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The Future Role of Active Distribution Load in Enhancing Reliability, Resilience and Security of the Electricity Grids

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SUMMARY

The introduction of active distribution load (ADL), often described as virtual power plant or prosumer, as an example, comprised of controllable load, photovoltaic (PV) generation, battery energy storage system (BESS) and/or mobile battery energy storage (part of electrical vehicle (EV) interfacing) is becoming a reality around the world. The ADL technologies bring about significant advantages to modern power systems, e.g., reliability and resilience enhancement, carbon footprint reduction, and flexibility of demand. The challenges caused by large integration of these technologies must be explored to avoid any potential drastic consequences that may impair delivery of electric power to the consumers.

In this paper we focus on three major issues that ADLs require to be effectively used in support of the key grid operation properties: reliability, resilience and cybersecurity. We envision a particular ADL configuration referred to as the nano-Grid (n-Grid), which is defined as a residential or commercial building containing roof-top PV generation, small scale on-site BESS, and EV charger(s). The n-Grid can offer ancillary services products (ASPs) such as frequency regulation and capacity reserve through aggregation in the wholesale electricity market (WEM) with the aim to improve the reliability of the system. The major reliability challenge we address here is the risks of insufficient realized ASP procurement due to the intrinsic uncertainties in the power output and availability of n-Grid assets. The n-Grid can be utilized to improve the electric grid resilience through proactive or reactive modes of operation. The proactive n-Grid services to improve the utility grid resilience are aimed at preventing the overloading of power grid components to avoid asset failures. The reactive n-Grid services to may be focused on providing back-up power to the load that lost electricity due to an outage. The cyber-security challenges arise from the vulnerability of ADL communications via internet of things (IoT) that aggregator or distribution system operator (DSO) may need to use. We investigate potential vulnerabilities of such communication systems to multiple types of cyber-attacks and propose the usage of blockchain technology to detect possible attacks or anomalies.

The results presented in this paper are obtained through an elaborate study of the future grid developments with a focus on energy storage undertaken by a larger research team. We have focused on the very specific issues outlined in this paper as applied to the use of the n-Grids.

KEYWORDS

Active Distribution Load, Resilience, Reliability, Cybersecurity, Wholesale Electricity Market, Retail Electricity Market**.**

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1. THE n-GRID FEATURES

1.1. The n-Grid Components

Generally, an n-Grid is defined as a commercial/residential building equipped with rooftop solar panels, controllable electric load, a fixed BESS and EV chargers as depicted in Figure 1 [1]. All these components are connected to a common AC bus rated at 230-240V. The rooftop PV is rated at 4-30 kW, the BESS capacity is rated at 10-20 kWh with 4-8 hr charging cycle. The EV charger is able to fully charge an EV battery rated at 30-60 kWh in a span of 4-8 hrs [2]. The n-Grid loads are either fixed, adjustable or deferrable. Fixed loads must be supplied as needed, adjustable loads can be adjusted in the comfort range set by the occupants, and deferrable load can be postponed to the hours with low electricity prices [3]. The n-Grid is an ADL receiving great interest recently due to its various capabilities: lowering building load curtailments by acting as backup or lowering owner's electricity bills by providing ASPs to the grid and performing energy arbitrage (storing energy at times with low electricity prices and generating energy at times with high prices) [1].

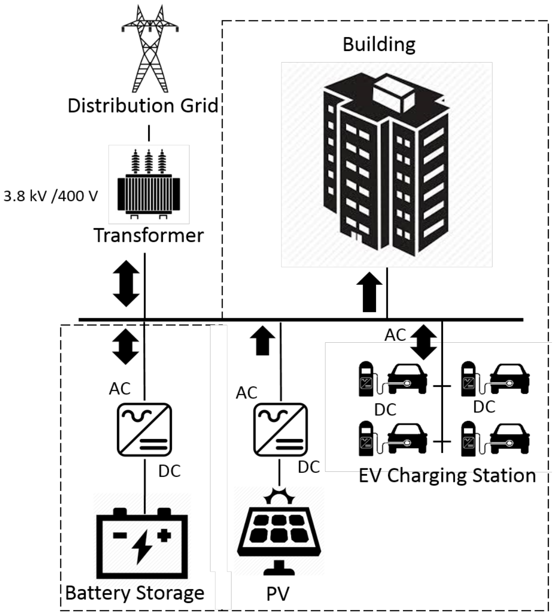

Figure 1. N-Grid architecture [1]

1.2. The n-Grid Applications

According to Figure 2, the n-Grid can bring advantages to the grid through three participation modes: (i) engaging in WEM's ASPs, (ii) responding to retail electricity market (REM) demands, and (iii) supporting peer-to-peer (P2P) energy trading schemes [4]-[10]. In the USA, recent Federal Energy Regulatory Commission (FERC) Order 2222 has encouraged the participation of such distributed energy resources (DERs) in the WEM [11]. Their response to the retail market, and support of P2P energy exchange as a part of the demand side management programs has been underway for some time.

1.3. The n-Grid Uses Reported in Previous Studies

The aggregation of n-Grids enables offering different ASPs to the WEM which brings about higher profitability for the owners. In [4], the authors proposed a bi-level optimization model for participation in the WEM where the n-Grid capability in its own resource management was considered. The authors

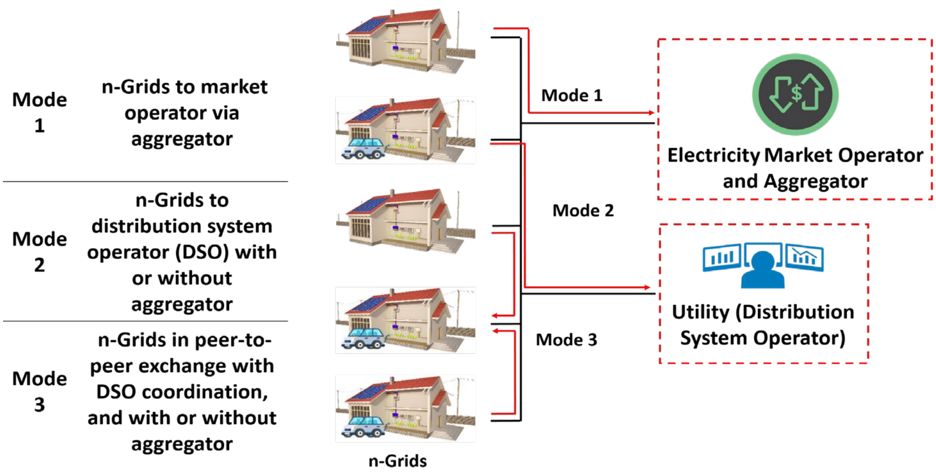

Figure 2. N-Grid Operating Modes [1]

in [5], investigated the ability of n-Grids in flexiramp ASP procurement for the WEM. The simulation results demonstrated how the n-Grid resources, BESS and EV charger in particular, can bring about significant flexibility to the utility grid. In [6], the authors proposed a model to adjust the price-quantity energy bids in real-time market to account for flexible ramping product provision. It was justified that the n-Grid aggregator can gain extra profit through provision of such ASPs. N-Grid aggregator participation in the WEM might be impacted by weather-related outages. In [7], the authors developed an optimal bidding strategy model for the aggregator considering weather-related distribution feeder outage forecasts. Such forecasts were obtained by performing a gradient boosting algorithm on historical weather and feeder outage data.

Several research efforts tried to provide a clear definition for resilience in power systems. In [8], a definition for resilience is provided, and the differences between resilience and reliability are explained. In [9], the authors provided a review of the definitions for resilience and reliability as well as reliability enhancement methods. Research gaps, the challenges, and solutions with regards to resilience enhancement are explained in [10].

The cyber-security of n-Grid communications is not well explored yet. In [12], different aspects of cybersecurity in a real-world setup of a PV-based prosumer were investigated. A real-world test case to assess the cybersecurity of DERs was studied in [13]. In [14], the blockchain technology was offered to improve the security of communications between the n-Grids and aggregator. The data to be stored by the involved entities were defined. Such a framework offers a promising solution to cybersecurity of n-Grid communications and visibility of these ADLs to the market operator. In [15], a detailed case study of this scheme was investigated which demonstrated its applicability and scalability in market participation through aggregation.

In summary, the DER solutions in the form of ADLs are a promising approach to solving many pressing electricity grid issues such as environmental pollution or lack of controllability in face of climate change and operational complexity respectively. This paper highlights some important results that contribute to addressing the reliability, resilience and cybersecurity components of the future solutions.

2. THE n-GRID UTILIZATION IN GRID RELIABILITY ENHANCEMENT

The North America Electric Reliability Corporation (NERC) defines the term reliability as "the ability of the system to meet the electricity needs of end-use customers even when unexpected equipment failures or other factors reduce the amount of available electricity [16]". It further divides the reliability into two categories of adequacy and operating reliability (security). Adequacy refers to having sufficient resources to provide customers with a continuous supply of electricity at the proper voltage and frequency at all times, considering scheduled and reasonably expected unscheduled outages of system components, e.g., generators, transmission and distribution lines, transformers, etc. Operating reliability (security) is the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components [17].

In order to meet the reliability requirements, NERC requires the system operators to provide ancillary service products (ASPs) for normal and contingency operations. Frequency regulation and load following reserve ASPs are procured to address normal operation reliability requirements, whereas spinning and non-spinning reserve, and replacement or supplemental reserve ASPs are procured to address reliability during and after contingencies [18].

2.1. The n-Grid Role in Improving the Utility Grid Reliability

The role of n-Grids in the wholesale market ASPs to support the most critical transmission system reliability issues such as frequency regulation and capacity reserve has many promises. An n-Grid aggregator can harness the flexibility and high ramp rates of the n-Grid resources to respond to the ASP requirements set by the market operator. As depicted in Figure 3, the aggregator is envisioned as the mediator between the ISO and n-Grids. By controlling the resource of n-Grids, the aggregator can offer ASPs to the WEM. Through home energy management system (HEMS), the aggregator receives the n-Grid measurement signals and sends control signals to n-Grids.

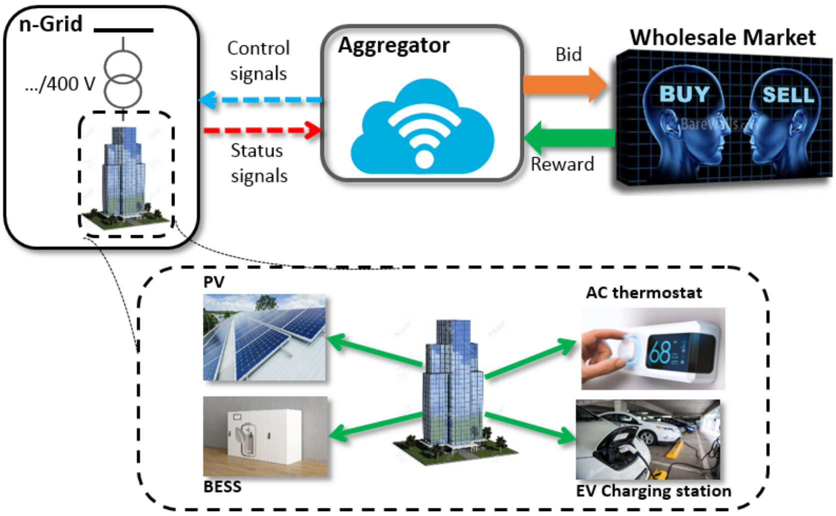

Figure 3. N-Grid/Aggregator/ISO coordination [4]

The main n-Grid resources that can provide capacity reserve are BESS, EV charger and air conditioning (AC). In discharging mode, the BESS can offer up to its maximum power minus current power for capacity reserve. In charging mode, it can offer reserve up to the summation of current power and maximum discharging power. The BESS reserve must not exceed its stored energy. The same is valid for EVs during the times they are connected to the n-Grid. The AC can offer reserve up to its current power output. It is also limited to minimum and maximum temperature levels set by the building occupant.

The major challenge is the uncertainty in the availability and power output of the n-Grid assets, which calls for proper stochastic algorithms to manage the risk of insufficient realized available capacity for the ASPs and avoid the consequent penalties.

2.2. Case Study and Simulation Results

We consider an aggregator participating in the energy and spinning reserve markets on behalf of 1000 residential n-Grids. The n-Grids' BESS capacity is uniformly distributed in the range 10-20 kWh and EV battery in the range of 30-60 kWh. Their minimum comfortable temperature is 68-73 °F and its maximum is 75-80 °F.

We assume probability of failure for each n-Grid at each hour to be 0.1. We assume two use cases (UC) and investigate the effect of these two use cases on the expected energy not supplied (EENS) and the aggregator profitability:

- UC#1: the n-Grid BESS, EV charger and AC are controllable, and the aggregator participates in the energy and spinning reserve markets.
- UC#2: the n-Grid BESS, EV charger and AC are NOT controllable, and the aggregator participates in the energy only market.

The EENS of n-Grids in UC#1 is 1.96 MWh and in UC#2 is 2.12 MWh. In UC#1, the aggregator's expected energy cost and spinning reserve profit are \$3214 and \$663, respectively. In UC#2, the aggregator's expected energy cost is \$3720. In total, the aggregator provided 185 MWh of spinning reserve for the grid during the day. The aggregator made more profit from energy trading in UC#2 since it can use the battery capacity to perform energy arbitrage. In conclusion, the simulation results demonstrate the significant advantages that this framework brings to both the aggregator and power grid.

2.3. Discussion and Recommendation

The FERC Order 2222 enables DER participation in the WEM with the aim to improve the reliability of power grids. This can be achieved through DER aggregation and participation in ASP markets. The aggregator must manage the profitability risks which are imposed due to uncertainties associated with the n-Grid resources. Based on our use case studies, the recommendation is to engage n-Grid owners, aggregators and market operators in a planning study to determine optimal n-Grid displacements and ratings for a maximum benefit to all the stakeholders.

3. THE n-GRID CYBERSECURITY ENHANCEMENT

In order to participate in the WEM, the n-Grids must regularly communicate with the aggregator and ISO enabled via the internet of things (IoT), which is highly vulnerable to cyber-attacks. The cybersecurity aspect is related to the use of secure and robust communication protocols to exchange the information between the wholesale and retail market participants and the owners of n-Grid, either through a direct communication or an exchange of related messages through an aggregator. While the software defined networking (SDN) provides a promising solution to cope with cyber vulnerabilities, novel algorithms to detect cyber intrusions are vital.

3.1. The Use of Blockchain for n-Grid Information Exchange

We propose implementing the blockchain technology to overcome the cyber vulnerability in this framework. Proof of Authority (PoA) algorithm is a proper selection for the consensus algorithm in this framework since it does not need sophisticated computation resources, the identity of the block validators is verified, it is fast, the validators' reputation is at stake, and it can be applied to private and consortium networks. Among the public, private and consortium blockchain networks the latter is the best option for our framework since it limits the decentralization, provides multiple entity ownership, is fast and permission is required to access network. On this basis, the measured power and stored energy of BESS and EVs, EV availability, current temperature and AC power, PV generation and other loads of n-Grids are stored in the blockchain every five minutes. The aggregator control signals to n-Grids are stored every five minutes. The energy and ASP bids of aggregator to the day-ahead and real-time markets and the corresponding cleared amounts in the market are stored in the chain as well. Any anomalies and/or cyber-attacks can be detected by comparing the signals received from n-Grids and the data stored in the blockchain. Other advantages of the blockchain technology are monetary and ASP settlements between the aggregator and ISO.

3.2. Case Study and Simulation Results

We further investigate the cyber vulnerabilities of the n-Grid communications through software defined networking (SDN). As shown in Figure 4, we model a typical n-Grid communication system in Mininet-WiFi software. Mininet-WiFi is a fork of Mininet which enables analysis of WiFi communications [19]. In this simulation, a typical n-Grid with EV charging station (EVCS), BESS, AC and load meter (Meter) are modelled. The n-Grid resources are connected to a switch (s1) and communicate with the aggregator's data center through two routers (r2, r3), and a switch (s4). We performed the following use case studies: network reconnaissance, man in the middle (MiTM) and denial of service (DoS) using Kali Linux. The results showed that the n-Grid is vulnerable to these attacks which calls for proper solutions to improve its cyber-security.

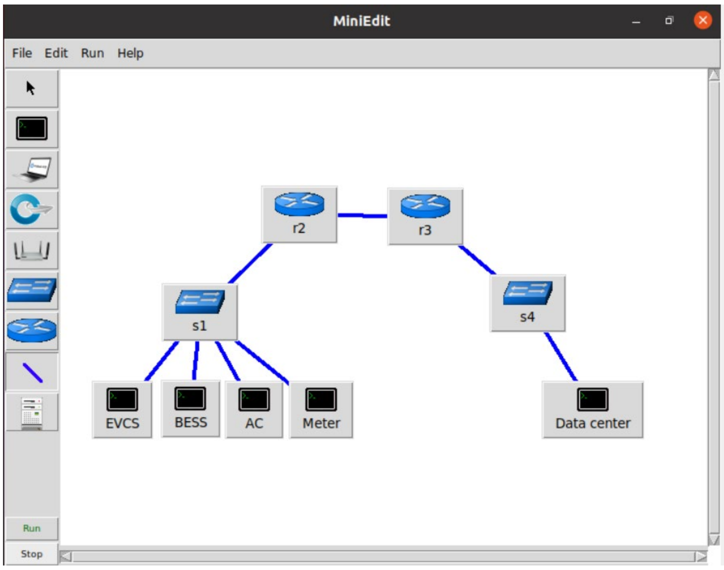

Figure 4. The aggregator/n-Grid framework simulation in Mininet-WiFi.

3.3. Discussions and Recommendations

Th n-Grid applications in ASP procurement in the WEM are inevitable. The n-Grid owners will have to communicate with the aggregator and other entities through IoT. The cybersecurity of such communications must be assured to enable well-protected energy exchange transactions. Our simulation results show that such communications are vulnerable to cyber-attacks. We recommend data recording in blockchain as a solution. Implementing this technology enables the aggregator to detect any cyber-attacks and anomalies in n-Grid communication system.

4. THE n-GRID UTILIZATION IN RESILIENCE ENHANCEMENT

Providing a definition for resilience in power systems has been a controversial topic among researchers [20]-[22]. We define resilience as the ability of the grid to predict and resist a disturbing event as well as respond and recover if the event takes place. Based on this definition of resilience, the resilience can be proactive and reactive. For proactive resilience, the actions should prevent assets, e.g. transformers, from failure due to overloads. Proactive resilience actions include demand response, load management, through deployment of n-Grid energy resources to decrease the overloading. Reactive resilience refers to the situation in which n-Grids react as a back-up power source in cases the feeders or assets fail causing an outage. This includes deploying n-Grid resources in an islanded mode to isolate and feed the on-site load during the outage while the utility company staff removes the cause of the outage and reconnects the islanded section to the main grid. Proactive resilience improvement is achieved through the preventive actions before an outage while the reactive resilience improvement is in the actions after an outage.

In order to enhance the resilience, four main steps need to be taken:

1. Predict a disturbing event;
2. Prevent the event from happening;
3. Mitigate the impacts of the event for the possibility that it happens;
4. Take actions to recover utility services quickly.

The n-Grid resources provide the flexibility to the grid operator to use them in several utility grid operating contingencies: a) mitigate the risk of asset failure, b) dispatch battery energy storage systems for WSM and RTM services, and c) support as much load as possible during outages.

4.1. Proactive Resilience Enhancement

There are some events such as heat waves that make grid assets such electric transformers operate under considerable stress. If not mitigated, a prolonged stress may lead to failure of these assets. In proactive resilience enhancement, the n-Grid resources may be deployed to alleviate the stress and prevent asset failures.

The effectiveness of using n-Grid resources in mitigating the risk of power transformer failure and loss of life is extensively studied in authors' publications [23]-[29]. In [24], battery energy storage, PV generation, and EV charging are optimally coordinated with an objective function including electricity and transformer loss of life cost. In the use case study in [24], the value of total revenue for the utility company and n-Grids owners was up to twice the case when compared to the approach where the resources are optimized based on electricity costs only. The profit for utility company is significant enough to motivate them to perhaps invest in the n-Grids resources to enhance the resilience proactively.

In [23], an on-site controller that coordinates the charging of EVs to mitigate the risk for transformer failure and improve the resilience of the grid is developed. In the mentioned study, the probability of failure for the distribution transformer caused by EV charging decreases from 74% to 13% with EV coordinated charging using on-site controllers and distribution system operator (DSO) decision support tool. In [26], a management system for apartment buildings that could operate independent from distribution system operator and mitigate the risk for the transformer connected to the building is developed. The schematic of such a system is shown in Figure 5.

4.2. Reactive Resilience Enhancement

The impacts of some contingencies such as feeder outage may not be preventable operationally and actions to improve the resilience of the grid for these events is reactive. The first step for reactive resilience enhancement is an ability to predict the probability of event occurrence. A few research efforts focused on predicting feeder Outages [30]-[32]. Once it is predicted that the outage probability is high, n-Grid owners can plan to have enough resources for two purposes:

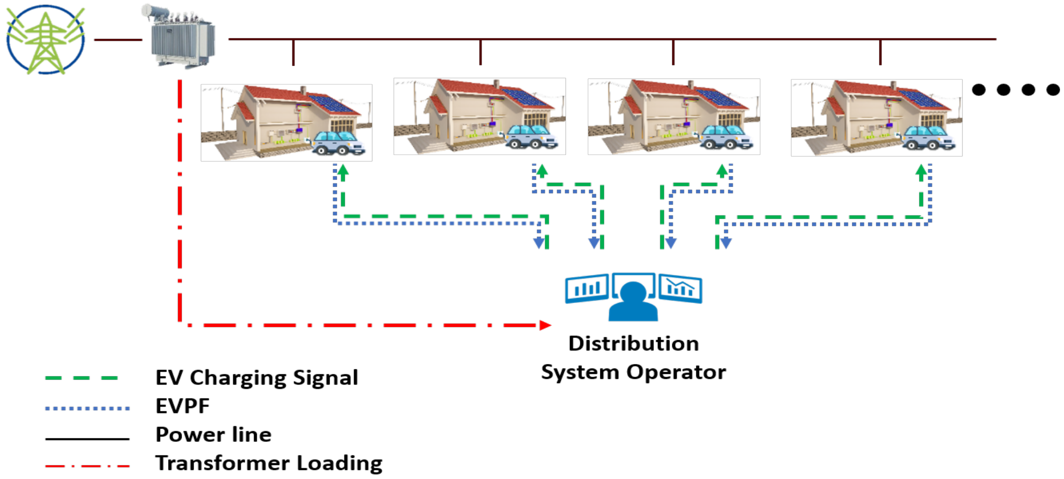

Figure 5. The schematic of the system under study [23]

a) Serve its own critical load;

b) Provide energy to other n-Grids experiencing an outage.

For this purpose, in addition to the predicting an outage, n-Grids should have an on-site control managing the resources based on the n-Grid owner's inputs. An example of such a system can be found in [23] and [25] where an n-Grid Resource Management System (nGRMS) shown in Figure 6 is described. The nGRMS shown in Figure 6 is based on a fuzzy logic controller that provides an index using the inputs from the n-Grid owner and EV's state of charge. The index is sent to the distribution system operator to manage the charging of EV in the n-Grid using DSO's decision-making algorithm. This system operates based on the n-Grid owner comfort level selection, and the status of the on-site resources (e.g. statement of charge, estimated time of departure and estimated distance of the next trip).

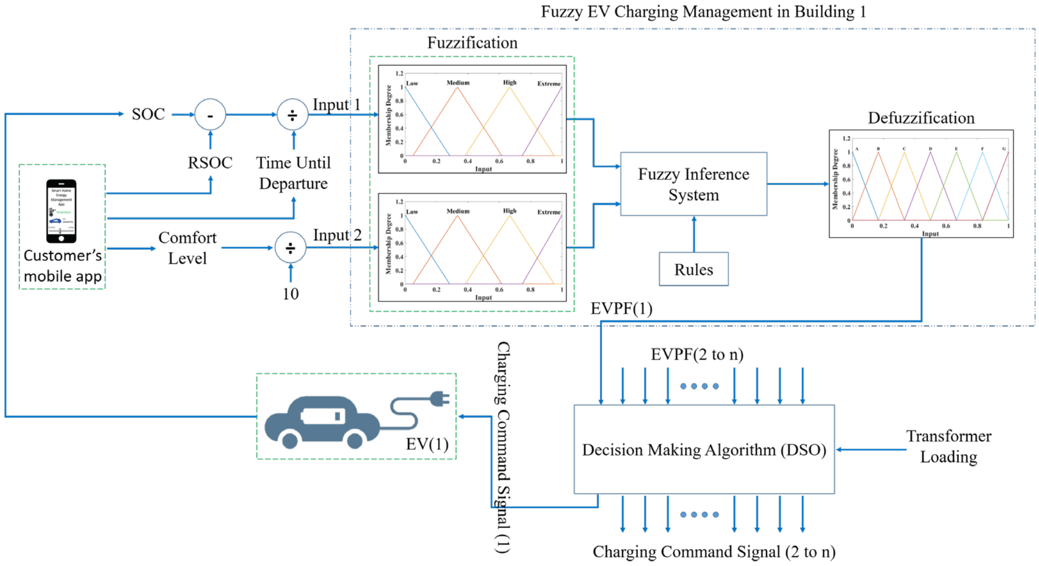

Figure 6. The schematic of the proposed nGRMS solution [23]

4.3. Discussion and Recommendations

The concept of n-Grid is a novel concept that provides challenges and opportunities. The utility customers have been viewed as passive loads traditionally, but when they deploy new resources and become n-Grids, predicting their consumption and generation is more complex for grid operators. In addition, penetration of EVs may cause new load peaks in the distribution grid. The n-Grid resources provide the flexibility for n-Grids to serve their own load and provide services to the grid. It is recommended that these resources can be used to improve proactive and reactive resilience of the distribution grid by preventing the assets from failure, as well as mitigating the impacts of an outage.

CONCLUSION

This study provides a comprehensive overview of the applications and challenges of interfacing ADLs to the utility grid, in particular using n-Grids as ADLs. The following are concluding remarks:

- The n-Grid aggregation can offer ASPs in the WEM which can improve the reliability of the grid while increasing the profitability for the aggregator. This application is emphasized by FERC Order 2222.
- The n-Grid resources can be deployed to enhance the proactive resilience of the electric grid by mitigating the risk of the asset failures and improving reactive resilience of the load serving as the backup for its own load and other loads through transactive energy services.
- The cyber-security challenges of n-Grid communications must be addressed before widespread usage of this technology in power grids. Implementing blockchain technology to improve cyber security of such communications is promising.

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