begins to increase in the evening and reaches its peak overnight. As this coincides with the valley in demand almost 50% of the total demand is being supplied by wind at 2am forcing the utility to constrain wind generation to maintain a reliable supply. This creates significant and pressing challenges for Ireland as wind availability is typically at its highest levels during the night when demand is lowest. In addition, Ireland's geographical position provides significant potential in wind energy, with ongoing investment seeking to increase capacity from current levels of 1500 MW to over 6000MW by 2025 [5] creating the potential for an abundant energy supply.

Effectively addressing these problems in the Smart Grid requires that consumption is optimized so that peaks in the demand cycle are shifted into the valleys, creating a flatter demand profile. This would reduce the requirement for reserve capacity to cope with peak periods and enable utilities to run traditional generators at an almost constant level, complimented with renewable energy sources. However, to effectively incorporate these intermittent sources it is essential that they are exploited when available, with system demand being increased when necessary. Achieving this will require a high-level of flexibility and cooperation between producers and consumers across the Grid.

III. Proposed Solution

We believe that these challenges can be met using dynamically adaptive software components or agents to monitor and control actors in the Grid, with our research to date seeking to understand the structure and adaptation requirements of the Smart Grid. Figure 2 contains a reference software architecture that we compiled by drawing on the disparate architectures that exist for the Smart Grid [6] [7] [8] [9] [10]. It details, at a high level of abstraction, each of the components in the Grid and their interactions with each other. These agents are located across seven distinct domains or layers in the Grid which include customer, service provider, markets, operations, distribution, transmission and bulk generation. The architecture illustrates that there is a high degree of interoperability between actors across the layers in the Grid.

Using this architecture as a system model, we examined the type of adaptation required to provide general flexibility to Smart Grid, including how it can help the Grid to manage fluctuating supply and demand in the context of an increasingly intermittent energy source. We found that various forms of adaptation are required extensively throughout the Grid's architecture to help balance these concerns. At the customer level, consumption behavior should be controlled by intelligently adapting control agents to schedule operation of consumer devices, electric vehicles and storage facilities, whilst balancing the customer's goals with those of the Grid. Real-time pricing that reflects current supply and demand levels is seen as a way of motivating this adaptation.

The Local Aggregator and Distribution System Manager must monitor consumption and production at both a micro and macro grid level, adapting their system models and control strategies when necessary, for example, directing consumption to increase in areas where renewable energy is plentiful. Finally, the producers and transporters of electricity from Bulk Generation to Distribution are required

[1]Data for October 4th and 5th 2011. From http://www.eirgrid.com

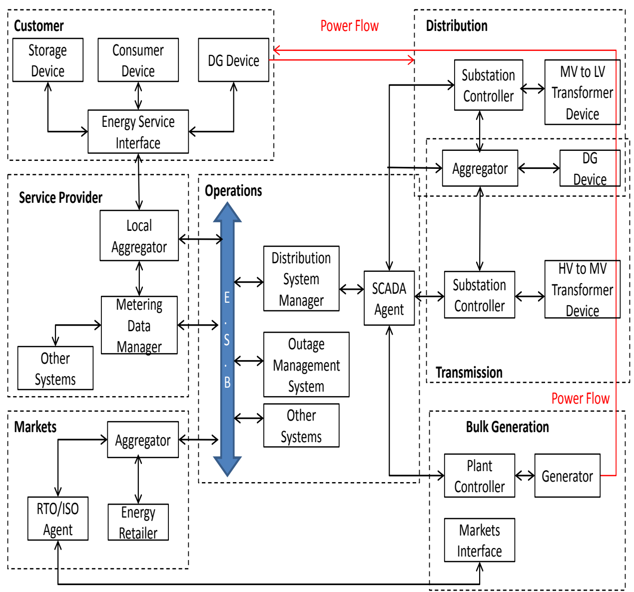

Figure 2. Reference Software Architecture for the Smart Grid

to react, increasing or decreasing production or rerouting power.

A. *Cross layered adaptation*

The high degree of interoperability between actors in the Smart Grid presents an obstacle to introducing this adaptability as any change in behavior or composition of an individual actor may have unforeseen consequences in different layers across the Grid. For example, if all customers simply adapt their consumption behavior to exploit cheaper overnight energy prices this will impact on the actors in the Operations, Bulk Generation, Distribution and Transmission domains, as it will create a new spike in demand, which must be satisfied with increased production.

Thus, we propose adopting a cross-layered adaptation approach to achieve both the flexibility and coordination necessary to facilitate effective demand optimization in the Smart Grid [11]. This approach uses a taxonomy driven approach to create a look up of adaptation actions that can be searched at run-time to find the appropriate adaptation actions when an application mismatch is detected. These indexes are defined for a specific layer, however they can be linked together through direct invocation or through adaptation events to facilitate cross-layer adaptation. In the literature, this method is adopted for a three-layered architecture, however we will extend this approach across the seven layers identified in our Smart Grid reference architecture.

Our application will adopt aspects of both a top down and bottom up approach to demand optimization in the Smart Grid, as achieving a noticeable impact will require a large-scale solution to be adopted across the Grid. To cope with the challenges of this scale, we will aggregate energy consumption and production at the periphery of the Smart Grid at both the Local Aggregator and Operation levels. This will facilitate the implementation of techniques such as virtual power stations, demand dispatch and negative demand to help reduce fluctuations in demand.

The criticality of electricity in daily life means that consideration must also be afforded to the customers perspective, who will not accept the Grid operator unilaterally discontinuing their supply to trim peaks in demand. Consumers want power when their circumstance demands it, so the behavior of individual customers must be influenced, typically using fluctuating tariffs, across the Grid network without alienating the customer. This requires localized control mechanisms in the customers premises that monitor and control consumption behavior to the satisfaction of both the individual customer and the Grid as a whole.

In our approach, mismatches will arise when energy consumption and production become misaligned or deviate outside target bounds. For example, it is desirable for wind energy to be used when available, thus behavior should be adapted to artificially increase consumption during these periods using storage devices, electric vehicles or the opportunistic scheduling of non-essential devices. Similarly, these devices and techniques can be exploited to help trim demand from the Grid, when consumption is reaching peak levels.

B. *Runtime Statistical Prediction*

Effectively addressing the issues highlighted in Section II above will require consumption and production from renewable energy to be constantly monitored so that adaptation actions can be triggered in a timely fashion. Forecasting can help to improve the timing of these adaptations further by predicting mismatches ahead of time enabling adaptation steps to be planned and adopted, thus smoothing the transition from one state to the next.

To incorporate this capability in our approach we will augment our cross-layered adaptation mechanism with TimePredict, a statistical based predictive model that can support runtime analysis of data[12]. TimePredict interacts with the adaptation manager in a dynamically adaptable system, and can be used to forecast when an adaptation may be required, and if the adaptation action has had the desired effect. It takes as its input a time-series of data, and by applying statistical models it will accurately predict expected future values in that data series.

TimePredict could potentially be used across all layers of the Smart Grid, however our implementation will concentrate on the operations and customer domains. The Grid operator will monitor supply and demand across the Grid, with TimePredict being used to predict future fluctuations in each. This will allow the Grid operator to adapt the behavior or architecture of actors in the Grid to meet the challenges of these new expected levels. In the customer domain, TimePredict can be used to adapt the consumption of individual customers to achieve the greatest benefit for that customer. For example, the Energy Service Interface, which monitors and controls devices in the customers premises, may predict an increase in energy prices, prompting devices to complete outstanding tasks as soon as possible, and scheduling the operation of non-essential devices to a future time period.

IV. Related Work

A number of European projects are currently examining ways to facilitate demand management and effectively incorporate renewable energy into the supply of the Smart Grid. The ADDRESS Project[13] is concerned with active demand management through the participation of consumers in the electricity markets and the provision of services to various grid participants and provides a conceptual architecture for the Smart Grid to facilitate distributed renewable generation.

Another interesting project is SmartHouse/SmartGrid project[14] that aggregates houses as intelligent networks that collaborate and negotiate to achieve maximum energy efficiency across the Grid. Among its field tests is the PowerMatcher system which uses intelligent software agents and aggregation to optimize the operation of large numbers of consumer devices, distributed generators and storage devices using a price bidding mechanism.

Other research efforts have also sought to meet these challenges using better renewable energy information [15] and distributed intelligence at the periphery of the Grid [16].

V. Conclusion and Future Work

In this paper, we outlined the operational inefficiencies caused by fluctuations in demand in the electricity network and the challenges this presents for effectively incorporating intermittent renewable sources such as wind into the energy supply mix. We proposed a holistic approach to tackling these issues using a cross-layered dynamic adaptation approach to facilitate flexibility and coordination between various actors in the Smart Grid. This method uses a hierarchical taxonomy to identify adaptation actions in response to system mismatches, supported by a run-time predictive statistical framework to enable timely adaptations to be triggered. Our future work will concentrate on applying and evaluating these methods in simulation environments.

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