Providing Microgrid Resilience during Emergencies using Distributed Energy Resources

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***Abstract*—Several incidents reported in the past have shown the inability of the existing power grid to provide reliable services during system failures. Moreover, the communication and control network in the smart grid inherently creates opportunities for the adversaries to launch cyber attacks to the system. Natural disasters may further exacerbate the challenge. Designing resilient (if not robust) solutions for the smart grid therefore, was, and remains a high priority. To this end, we present three solutions towards resilience of a microgrid during emergencies. First, we propose the use of electric vehicles (EVs) as temporary power supplies to support critical infrastructure during emergencies. Second, we recommend to use a combination of distributed renewable energy sources, EVs and a community-level storage unit to further enhance the resilience of the microgrid, by utilizing the locally available renewable energy options, exploiting the electric vehicles moderately, and by investing reasonably on the storage unit. Third, we introduce the software defined networking paradigm as a highly relevant platform for both power virtualization and network function virtualization, to support, coordinate and control the dynamic operation of the virtual power plants for reliable power supply and resilient operations of the microgrid in the disaster mode. Finally, we discuss the feasibility of each of these solutions for implementing them in practice.**

***Index Terms*—Community-level storage, distributed energy generation, electric vehicles, emergency, microgrid, resilience, software defined networking.**

I. Introduction

Several incidents reported in the past, including the 2003 US eastern blackout [1], the July 2012 India blackout [2] and the presence of the infamous industrial control system malwares *Stuxnet* and *Flame* [3] have shown the inability of the existing power grid system to provide reliable services during system failures and cyber attacks. The emerging smart grid offers promising solutions towards making the electric power grid more efficient and reliable. Nonetheless, a smart grid is a complex network of networks where sensing, monitoring, communication and control enable the performance of the system in terms of power generation, transmission, distribution and consumption. In such a network, a cascade of failures may occur, such that power failures can lead to communication failures, which, in turn, may lead to cascading power failures. In addition, the integration of advanced communication and networking into the power grid, unfortunately exposes it to vulnerabilities that can be easily exploited by adversaries to control and to compromise the grid by launching attacks such as data manipulation and false data injection [4]. Moreover, natural disasters such as earthquakes and landslides can also cause power outages for hours to several days, possibly affecting millions of lives and leading to public safety and economy disasters. For these reasons, it is important to explore the possible options to maintain a reliable power supply to critical infrastructures during such emergencies.

While economic losses are not desired either, cyber attacks and natural disasters can potentially cause physical damage to the grid, which can lead to grid instability, that can be extremely costly, and in many cases, irrevocable. A good volume of work exists on addressing reliability and security issues in the smart grid, e.g., [5], [6]. In [5], the authors have studied the utility-privacy tradeoffs of smart meter data and shed light on the impact of leakage of both user and supplier data from utilities. In [6] the authors have developed a formal model for the C12.22 standard protocol to guarantee that no attack can violate the security policy without being detected based on the concept of specification-based intrusion detection. We, however, observe that there are very few studies that research the challenges associated with emergency situations. Hence, new and viable solutions for power supply during emergencies are needed.

If an extended power outage occurs, buildings, services, businesses, and eventually millions of people, may be affected. However, there are certain buildings and services that should be labeled as critical, e.g., hospitals and communication infrastructures. During emergencies, it may be more important to support the operation of such infrastructures albeit with minimum possible power configurations. For instance, in a hospital only the operation-theaters and the other most important rooms and services can be operated. In this work, we explore different options for maintaining a reliable and stable power supply during emergencies to support the operations of critical facilities and infrastructure, and discuss the feasibility and implementation issues for these options.

Recently, the use of electrical vehicles (EVs) has been increasing at a good pace, and the potential for mobile storage and vehicle-to-grid (V2G) power supply/trade for efficient and stable power generation and scheduling, has been investigated extensively, e.g., [7], [8], [9], [10]. We propose to deploy EVs as temporary power supplies to operate critical facilities during emergencies. Moreover, we advocate the use of EVs along with distributed renewable energy resources and a community-level storage unit, as a more reliable and resilient solution to provide power supply to critical infrastructure. It might also be possible to extend the local coverage zone of the power resources to supply power for instance to residential buildings and other infrastructure in addition to the critical facilities. Finally, we present a software defined networking (SDN) paradigm as a potential and suitable platform for communications and coordination among distributed energy generation resources, EVs, the community storage unit, the control units and the distribution management systems during emergencies.

Our work in this paper differs from the literature in several ways. Compared to studies such as [7], [8], [9] and [10], we extend the usage of EVs from just *mobile storage* to supplying power to critical facilities, a more proactive role that can significantly exploit the capacity of the EVs during crisis. Some earlier works have considered energy storage with renewable energy generation e.g., [11], [12]. We combine the EVs as mobile storage units and emergency power supply along with renewable energy generation and storage, which essentially enhances the storage capacity of our schemes and also makes the system more dynamic. With the SDN paradigm, our scheme adds potential features like network function virtualization for communications and control, and power virtualization, which makes our idea innovative, and more practical during emergencies. Another work that is related to ours is [13], in which the authors have developed an optimization model to manage a residential microgrid including a V2G system and renewable energy sources. In our SDN based framework, the SDN controller connects all the entities in the microgrid, thus making it one logical entity, consequently simplifying the system view and reducing the communication and control overhead. Our SDN framework in this paper is inspired by [14]. However, while [14] suggests the use of an SDN platform for economic benefits including demand response management, our objective is entirely different: Power supply reliability and resilience of microgrids are the driving elements in our framework.

The rest of the paper is organized as follows. In Seciton II, we present the basic concepts such as distributed energy generation, storage, associated challenges, power outage and resilience. In Section III, we introduce the concept of our EV based power supply during emergencies, distributed generation and storage based supply, and the software defined networking platform. In Section IV, we discuss the feasibility aspects for implementing the three ideas. Section V concludes the paper.

II. Preliminaries

A. Distribution Energy Generation and Storage

One of the key features introduced by the smart grid is the transformation from centralized to decentralized power generation. Recently, there has been a notably increasing penetration of distributed energy resources (DERs) which includes both renewable energy resources such as solar panels and wind turbines, and mobile storage units such as EVs, into the power grid system. The benefits of using distributed renewable energy resources are two fold. First, they help to improve the greenness of power generation by reducing greenhouse gas emissions. Second, they may provide cheaper power to the consumers, while also reducing the load on the power grid, thus contributing towards more reliable and stable operations of the grid. On the contrary, the spread of the local renewable energy resources into the power ecosystem inevitably means that the intermittency issues associated with them may have a bigger role to play in the whole generation-consumption cycle. For instance, one of the consequences of using renewable resources is that fluctuations in the output from wind turbines and solar cells make it necessary to have a rapid-response power supply system.

EVs can act as storage units, charging during cheap electricity hours and supplying power to the household appliances during peak hours, and can respond to imminent electricity demands, during normal operations, thus flattening the consumption curve from the grid and contributing to a reliable, stable and more efficient operation of the grid. Moreover, the *mobile storage* features of the EVs can prove to be of great use during emergencies including the situation when parts of the power grid network is rendered dysfunctional. Nevertheless, a high penetration of EVs can also lead to overloading and further strain to the grid, if their charging and discharging are not properly scheduled and coordinated [15], [16].

B. Power Blackout and Resilience

Power blackouts can be caused by device failures, system faults, cyber attacks (especially in a communication and network facilitated cyber-physical system like the smart grid) and natural catastrophes such as earthquakes, landslides, flooding, lightning, etc. The consequences of a power blackout may be diverse. E.g., it may leave hundreds of residential buildings and thousands of people living without electricity for hours or even days, it may lead to temporary or long-term malfunctioning and/or shutdown of financially critical, security-critical or life-critical infrastructures such as banks, hospitals, heating, water supply and drainage.

While many critical infrastructures have backup solutions in the case of power outage, many may not have, and some may have local power generators or uninterruptible power system (UPS), but these may prove insufficient during crisis for longer durations such as cyber attacks or natural disasters. E.g., UPS backups or local generators may be helpful to supply the necessary power to high priority areas of hospitals only for a short duration. As we explore possible solutions towards power blackout emergencies, it is important to note that proper assessment and preparedness are essential for the envisaged solutions to be effective. Diverse options are possible for emergency power solutions. For instance, a large free standing generator may be one of the first choices, but it needs external fuel supply, frequent testing, and proper connections into the power grid. Alternatives like batteries and UPSs can be the solution for a limited amount of time.

The best option clearly depends on the amount of power necessary, the maximum duration that emergency power will be needed, and the cost of the backup option. In order to be prepared, the power requirements of the critical facilities and all other buildings in a disaster mode should be determined in advance. For this, the minimum configuration of all critical equipment including heating, ventilation and security systems, should be identified and put in a database. If there are any changes in the total power consumption due to additional new equipment or because of expansion of facilities or services, the minimum power requirement of the building in disaster mode should be updated in the database. Such update could even be automated, so that the system could learn, during installation and tests, what the minimum requirements are. Note that it is important to support the operations of the communication networks in order to provide connection to and between emergency response and rescue teams. Therefore the power requirements should take into account the consumption of the communication equipment too.

For our proposed distributed energy generation and storage based solutions for emergency power supply, which will be presented in detail in Section III, we focus on those infrastructures and buildings that either do not have backup solutions for power emergencies, or where the backup options are not sufficient to sustain the needed power for long.

III. Proposed Solutions

A. Electric Vehicles as Power Supply during Emergencies

Our proposed EV based emergency power supply scenario is depicted in Fig. 1. In this framework, EVs are used as temporary mobile power supplies to critical infrastructure until a sustainable option is available. The critical infrastructure and residential buildings as well as the EVs are connected through bidirectional wireless communication. When a power outage occurs, the residential buildings and the EVs will also be aware of the situation. As soon as a critical building has power outage, it will configure its operations to disaster mode and operate only the most important rooms and equipment. EVs in its parking lot will perform discharging immediately. If needed, EVs nearby will be asked to drive to the critical building and start discharging to support critical operations. If no EVs are available in the parking lot when the power outage occurs, then, the building's backup aggregates will supply power until EVs from the neighborhood arrive and start discharging. With proper communication and coordination among the EVs and between the EVs and the aggregates, multiple EVs can be used for discharging.

A natural concern for such applications is the capacity of the EVs and how long they can support such life critical infrastructure. Although one or a few EVs may have limited capacity, the supply from several EVs can be aggregated to provide electricity supply to several critical buildings, or to support them longer as EVs can be discharged flexibly and at various speeds. In Section IV, we explain the feasibility of using EVs in practice during such situations, through a brief case study showing that the capacity of the EVs currently available in the market is sufficient to supply power to critical buildings.

Because EVs are equipped with batteries, vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication can be smoothly carried out. Furthermore, we consider that critical buildings can communicate with the EVs or residential buildings even in disaster mode. Cognitive V2I and V2V Machine-to-machine (M2M) communications are technologies that may enable this communication, assist in battery charging/discharging and energy and mobility management.

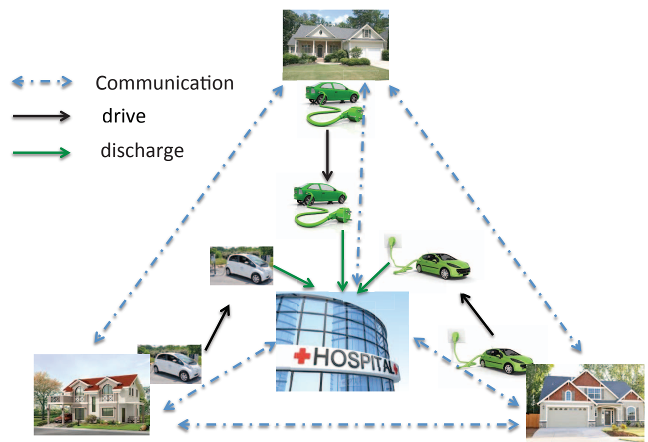

Fig. 1. Electric vehicles acting as power supplies to a critical infrastructure during an emergency

B. Distributed Energy Generation, Storage and Mobility for Enhanced Resilience

As the use of EVs has been increasing, charging them from local renewable energy resources instead of charging them from the grid reduces the total power consumption from the grid, as well as improves the utilization of green energy. Likewise, this option is inline with the aim of exploiting renewable energy resources to the extent possible. However, the available storage in the EVs depends on their traveling schedule, which may or may not match the peak local power generation times. Therefore, it is anticipated that if a community-level storage unit is available that stores power when excessive power is generated locally during times of low demands, this can drastically reduce the electricity consumption from the power grid, and thus results in substantial savings in energy costs for the consumers during normal operations. The advantages of investing in a shared community storage are not limited to cost savings. A microgrid with a local power storage can become a zero net energy building as in [17], or even more importantly, with proper scheduling, a self-sufficient community. Driven by such considerations we advocate a combination of local renewable energy resources, EVs and a community-level storage unit as a power supply solution during emergencies.

Power storage units are expensive. Nevertheless, a smaller size optimal community storage as proposed in [18], can keep the storage costs to a minimum while greatly enhancing the resilience and dependability of the micro-grid. Such a storage can provide power supply to operate the minimum required functionalities of the critical infrastructure, and the residential and commercial buildings in disaster mode if possible (in the order of their priorities), at least until sufficient amount of power is available from the EVs or until the local renewable power sources start generating power. Thus such a design can strengthen the reliability of the power supply while not investing a huge amount of money in storage.

In this framework, during an emergency, the local renewable energy resources are used first to maintain the supply to the critical infrastructure and to the residential and commercial buildings in a minimum power consumption mode. The buildings in the community are connected to each other by wireless communication technologies forming a neighbourhood area network (NAN). We assume that communication among buildings, EVs and the storage unit can be maintained so that necessary communication is available to seek help, and to communicate and coordinate power scheduling. If the renewable resources are not functioning or the power supplied by them is not sufficient to operate the critical infrastructure, the EVs are used next in line. If that is not sufficient, then the local storage is exploited. If none of these can ensure the operation of the critical infrastructure, then more advanced options such as power supply from the neighbouring communities can be sought.

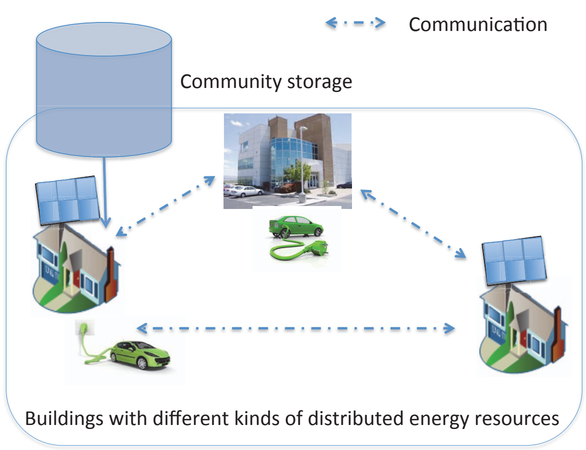

Fig. 2. Distributed energy generation and storage with mobility for enhanced resilience during emergencies

C. *Software Defined Networking based Framework for Implementing Virtual Power Plants*

A virtual power plant (VPP), also called an Internet of Energy, refers to a logical aggregation of local and non-local DERs including energy storage resources, collectively run by a central control entity [19]. Utilizing software-based systems, VPPs are dynamic, and can react quickly to changing customer load conditions, thus yielding benefits to both the end user and the distribution utility. During normal operations, a VPP can provide higher efficiency and more flexibility, compared to the conventional power grid. During emergencies, the ability of a VPP to deliver peak load electricity or load-aware power generation at a short notice, can be a highly valuable feature.

Software defined networking (SDN) is a platform that abstracts the data, management, and control planes. The main controller is software-defined, and its programmatic interfaces to individual networking devices are exposed to other software applications. As a result, applications and services based on such an architecture can be more agile. The features offered by SDN are highly relevant and effective for establishing communication between distributed energy sources, EVs and the community-level storage unit, and for controlling them and coordinating their activities, especially during emergencies. SDN therefore, stands out as a typical and distinct platform to implement VPPs from distributed renewable generation and storage, for the emergency scenario of our interest.

Our SDN based framework for coordinated distributed energy generation, storage, aggregation and dispatch is shown in Fig. 3. The different energy resources are aggregated according to their geographical, technical or other characteristics, and VPPs are formed accordingly, thus enhancing virtual mobility of the local generation and storage resources, and avoiding the requirement of specific resources to supply power to one or a limited number of buildings. In addition to the functions performed during normal operations, such as data transmission, real-time monitoring, virtual network control and aggregation control, power requirements during emergencies are available to the SDN controller so that the VPPs can reliably supply power in disaster mode.

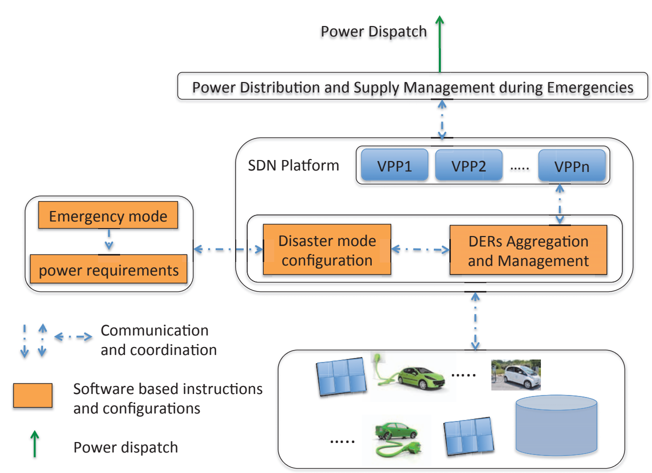

Fig. 3. SDN coordinated distributed energy generation, storage, aggregation and dispatch

IV. Feasibility and Implementation Aspects

The number of EV per capita in the world has increased dramatically in recent years. Currently, Norway is in the first place in the world regarding EV market share and by August 2015 the country had more than 62,000 registered EVs [20].

A. EV Battery Capacity and Power Requirements of Critical Buildings: A Brief Case Study

The range of different EV models vary widely. For instance, a typical battery capacity of an EV passenger car is 24 KWh, while the battery capacity of a Tesla van can be as high as 80 KWh [21]. The battery can be fully charged or discharged in 1 hour in *fast* mode. Nonetheless, high charging rates can cause accelerated ageing, which is a natural concern for the EV owners. Most cell manufacturers therefore recommend a charging time from 2 to 3 hours. Typical requirement for an average household is about 25 kWh for one day. [21]. We consider that a commercial building or a critical infrastructure building such as a hospital requires about 10-15 times the consumption of a residential building, i.e., $250-375$ kWh per day. Thereby, about 16 EVs of moderate battery capacity (24 KWh) should be sufficient to sustain the operation of a critical infrastructure for one day. Note that during emergencies, the buildings scale down their power consumption to the minimum possible values, which means that the total power required from the EVs or the total number of EVs required to supply power to them is less than 16, even if the critical buildings should be supported for the whole day. Taking into consideration the fact that the EVs are likely not to be fully charged when they start discharging at the critical facility, it is reasonable to consider that 15 to 16 EVs are sufficient to support the operation of a critical building.

Another issue about the feasibility of EVs as power supplies to critical buildings is more subjective. Even as promising as the V2G concept of the Smart Grid sounds, it has been much debated. During normal operations, EV owners may not be willing to use their expensive batteries to serve the grid for the benefit of the utilities. Even economic incentives like reduced electricity bills may not be strong enough, as fast and frequent charging/discharging may shorten the life of their EV batteries. During emergencies however, one can still assume that the EV owners may volunteer, but better approaches to manage such issues e.g., with sufficient economic incentives without having to charge/discharge fast, are certainly needed.

B. Distributed Energy Generation and Storage: Projects and Implementations

With distributed energy generation, mobile storage and community-level storage, as shown in Fig. 2, a reliable and stable power supply to critical buildings can be maintained in an emergency sitiation. If surplus power is available, residential buildings can also be operated in disaster modes. However, precise assessment, modeling and analysis are necessary to develop specific scheduling algorithms.

Regarding the feasibility of deploying such an approach, we would like to mention a few projects that supply power to a village or a community based on local renewable energy sources and storage. For instance, University of California San Diego (UCSD), USA, has implemented and controls a fully functional microgrid with 1.2 MW of power generated from photo voltaics [22]. Furthermore, the authors in [17] have developed strategies to make a densely metered mixed-used office building a zero net energy building (ZNEB), a building with zero net annual energy consumption. The authors have conducted a virtual experiment to determine how the Computer Science and Engineering (CSE) building of UCSD, could become a ZNEB, by powering the CSE building by local renewable sources. Likewise, the Institute for Solar Energy Supply Technology of the University of Kassel in Germany pilot-tested a combined power plant linking solar, wind, biogas and hydrostorage to provide load-following power around the clock, totally from renewable sources [23].

An important prerequisite for our solution based on distributed generation, EVs and community-level storage, is that power may flow locally between the buildings of a microgrid. Recently, under an initiative called *Empowering people to build their own microgrids*, a team of MIT researchers and students have developed a simple device named *the power management unit (PMU)* for deploying in remote rural India [24]. The PMU regulates the direct use of electricity from solar panels or other sources to immediate uses such as powering lights, cellphones and rechargeable batteries. With the help of the PMU the houses in the neighbouring villages which do not have local generation, can receive power from the buildings with solar panels, as it monitors power transfer to each user, providing a record that can be used for billing without a need for individual meters. Such innovative initiatives are deeply inspiring, and thereby we can envisage that power flow between buildings locally, is not a far fetched goal. Moreover, we can envision that different neighbourhoods acting as power clusters, and the flow of power between these clusters when one or some of them are affected by the system failures, cyber attacks or natural disasters, are challenging, but the challenges can be simplified with advancing technology, power virtualization, and proper communication and coordination among distributed generation, storage and power distribution management system.

C. Feasibility of an SDN based Framework for Network and Power Virtualization

Issues such as local power flow can be greatly simplified by deploying VPPs. VPPs not only deal with the supply side, but also help manage demand and ensure reliability of the grid operation through demand response and other load shifting approaches, in real time. Nevertheless, a VPP is also a complex system requiring complicated optimization, control, and reliable communication methodology. As a VPP is run by a central control entity, SDN stands as a typical and highly relevant platform for deploying VPPs.

SDN allows aggregating distributed energy sources with virtual networks by dynamic software configuration.

Network resources for communication between DERs such as EVs, renewable generation and community-level storage, can be allocated dynamically on-demand based on software instructions. In such an infrastructure, DERs aggregated to the same VPP are controlled and communicate in an exclusive virtual network, which can be easily deployed and configured by a centralized SDN controller. As the state of the different available resources needed to operate a specific building or community may change dynamically, the scalability of the network and the timeliness of delivering the monitoring and control data of distributed generation and storage, are critically important during emergencies. SDN facilitates pub-sub or other content-based processing at the network layer for enhancing data exchange [14] . Furthermore, when an aggregation criterion in a VPP is modified, or the energy production rate of a DER has changed for e.g., due to EVs joining and leaving a VPP dynamically, the resource can be relocated to a different VPP aggregation efficiently through the programmatic interfaces to the SDN controller. A distributed energy resource management system that is aware of the network status can automatically reconfigure to respond to new aggregation changes. The management complexity can be reduced since the whole process from networking to aggregation can be handled by software services based on SDN extensions. These potential features imply that SDN is not only one of the suitable platforms but the distinctly preferred one to implement VPPs dynamically and autonomously for providing resilience to the microgrid during emergencies.

V. Conclusion

We have proposed the use of electric vehicles as temporary power supplies to support critical infrastructures during emergencies caused by device failures, system faults, cyber attacks to the power grid system, or due to natural disasters. We have further recommended to use a combination of distributed renewable energy sources, EVs and a community-level storage unit for enhancing the resilience of the microgrid to such emergencies, by utilizing the locally available renewable energy options, exploiting the electric vehicles moderately, and by investing reasonably on a storage unit. To this end, we introduced the software defined networking paradigm as a highly relevant platform for both power virtualization, and network function virtualization to support, coordinate and control the dynamic operation of the virtual power plants for reliable power supply and resilient operations of the microgrid in the disaster mode. Furthermore, we have emphasized the advantages and have also discussed the feasibility of each of these solutions. Nevertheless, there are challenges that must be addressed before these solutions can be effectively applicable in particular emergency scenarios. E.g., the modeling of device failures or system faults may require power of different scale for a shorter duration compared to natural disasters. Solutions tailored to specific requirements need to be designed, to mobilize the available resources efficiently and reliably. We, however, hope that our work may create further interest in the resilience aspects of a smart grid during emergencies, and that it encourages developing efficient and reliable solutions for specific scenarios.

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