Harvesting the Nano-Grid Flexibility

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SUMMARY

Development of consumer-owned Distributed Energy Resources (DERs) is accelerated driven by different motivations: carbon-free future, local power supply resilience, favourable electricity time-of-day pricing, and possibility to trade power. As a result, many projects around the USA and world-wide are undertaken to demonstrate benefits of mass-deployment of such resources. The most common approach to the implementation is to have either a very simple on-site deployment of a single energy resource such as roof-top PV generation, or residential EV charger, or more complex microgrid for a commercial or industrial setting with several types of local generation and storage resources for on-site load demand management. Such a DER infrastructure that can consume or produce power is often called prosumer or virtual power plant. It is designed to provide much needed electricity grid resource management flexibility.
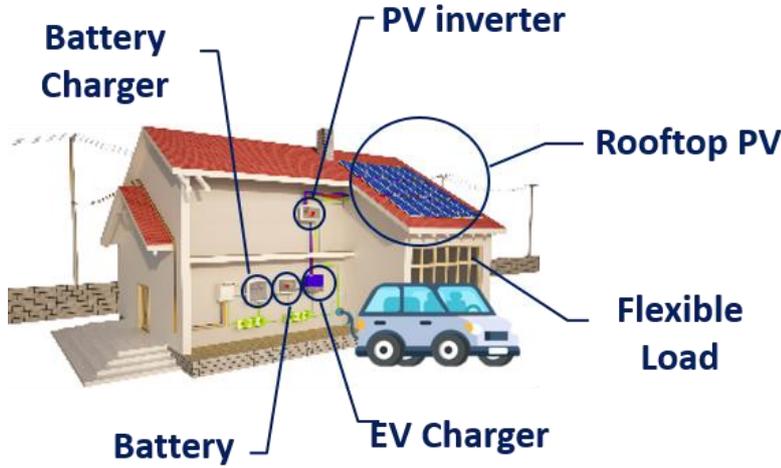
This paper is focused on a very specific configuration of such a DER that is aimed at residential applications and consists of Photovoltaic (PV) generation and Battery Energy Storage System (BESS) that comprises stationary battery storage and Electrical Vehicles (EV) charger for interfacing vehicle's mobile battery energy storage. We define such configuration as a nano-Grid (n-Grid) due to its simplicity and relatively small power rating. Combined with the local load, the n-Grid can utilize fairly sophisticated energy management system aimed at several objectives: a) minimize the cost of energy use by the n-Grid owner, b) offer its energy capacity in the wholesale market Ancillary Service Products (ASP) through an aggregator, and c) provide the distribution grid support through a retail market service. To play such different roles, the n-Grid has to rely on a local (on-site) energy management system capable of harvesting the n-Grid flexibility while accounting for spatiotemporal planning of the n-Grid energy resources. We will summarize several use cases of the utilization of n-Grid's flexibility with an assumption that the n-Grid interface to the distribution grid is capable of bidirectional energy exchange. In the examples, the basic components of the n-Grid are selected from today's product offering. We have also included an example of a customized grid interface controller capable of performing smart inverter functionalities through a unified (common) n-Grid interface.

KEYWORDS

Distributed Energy Resources, nano-Grid, Energy Management System, PV generation, Battery Energy Storage, Wholesale Electricity Market, Retail Electricity Market

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1. NANO-GRID FEATURES

The basic architecture of an n-Grid is shown in Figure 1. The commercial products that may be considered for the implementation are a typical home PV system rated at 4-26kW [1], a stationary battery energy storage rated at 13.5kWh [2], and a standard EV with a mobile battery energy storage of 40-66kWh [3]-[5]. The EV charger of Type 2 with a rating of 7.4kW may typically be used for an 8-hour charging cycle. The controller used to interface the PV and stationary BESS is a bidirectional inverter that may be used for self or grid-tied consumption. All the components may be connected to a common AC bus rated at 230-240V. While such components are readily available on the market, a single customized bi-directional controller for the n-Grid may be needed to achieve full flexibility.

Figure 1 n-Grid Architecture

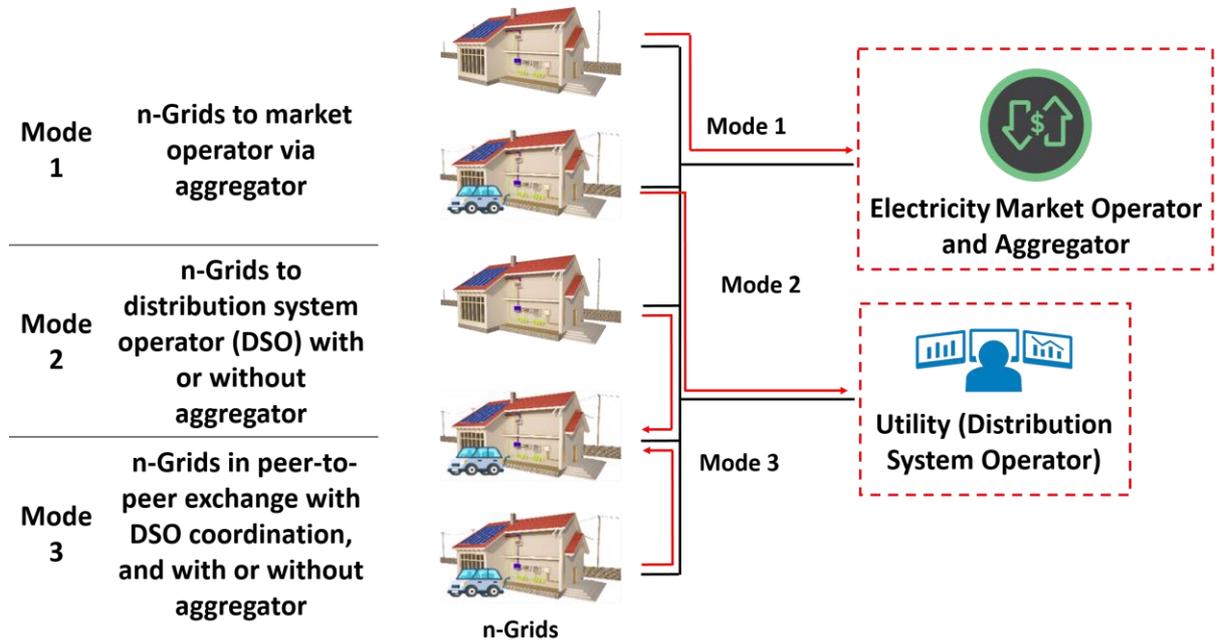In pursuing the n-Grid flexibility, we assumed several n-Grid operating modes (Figure 2).

Figure 2 n-Grid operating modes

The operating modes envisioned for engaging an n-Grid in the energy exchange are: a) with the wholesale market, b) with the retail market, and c) peer-to-peer (n-Grid to n-Grid). In this paper we will only cover the first two types exploring the n-Grid flexibility achieved by aggregating n-Grids for ASP participation in the wholesale market (WSM), and enabling individual n-Grid interaction with the distribution operators to offer the retail market (RTM) services. In each of the approaches we focus on the design of an energy management solution in a form of the optimization software or a physical

controller with the embedded energy management functionality. The energy management solution may reside at the n-Grid and/or an aggregator.

The aggregation of n-Grids enables offering different ASPs to the WSM which brings about higher profitability for them. The authors in [6] proposed a risk-averse model for participation of n-Grids in the WSM when offering the frequency regulation ASP. In [7], the authors developed a collaborative market participation model for n-Grid aggregators using the information gap decision theory. The scenario trees are employed to model the EV fleet as a virtual battery which participates in the WSM using a novel regrouping algorithm [8]. A quantitative compensation mechanism is proposed in [9] which secures the n-Grid profitability in demand response programs. In order to ensure deliverability of ASPs in the WSM, a hierarchical model predictive control (MPC) is developed in [10].

The operation of the components in the n-Grid may impose several challenges to the distribution grid. An example is an extra demand on specific feeders, which may experience earlier-than-expected need for the upgrade of the distribution transformers [11]-[13]. It also may cause under-voltage condition in the grid [14], [15]. Considering that these components are usually accompanied by inverters, the power quality is another main issue that may be affected [16]. On the other hand, the same n-Grid components can provide the flexibility of providing various services to the grid to mitigate the impacts of the very same challenges. Such services may be mitigating the risk of transformers operation [17], [18], providing voltage regulation [19]- [21], and improving power quality [22].

2. N-GRID PARTICIPATION IN WHOLESALE MARKET

The minimum capacity required for direct participation in the WSMs in the US is 100 kW to 1 MW, depending on the market. Hence, participation of n-Grids in the WSM calls for an aggregator or a load serving entity to aggregate n-Grids' resources and participate in the WSM on their behalf.

The major APSs in the WSMs are given in Table 1 [23]-[24]. The frequency regulation ASP is procured to maintain the system frequency at 60 Hz. Procurement of this ASP requires (i) being equipped with the automatic generation control (AGC) system and (ii) ability to be dispatched in every 4-6 seconds. The spinning reserve (SRP) and non-spinning reserve ASPs are procured to respond the potential contingencies in the system. In order to be eligible for these ASPs, the market participant must be able to deliver energy within 10 min of the ISO's command. Besides, for SRP procurement, the resource must be connected to and synchronized with the grid whereas for the non-spinning reserve ASP, the resource must be able to connect, synchronize and deliver the energy within 10 min.

Table 1. different ASPs offered in various WSMs

| Type of ASP	Main purpose	Requirements	Time-frame
Frequency regulation	Maintain Freq. to 60Hz	Equipped with AGC	~ 4 Sec
Spinning reserve	Contingency Response	Sync. to Grid	< 10 min
Non-spinning reserve	Contingency Response	Be able to Sync. to Grid	< 10 min

2.1. N-Grid Resource Management for WSM

Next, we elaborate on how flexibility of each n-Grid resource can be employed to procure ASPs for the WSM with the focus on spinning reserve ASP.

The fixed BESS located inside n-Grids can operate in three states: idle, discharging, or charging modes. The energy storage capability of BESSs can be harnessed to perform energy arbitrage, i.e., storing energy when the market prices are low and generating energy when the market prices are high. Furthermore, due to their high ramp rates, they can offer ancillary services which can be delivered quickly upon ISO's request. The BESS can offer SRP by increasing the discharging power or

decreasing the charging power. As shown in Figure 3, in discharging mode, the BESS's SRP is limited to the remaining power capacity (maximum discharging power limit minus current power output). In charging mode, the BESS can be assumed as a load and its SRP is limited to the current power output minus minimum charging power limit. The available capacity for SRP is lower than the available state of charge (SOC).

As depicted in Figure 3, the aggregated EVs can be employed similar to BESSs for energy arbitrage and ASP procurement. However, they can offer such services only when they are connected to the charging station. Since the aggregator must submit energy and ASP bids to the DAM, it must forecast the availability and status of EVs in advance. Accurate forecasting methods become vital since any inability to deliver the ASPs imposes serious penalties to the aggregator.
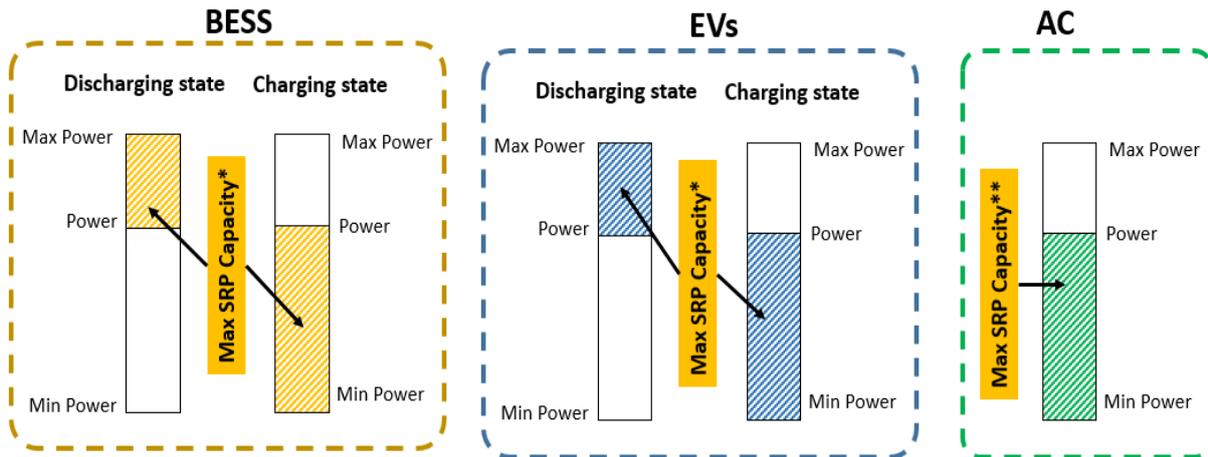
Figure 3 Flexibility of n-Grid resources deployed for SRP
*In BESSs and EVs, the SR capacity is limited by the remaining SOC.
**In HVAC, the SR capacity is also limited by the temperature comfort range of occupants.

The AC thermostat inside each n-Grid dwelling can be controlled by the aggregator aiming at offering ASPs to the market. As an instance, the SRP can be procured by lowering the AC load as needed. As shown in Figure 3, the SRP capacity of ACs is limited to the average power output minus minimum power over a given period of time. Since the building temperature must remain inside the temperature comfort range set by the occupants., an optimal offering of ASPs procured by the ACs relies on an accurate forecast of the outside temperature, proper modelling of the building thermal capacity, and building occupancy.

Some other loads of residential n-Grids such as dishwashing and laundry machine can be controlled or deferred, as well. On this basis, the occupants may set a range of time in which the work must be done. The aggregator uses this range to schedule the load at the times with lower energy prices.

2.2. Aggregator Decision-support Tool

In our framework, the aggregator is a load serving entity envisioned as a mediator between the n-Grids and the WSM. It can manage the n-Grids resources directly through internet of things (IoT) and offer ASP participation in the market. The interaction of the n-Grid/aggregator/ISO is depicted in Fig. 4.

The ISOs tend to procure 100% of their ASPs needs through the day-ahead market (DAM) and procure marginal amounts through real-time market. The energy and ASP prices of DAM, compared to real-time market, are much less subject to fluctuations and uncertainties. Hence, participation in the DAM is of a vital importance for the aggregators to assure profitability.
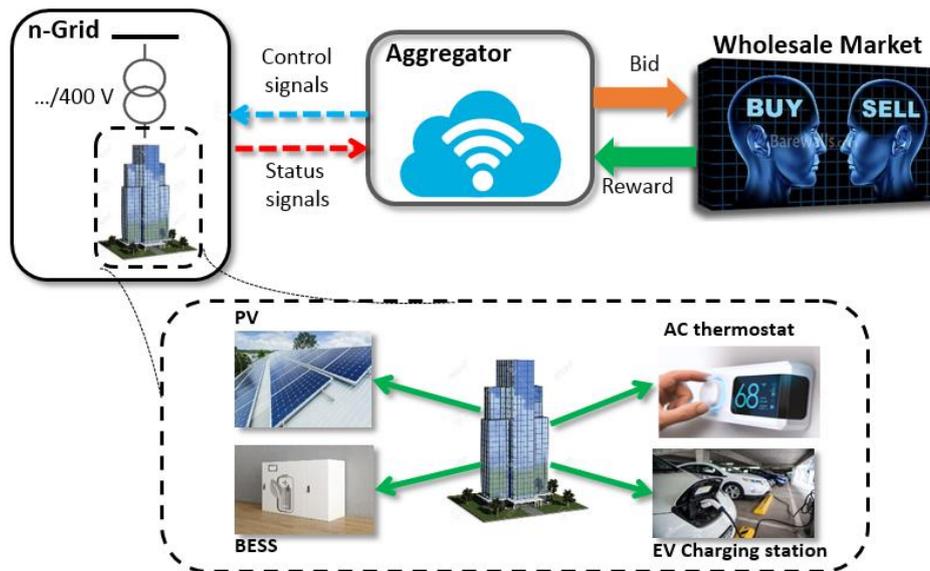
Figure 4 The n-Grid aggregator framework for participation in WSM

Further, in order to participate in DAM, the aggregator must capture different uncertainties to assure its profitability which otherwise, may lead to a drastic profit loss. These uncertainties include market prices, EVs arrival, departure and initial state of charge (SOC), ambient temperature, PV generation and n-Grids' electric load. The aggregator may benefit from stochastic programming methods to manage such uncertainties. A proper optimization framework is a bi-level optimization in which the uncertainties are captured through predefined scenarios. The aggregator schedules the n-Grids at the upper-level optimization and runs an estimate of the market at the lower-level to obtain the forecasted marginal prices. It enables the aggregator to anticipate the behaviour of other market participants and submit optimal energy and ASP bids accordingly.

Our case studies demonstrate that under proper market participation model, the aggregator can make significant profit out of ASPs in the market. In fact, the SR profitability is ~10% of the total energy costs. Also, ASP is mostly provided by the EVs connected to the commercial buildings. Then, EVs in residential buildings, BESS and AC. The reason is (1) the capacity of EVs is much higher than other resources (ii) the EVs are connected to commercial buildings during working hours (usually 9 am to 5 pm) when the energy and ASP prices are high, and the aggregator can make higher profit. EV and BESS provide high ASP energy amounts since they can operate in both charging and discharging modes. The AC load is not significant and cannot offer much capacity due to temperature limits set by the occupants.

2.3. Benefits of n-Grid Resource Flexibility for WSM

N-Grids are valuable assets to the WSM. Modern WSMs suffer of low flexibility caused by high penetration of intermittent renewable resources, e.g., wind farms and solar plants. The high ramp rate and storage capacity of n-Grids can be utilized to charge when there is extra renewable generation and discharge when there is generation shortage. Their ramp rate can be also employed in procurement of different ASPs, namely, SR and frequency regulation. Their ASP can be activated immediately which compared to thermal generators is significantly faster.

Under attractive incentives, they can participate in demand response and load shedding programs. These programs are particularly useful for the market operators in managing sudden market price spikes and transmission congestion mitigation. However, one needs to notice that such capabilities can be only harnessed when the intrinsic uncertainties associated with the n-Grid resources are properly managed.

3. N-GRID PARTICIPATION IN RETAIL MARKET

One way to deploy the flexibility provided by n-Grids through services for supporting the grid is through direct interactions between Distribution System Operator (DSO) and n-Grids, which relates to the retail market. In this framework, the available resources in the n-Grid can be used to provide services based on the need of DSO through incentive programs or real-time bidding using either direct arrangements made between n-Grids and DSO or arrangements between an n-Grids aggregator and DSO.

3.1. N-Grid Resource Management for RTM

When n-Grid is owned by small consumers such as residential customer, it is important that participation in the market does not make significant discomfort to the consumer. Since the impact of each n-Grid on the distribution grid is low, and the incentive is relatively small, the n-Grid resource management and the interactions between n-Grids and DSO should be designed in a way to avoid consumer inconveniences of frequent communications. As a result, it is necessary to automate the management of resources and interactions between DSO and n-Grids using an n-Grid on-site controller.

An example of an on-site controller designed for demand load management is shown in Figure 5. The controller assesses the risk for each resource based on its current status and the duty that they are supposed to complete in a timely manner. For example, the risk related to EV charging is the time that EV charger needs to charge the EV to the required level for the next trip, divided by the estimated time, which is left until the next trip. Then, controller sends the quantified risk values for each EV
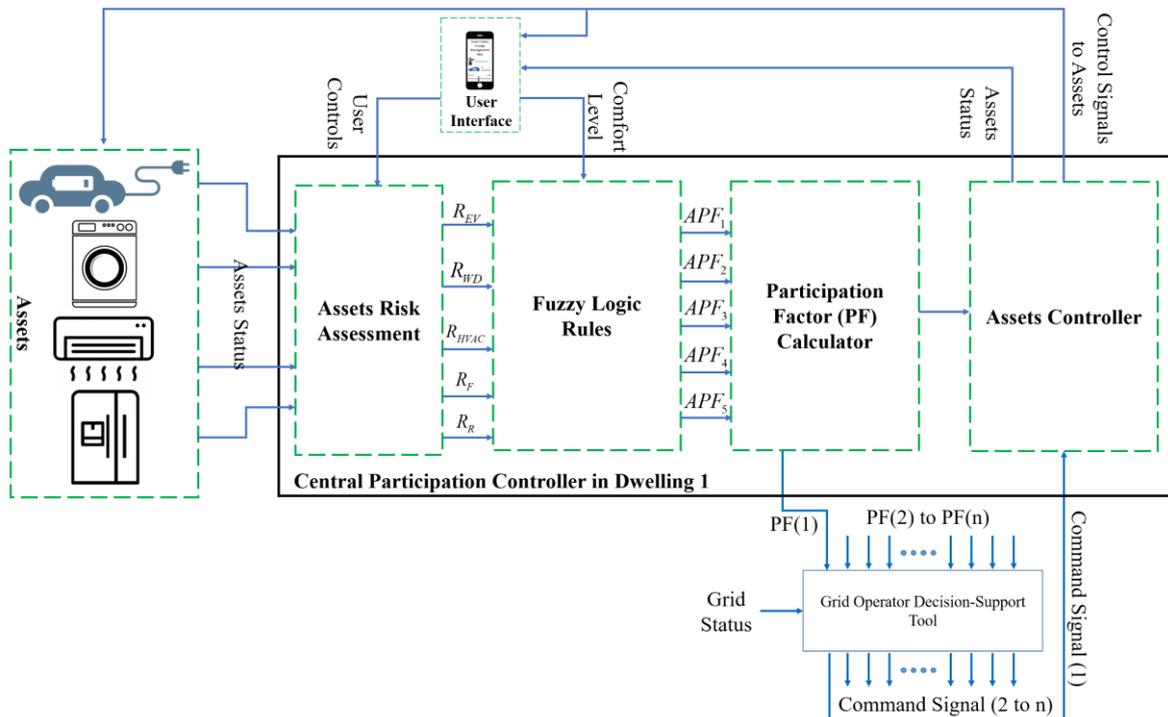

Figure 5. The schematic of an in-site controller [25].

asset to a fuzzy logic system which uses them along with the charging comfort level selected by the consumer and provides an index namely participation factor. It is sent to DSO and used as a bid in the retail market as the availability of n-Grid resources to participate in an incentive program. When the n-Grid resources are selected to provide a service to the grid, the command signals will be sent from DSO to the on-site controller and the controller will manage the resources accordingly.

3.2. DSO Decision-Support Tool

The bids submitted by the n-Grid can be deployed by the DSO operator to use the resources for different purposes such as voltage regulation, power quality improvement, or mitigation of transformer overloading. For example, assume that the residents of a neighbourhood start deploying EVs. Considering the significant level of the on-board EV chargers' nominal power in comparison to a residential load, high penetration of EVs may have a conspicuous impact on the distribution transformers by causing significant overloading [26].

Due to this particular clustering of consumers that own EVs, the transformers of this feeder may be imposed to stressful operating condition and prone to failure resulting in a replacement with a transformer of higher kVA rating much earlier than their life expectancy would suggest. In [17], a decision support tool is developed for DSO to coordinate the charging of EVs in the grid based on the participation factors it receives from the n-Grids. This algorithm calculates the economic impact that deployment of each resource can have on mitigating the risk of transformer failure. It starts to deploy the resources from the one with the lowest bid and compares whether the economic impact of deploying the resource can outweigh the bid. If it does, a command will be sent to the n-Grid to postpone the charging of that particular EV. Then, the impact of the next EV with the lowest bid continues until the point where it is not economically reasonable to deploy more resources. The schematic of such a system is shown in Figure 6.
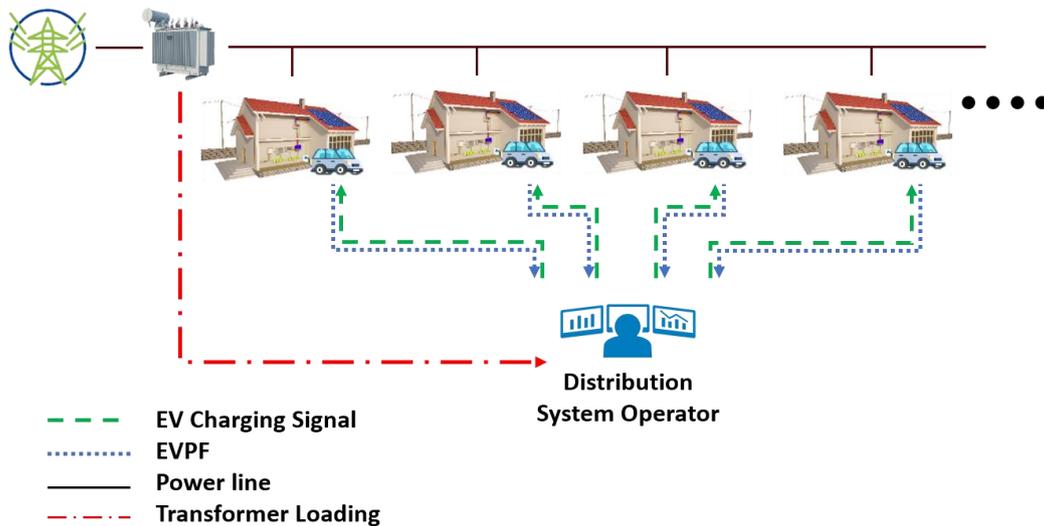

- – – – EV Charging Signal
- ·········· EVPF
- ——— Power line
- —·—·— Transformer Loading

Figure 6. The schematic of the system under study [25]

3.3. Benefits of n-Grid Resource Flexibility for RTM

Deployment of the explained control method for mitigating the risk for transformers appeared to be extremely effective and economically profitable. As explained in [17], it could decrease the probability of failure for a distribution transformer during one year from 73% to 13%. Also, it decreased the per kW electricity price for consumers to cover the replacement of transformers cost by 83%. The remaining cost after deploying the controller is the sum of the cost of the paid incentives as well as the cost of transformer loss of life and probability of failure after charging control. During the case study, no occasions where found when an EV did not have enough charging power for its next trip which means that the idle hours that EV was parked and connected to the grid are effectively used to mitigate the impact on distribution transformers.

There is a flexibility for n-Grid resources and if harnessed effectively, it can be beneficial both for n-Grids and distribution system operator. In the n-Grid resources management example for mitigating the transformer overloading, if this flexibility was not harnessed, DSO had to spend a lot of money upgrading the transformers of this feeder, some may have failed before the upgrade and caused an

unexpected outage while the EVs are parked with full charging for long hours when they may not be needed.

A similar flexibility can be defined for PV generation and battery energy storage systems. Considering that the assets are ageing, the penetration of renewable energy is expanding, and the incidents of severe weather are increasing, the flexibility provided by n-Grid resources can provide an unprecedented opportunity which may be utilized by DSO for supporting the grid and mitigate the impact of abovementioned threats. Harnessing this flexibility can happen in a regulated structured RTM framework. The harnessing this flexibility should not significantly affect the main role of these components which are left with enough energy to give the EV owner a ride to their desirable location to feed the n-Grid load should the battery energy system experience an outage.

CONCLUSION

Based on the reported activities, several conclusions may be reached:
- The n-Grid flexibility may be utilized in both WSM and RTM
- For best results, the WSM participation may be coordinated through an aggregator as outlined by the FERC Order 2222
- A local n-Grid energy management function may be needed to allow individual consumer decisions about an optimal use of the n-Grid resources
- The WSM and Distribution company operators are expected to gain benefits from the n-Grid flexibility through ASP and grid support services respectively

ACKNOWLEDGMENT

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