An Optimal Allocation of Reactive Power Capable End User Devices for Grid Support

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***Abstract*—The increasing penetration of photovoltaic (PV) systems in low voltage residential feeders has elevated the need for grid support at the distribution level to prevent violations of local voltage constraints. In this paper, a coordinated reactive power support methodology is presented that utilizes the demand-side flexibilities of the end-user to keep local voltage levels within allowed levels. A cloud-based architecture is implemented to optimally coordinate consumers' reactive power capable demand-side resources such as electric vehicles (EVs), solar PV systems, flexible home appliances etc. considering their varying characteristics, ratings, and purposes. An optimization-based two-stage device scheduling and management model is presented for the cloud server that schedules consumers' devices in day-ahead for cost minimization, and optimally allocates the required reactive power support in real-time among the candidate devices based on priority. Two device prioritization strategies are proposed that consider the reliability of reactive power capable consumer devices and management complexity, thereby allowing consumers to either enhance the candidate devices' lifetime or reduce management complexity while participating in grid support. The proposed reactive power support methodology is validated using simulation studies, and an experimental setup is established to verify the viability of the proposed cloud-based coordination system for reactive power support. Case studies indicate that the proposed method can effectively prevent over-voltage situations by using coordinated reactive power support from consumers' devices while maximizing their reliability. Results also indicate that the proposed methodology is economically more viable than state-of-the-art voltage control strategies.**

***Index Terms*—Reactive power support, optimization, cloud communication, demand-side management, device to grid**

I. Introduction

THE power demand in future grids is supposed to be supplied by distributed renewable energy sources such as from PV units and wind generators. The use of these energy sources is desirable because of their environmentally friendly nature. Integration at the distribution level consists of low-powered commercial or residential PV solar panels with or without battery storage systems [1]. One of the major concerns associated with increased PV penetration at the residential level is the overvoltage problem faced by low voltage (LV) distribution systems due to their limited capacity, combined with low power demand at that instant [2]. This prevents more active power from being injected into the grid, and it is also detrimental to the devices connected to the grid. Although the liability is currently on utility for maintaining power quality and reliability, this responsibility is expected to be reduced in future grids, requiring broader participation, perhaps even from consumers.

Traditional approaches to addressing overvoltage issues include the use of voltage regulators or providing reactive power support (RPS) using an On Load Tap Changer (OLTC) and capacitor banks. However, these methods are slow at responding to the required support and high maintenance is needed for frequent switching [3]; therefore, they cannot deal with the variability of power flow in modern power grids that introduced by intermittent renewable resources [4]. Another approach alters the operating times of home appliances to control the active power flow in the network through certain incentives and energy price variations, referred to as demand-side management [5]. However, the benefit of this approach may come at the cost of consumer convenience. One of the most effective mechanisms is to consume reactive power to offset the voltage rise from PV integration. This can be done through static synchronous compensator (STATCOMs), but they are generally installed in transmission lines, and providing reactive support to distribution lines from STATCOMs is unfavorable due to high network loss. In this regard, the presence of distributed reactive sources is highly desirable. The authors in [6] have highlighted the advantages and effectiveness of distributed reactive support. An interesing alternative is involving the end user electrical appliances with reactive power capacity as a resource of reactive power itself [7]. Various studies have examined probable sources of reactive power at the low voltage distribution level through utilizing the spare capacity of PVs and EVs [8], [9].

Recently, a notable approach was suggested for voltage regulation in low voltage distribution grids, where the active power injection of PV inverters is limited [10], [11]. The main idea is to restrict the active power output such that the root cause of the voltage rise is addressed. However, there are two main drawbacks that make this a non-preferable solution. First, this approach causes financial loss to the PV owners because of energy wastage, which otherwise could have been transferred to a remote location or stored [12]. Secondly, the PV hosting capacity (capability of the distribution grid to accommodate more PV power) is reduced [13]. These facts again restate the benefits of using distributed reactive power support through

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widely distributed reactive capable devices. Apart from PV and EVs, other power converter based devices such as uninterruptable power supplies (UPS) and home appliances (HA) are also potential reactive sources [4]. They can be utilized fully for reactive support while they are idle, or using their spare power processing capacity while in operation [14]. These devices will inevitably have to be multi-functional, and research has reinforced their important role in grid support, especially reactive power support [15], [16]. The key idea is to use the DC link capacitor (reactive buffer) present in these grid-interfaced power converters forming the power supply for electrical loads, and EVs and PV systems. They are widely prevalent in low voltage networks and are located close to where the reactive support is desired. Due to their fast and accurate response to reactive demand, they easily outperform conventional reactive resources like capacitor banks. Moreover, these reactive sources can also be employed to generate reactive power to local loads and improve the power factor. This also reduces the reactive power flow in the network and consequently decrease network losses.

The main challenges associated with engaging multiple power converter-based reactive capable devices are their management and reactive power allocation. The forthcoming home appliances, PV inverters and EVs are all integrating smartness into them to gain the benefits brought by smart homes and smartgrid systems [17]. The devices will be able to communicate effectively with a home aggregator, which will also provide the operation commands. The platform provided by smart grid and smart homes can be utilized by the device to support the grid through reactive power exchange whenever required [18].A example of such implementation is carried out in [19] where authors use HEMS to realize an optimization algorithm considering both the active and reactive power consumption and scheduling of home appliances and distributed energy resources.

One of the key concerns associated with employing different reactive devices, made of power converters, is managing these devices, and the key concern is how to optimally allocate the reactive power. The authors in [20] used an online supervisory voltage control mechanism to allocate reactive power support among PV inverters to improve the network voltage profile. The reactive power allocated to each inverter is a function of the PV inverters' capacity and the active power generated. Correspondingly, PV inverters generate less active power and contribute more reactive power and vice versa. In [14] home appliances are employed for grid reactive power support. The reactive power allocation is a function of the total usage time of the appliances. Hence, the least used appliances are ranked higher and prioritized for reactive power support. Likewise the authors in [21], suggested using a grid-interfaced voltage source converter of a doubly fed induction generator (DFIG) wind park to exchange reactive power for voltage control. In the study, six wind turbines are connected to a medium voltage network and communication delay is taken into account for coordinated optimal tracking secondary voltage control. The allocation algorithm considers all have the same capacity, and they are again located far from a distribution network, where reactive support is generally required. However, most studies either consider one type of device at a time for reactive power allocation, or ignore the variability of the rating and type of reactive capable devices, especially at low voltage distribution level. In addition, consumers' preferences-reservation is a major concern when utilizing their flexibilities for grid support services [22]. To this end, a coordinated reactive power support mechanism is presented in this paper to maintain local grid voltage within allowable limits. The coordination among reactive power capable devices in the network is realized by implementing a cloud-based architecture, where the consumers submit their preferences and a cloud server optimally allocates the required reactive power support among available devices. The key contributions of this paper are to:

- design and implement a cloud-based coordinated reactive power support mechanism to optimize demand-side flexibilities for local voltage control in LV residential networks.
- develop a two-stage device scheduling and management methodology to minimize consumers' energy costs in the day-ahead stage and optimally allocate the required reactive power support among candidate devices in the real-time stage.
- develop a device prioritization strategy based on reliability and management complexity to enhance the device's lifetime and preserve consumers' preferences while providing reactive power support.

The proposed architecture is validated through simulation in MATLAB® Simulink, and case studies are presented to validate the efficacy of the proposed methodologies for effective reactive power support during overvoltage and improvement of the power factor at home. Moreover, the financial benefits of the proposed approach are also analyzed for maintaining a nominal grid voltage level while maximizing power import to the grid. In addition, the communication of various RPS devices with the cloud server and proposed algorithm is validated in the laboratory.

The structure of the paper is as follows: Section II introduces the proposed architecture and gives a brief overview of the available reactive sources. Section III discusses the proposed architecture of the smart home support system and proposed algorithm of reactive power allocation. Simulation results for the proposed grid support system are presented in Section IV and the corresponding experimental results using ThingSpeak® are discussed in Section V. Finally, Section VI presents the concluding remarks and a summary of the paper.

II. Feature of Reactive Sources

Future smart homes will have multiple reactive power support capable sources. Although all of these sources will be designed for their primary purpose, through minor control modifications they will be able to utilize spare capacity for grid reactive power support. This modification will mainly be carried out in power converters that will make the device capable of supporting reactive power to the grid. The power converter topology employed can overall be segregated into two stages: a grid-side converter (GSC) interfaced with the grid and a load-side converter (LSC) connected to the load. The LSC can either be a DC-AC or DC-DC converter depending on the type of load or source as given in Table I. Although LSCs can be different for a range of devices, the GSC will be the same and mainly responsible for AC–DC/DC-AC conversion. The converter interfaced to the grid is generally a single phase full bridge converter with bidirectional power flow capabilities. A DC link capacitor isolates the grid connected converter (GSC) with the LSC. This DC link capacitor is the source of reactive power, both capacitive and inductive. In general, the operation of these candidate resources can be divided into four quadrants as shown in Fig. 1. The flow of active power is in one direction while the reactive power can either be capacitive or inductive depending upon the type of support required. Fig. 2. represents the standard reactive power control method for voltage regulation. If the grid voltage increases above Vnl or decreases below Vnh , a suitable amount of reactive power is either consumed or injected into the grid, respectively, to ensure the grid voltage remains within a nominal value.

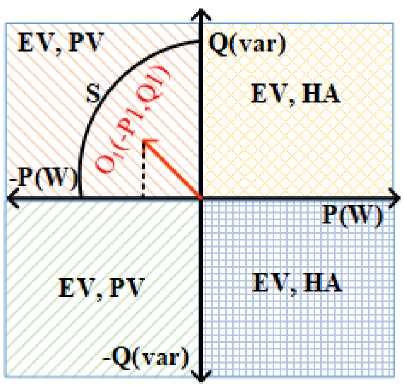

Fig. 1: Different reactive resources and their quadrant of operation

The required reactive power support can be achieved through appropriate converter current control of AC-DC/DC-AC GSC. The converter should monitor and calculate the active power consumption to determine the remaining spare capacity for reactive support. The standard control structure generally used for control of grid-interfaced converter is shown in Fig. 3. It is a dual loop control system, with the outer loop regulating the voltage of the DC link capacitor to a reference value. The outer loop regulates the real power flow by drawing the active power component (I_d) from the grid. The reference reactive current (I_q) is adjusted to account for the reactive support from the devices. These two current components serve as the reference current for the inner current loop. The inner current loop forces the converter to follow the reference current. The active and reactive current components are calculated to be

$$\begin{cases} I_d = \frac{2P}{V_d} \\ I_q = \frac{-2Q}{V_d} \end{cases} \quad (1)$$

where, P, Q and V_d are the converter's active power, converter reactive power and grid voltage amplitude respectively. It is crucial to guarantee that the reference current does not surpass the converter's capacity. To ensure that a limiter is included

TABLE I: Home devices with their LSC's

Devices	Power rating (kVA)	Power Consump- -tion dependence	LSC
EV	5	Mobility of vehicle	DC-DC
PV	6	Amount of sunlight	DC-DC
AC	0.2-3	Heat/Cool setting	3ϕ DC-AC
IH	2-7	Cooking zones used	1ϕ DC-AC
WM	0.25-0.5	Washing load	3ϕ DC-AC
DW	1.5-2	Size and capacity	3ϕ DC-AC
MW	1.2-1.7	Capacity	DC-DC

before the reactive current reference,

$$Q^{ref} = min(Q^{free}, Q^{ref}) \quad (2)$$

If S is the rated power processing capacity of GSC and $p(t)$ is the active power consumption the reactive power support potential is obtained as:

$$Q(t) \leq \sqrt{S^2 - P(t)^2} \quad (3)$$

In the following we briefly present the power characteristics presented by these resources

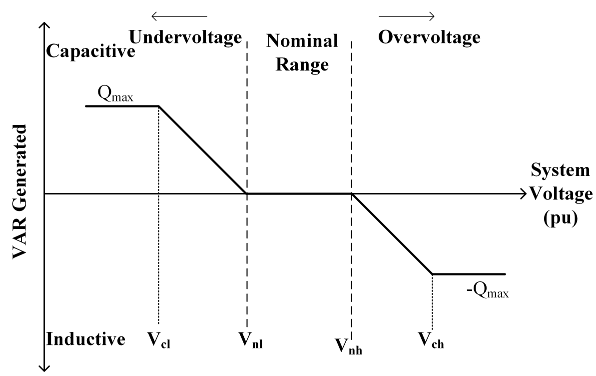

Fig. 2: Voltage regulation through reactive support

1) PV Inverter

The output power from a PV unit varies widely throughout the day. It is intermittent in the absence of a battery storage system, which may also bring fluctuations in the grid voltage. Generally, they inject active power in the daytime and remain idle at night. Due to weather conditions and irradiance, the inverter may operate below its rated capacity even in the day time. The PV inverters present intermittent and low spare reactive capacity in the daytime, while full reactive potential can be realized in the night. The PV inverter can operate in the 3^{rd} and 4^{th} quadrants of the power profile. The free spare available reactive capacity while generating active power of P_{MPPT} is given as:

$$Q^{free} = \sqrt{S_{PV}^2 - {P_{MPPT}}^2} \quad (4)$$

It should be mentioned here that the PV system can also participate in grid support through its active power curtailment (APC). If the available reactive support is not enough to

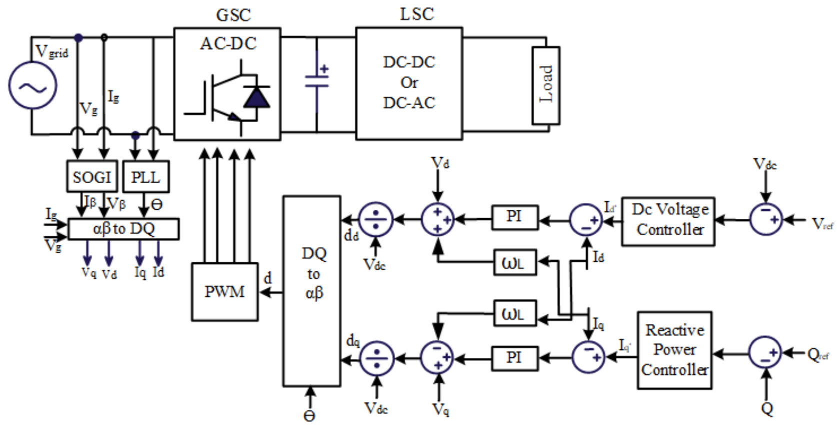

Fig. 3: control structure for reactive power support

regulate the grid voltage, the active power injection from the PV inverter is reduced to restore the voltage within the nominal range.

2) Electric Vehicle

EVs are the only resources that can operate on all four quadrants and provide both active and reactive support to the grid; this means that if required, EVs possess the capability to inject active power to grid during peak demands through its battery storage system. The on-board charger can be utilized to provide reactive support to the grid, which can either be inductive or capacitive. However, they are mobile in nature and their location keeps changing and mostly away from residential areas at daytime in weekdays. However, they are fully available at evening and night subjected that they are put in charging (for next day use) after midnight when the active power demand is low.

3) Home Appliances (HAs)

HAs are found in almost every home, and in the future, smart home appliances will be designed with the capability to provide support to utility in maintaining power quality and reliability. Although they are currently providing support to the grid through active demand management, (whereby their operation times are changed to avoid peak load demand without affecting the consumer convenience), they are also capable of providing both inductive and capacitive reactive support to the grid. Considering the usage pattern of the HAs, it can be inferred that the high capacity from HAs can be attained at day and are lower in the morning and night time. These also reflect human activity at home, which is relatively higher in the morning and at night. Moreover, the stationary nature of HAs is an attractive feature that guarantees a minimum available reactive capacity depending on the amount of consumed active power:

$$Q^{free} = \sqrt{{S_{HA}}^2 - {P_{cons}}^2} \tag{5}$$

Despite the differences in their operating scenarios, all these converters have a similar grid connected converter and control structure. The major difference lies in the direction of active power flow.

III. Proposed Architecture

The electrical loads of future residential areas will have a range of smart appliances such as refrigerators, washing machines, induction heating, air conditioners, televisions, and dishwashers. Furthermore, they will have integrated renewable energy generation sources such as PV and batteries. To optimally utilize the energy for electrically diverse loads, a home energy management system (HEMS) and smart meters are inevitable. The HEMS is an energy management system that monitors electrical loads and sources to efficiently control the consumption and storage of power.

The architecture proposed in this paper for the reactive power support in the grid is shown in Fig. 4. The architecture is a three-layered hierarchical control system. The centralized controller operated by the utility and cloud server is at the top layer of the control system. The HEMS and the devices participating in reactive power support are in the middle and bottom layers, respectively. The HEMS mainly consists of an energy management and communication unit (EMCU) and home aggregator. The EMCU is installed in each outlet participating in reactive power support whether it is a home appliance, PV, UPS or EV. The EMCU contains measurement and communication blocks. The measurement block measures the voltage, and current profile of each outlet to be used by the home aggregator. The communication block is responsible for communicating the data of the measurement block to the home aggregator. The communication block also receives commands from the home aggregator to switch a device on or off to either provide reactive power support or perform its primary function. The Home aggregator gathers information from all the EMCUs and sends it to the cloud server. Additionally, it supports user input regarding appliances' schedule, appliances' priorities for reactive power support, etc., and feeds it to the cloud.

The cloud server is the brain of a smart home, as this is where all the data processing and control algorithms are implemented. It also has data storage for receiving information regarding the voltage and current of the devices including the user input from the home aggregator. The information is used to find the status of the devices and their availability

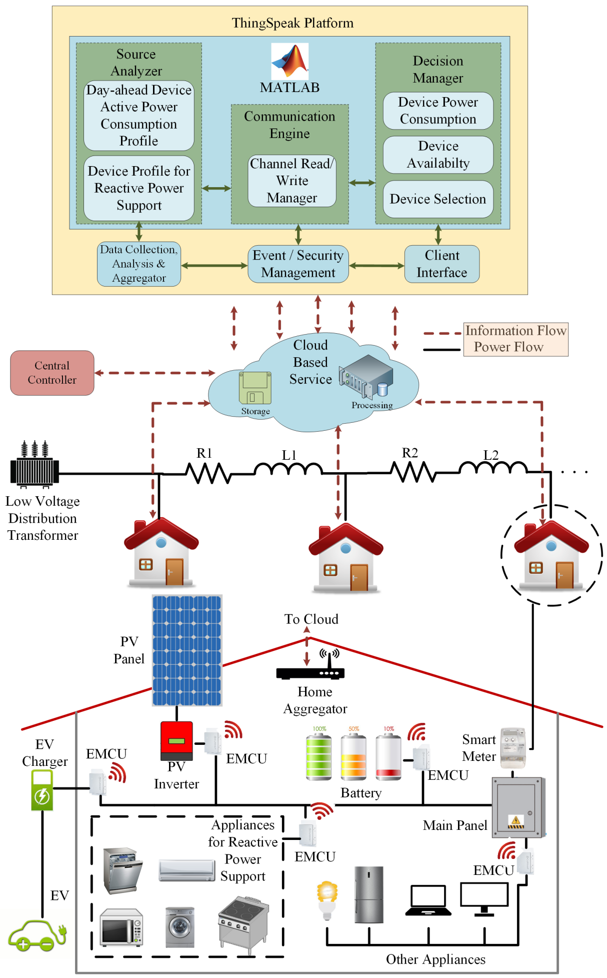

Fig. 4: Proposed architecture

for reactive support and are scheduled accordingly. The cloud server also communicates with the central controller on the utility side through a communication link if any reactive support is required. The cloud server gathers data related to weather forecasts for estimating the energy generation from a PV unit. Since the PV unit performance is strongly influenced by solar radiations, data on weather forecasts can also be used to estimate the generation expected from the renewable energy sources. Thus, based on the PV energy generation profile, the cloud server can optimize and modify the home appliances schedule so that the least energy possible is used from the grid. It can also organize the appliances for reactive support more efficiently.

At the lowest level, a controller is implemented in the device to regulate the active and reactive power output of the converter. Therefore, besides having the ability to consume active power, the devices will exchange reactive power with the grid either by injecting or consuming reactive power. The cloud server receives the required reactive support for each home from a centralized controller that comes through local measurements and some optimization algorithms. Since the cloud server has information on the devices' status and their availability for reactive power support day ahead, the cloud server already knows the total available devices and corresponding reactive power from each home. If a particular home is only able to be partially supported, the cloud server distributes the requested support to other homes such that the overall requirement is met. The cloud server also has additional algorithms for prioritizing the devices for reactive power support.

Communication network is crucial in smart homes for linking the reactive sources to the cloud server via the home aggregator. The cloud server monitors and controls the reactive resources available in smart homes through bidirectional communication with the home aggregator. As the HEMS and the reactive resources are in the close proximity within the home, a Home Area Network (HAN) is suitable for the information and data transfer. HAN communication is low cost, requires a low bandwidth and a short range, and utilizes either wired (Power Line communication (PLC)) or wireless communication. Wi-Fi is generally prevalent in all homes, though ZigBee can be another alternative. In the proposed architecture, the EMCU in each device is equipped with a wifi module to provide the device voltage and current profile to the home aggregator. The home aggregator transfers the real-time device information and the device day-ahead schedule to the cloud using the local area network (LAN). The data stored in the data aggregator in the cloud is accessible by the cloud MATLAB® interface which runs a designed algorithm for the selection of the devices for RPS. In this paper, the ThingSpeak® platform is used as a cloud server for processing the information. ThingSpeak® has the ability to execute the MATLAB® code, through which online analysis and data processing can be done.

IV. Proposed Reactive Power Support Methodology

A two-stage energy management system is proposed for residential houses that includes day-ahead scheduling of the home appliances, and based on that, a device prioritization strategy is proposed for real-time reactive power support. The overall methodology is discussed in the following sections.

A. Day-ahead Scheduling

The day ahead schedules of the appliances help in calculating the approximate reactive power support available at any particular time of day. It is considered that each consumer, $u \in U$ in the community notifies the preferred time slots of the appliance operation in day-ahead to the cloud server via the home aggregator along with the minimum and maximum power levels of the appliances. The home appliances are indicated by indices $n \in \mathcal{N}$, where indices j and k represents the shiftable and non-shiftable home appliances respectively, i.e. $n = j \cup k \in \mathcal{N}$. The cloud server schedules the consumers' home appliances in day-ahead based on the user preferences and the operational constraints of the appliances. The main objective of the day-ahead scheduling is to minimize the net energy cost for the community, and maximize the self-consumption of on-site generation from renewable resources, e.g, a rooftop solar PV system. The day-ahead scheduling model is formulated as a mixed-integer optimization problem to minimize the energy cost for the community. It can be written as:

$$\min \sum_{t\in\mathcal{T}} \sum_{u\in\mathcal{U}} \pi_{u,t} \left(P_{u,t}^{tot}\right) \Delta t \tag{6}$$

$$\begin{aligned} s.t. \qquad & \pi_{u,t} = \alpha_{u,t} \left(P_{u,t}^{tot}\right)^2 + \beta_{u,t} P_{u,t}^{tot} + \gamma_{u,t} \quad \forall u,t \\ & P_{u,t}^{tot} = \sum_{j\in\mathcal{N}} x_{j,u,t} P_{j,u,t} + \sum_{k\in\mathcal{N}} x_{k,u,t} P_{k,u,t} - \mathcal{P}_{u,t}^{pv} \quad \forall u,t \\ & \sum_{t=t_s}^{t_e} x_{n,u,t} P_{n,u,t} \Delta t = \mathcal{E}_{n,u} \quad \forall u \\ & \mathcal{P}_{n,u}^{min} \leqslant P_{n,u,t} \leqslant \mathcal{P}_{n,u}^{max} \quad \forall u,t \end{aligned}$$

here, π is the real-time tariff, which depends on the consumer's total active power consumption from the grid, P^{tot}, as indicated in the first constraint. The second constraint indicates the power balance of a consumer house, where x is the binary variable indicating the operating status of the home appliances (ON or OFF), and P is the active power demand of the home appliances. For the purpose of this study, it is considered that the customers have onsite power generation from PV. The power generated onsite by a consumer is denoted by $\mathcal{P}^{pv}$. The third and fourth constraint ensures the user preferences and operational constraints of the home appliances for the day-ahead schedules, where $\mathcal{E}$ is the energy consumption requirement for home appliances. The user preferences are indicated by the desired operation window for each appliance as indicated by the start time, t_s and end time, t_e. Each user communicates the preferred time slot of the appliance operation, the minimum and maximum power levels of the appliances and the set of shiftable and non-shiftable appliances to the cloud server via the home aggregator. The cloud server solves the optimization equation (6) and sends back the operating schedule of the appliances to the consumers.

B. Device prioritization for real-time RPS

In the real-time stage, the cloud server utilizes the day ahead scheduling data, devices status, and requested reactive support in order to distribute and allocate the reactive power to candidate devices. But prior to that, the cloud server runs a prioritizing algorithm to rank the devices in order of their RPS. For utility, each reactive source looks alike as they are collectively providing the requested reactive support to the grid. However, from the perspective of the cloud server, it has to make a distinction among them because the effect of reactive support on each of them would be different from the other. The cloud server utilizes two criteria: Reliability and Management complexity to generate two different sets of candidate devices, indicated by sets R and M respectively. The cloud server will decide which set to opt for based on the selection factor, k which implements the switching between these two sets as:

$$S = k \times R + (1-k) \times M \tag{7}$$

where, S is the selected set of devices and depends upon the selection factor, k which assumes a binary value. The selection factor assumes '1' if the reliability aspect is considered in devices selection, while it is set to '0' if the devices are to be used based on reducing management complexity.

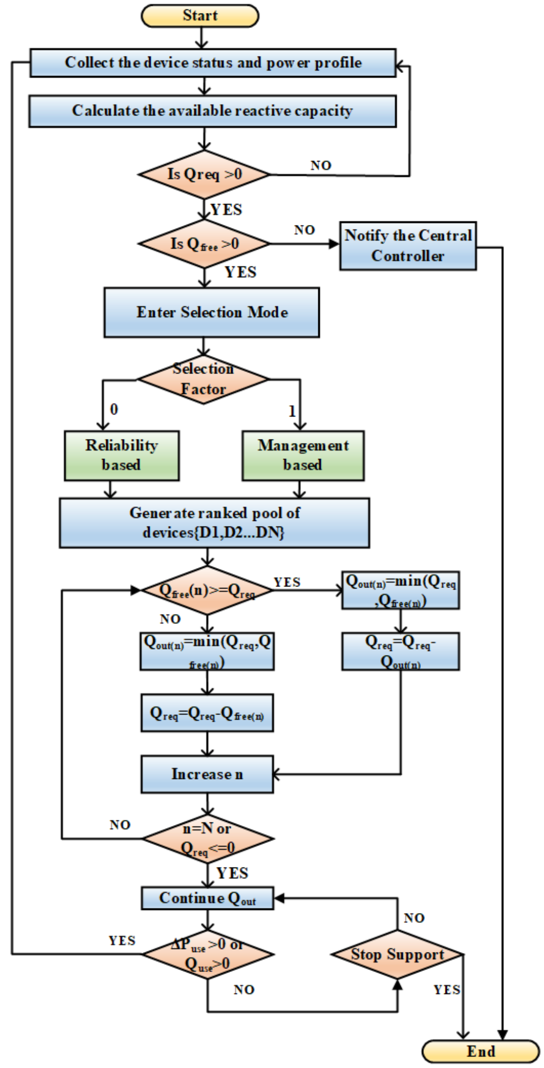

Fig. 5: Algorithm for allocation of reactive power to reactive capable devices

1) Reliability

The additional usage time of the reactive cable devices put additional stress on the device's components. To maintain a higher lifetime period of each device, it is important to space the RPS from each device. Power semiconductor devices are considered the most sensitive components in power converters and if the net failure rate of a particular device is given as λ, its reliability is given as below:

$$R(\tau) = e^{-\lambda\tau} \tag{8}$$

λ for each device maybe different and is pre-known to the cloud server based on the input provided. The devices feedback the usage time, τ, which is used to calculate the reliability at different intervals. For the set of all appliances $n \in \mathcal{N}$ in the building, the inputs to the prioritization algorithm that decides the rank of appliances participating in reactive power support are: appliances' available reactive support levels $Q_{n,u,t}^{free}$, statuses (ON/OFF) of the appliances based on the day-ahead schedule indicated by binary variables x, and the usage time of the devices, τ. Then, the cloud server determines the optimal set of R by maximizing the total reliability, which can be written as:

$$\max \sum_{n \in N} y_{n,u,t} \times (x_{n,u,t} + R_{n,u,t}) \quad \forall u, t \tag{9}$$

$$s.t. \sum_{n \in N} y_{n,u,t} Q^{free}_{n,u,t} \leq Q^{req}_{u,t} \quad \forall u, t$$

where the binary variable y indicates the optimal set for RPS based on reliability, i.e.

$$\begin{array}{ll} n \in R & \text{if } y_n = 1 \\ n \notin R & \text{if } y_n = 0 \end{array} \tag{10}$$

2) Management Complexity

The available reactive sources can be selected to minimize the number of devices participating in reactive support. This however will not guarantee the equitable distribution of reactive support among the devices. Having fewer devices for RPS reduces the complication associated with controlling them while being used for reactive support. This will utilize the communication assets and processing resources as little as possible. However, there is a high possibility that only high capacity appliances may be requested all the time for support, leaving them vulnerable to failure.

C. Reactive Power Allocation

An algorithm for reactive power allocation among the candidate devices is shown in Fig. 5. The server continuously collects the device status and power profile to calculate the spare reactive power. There are two modes for device selection based on management complexity and the usage factor. The user can input the selection factor, and accordingly, two sets of devices that can provide the requested reactive support are determined. Both the methods rank the devices in terms of their reactive support priority. The reactive support request is allocated in a descending order i.e. high ranked device are considered first, and the remaining reactive support is then obtained from the second, and third ranked devices until the requested reactive support is met. If the available reactive support is lower than the requested support, the cloud server notifies the central controller of this deficit. The reactive support obtained from the devices is stable until there is either a change in the power profile of the devices or the requested reactive support. If such a change occurs, the algorithm reallocates the reactive support to the devices based on the updated scenario.

V. Validation and Results

In this section, the proposed smart home reactive power support algorithm is validated via simulation studies (MATLAB®/Simulink) for an LV network and the cloud communication architecture is validated in laboratory experiments.

A. Reactive Power Allocation Algorithm

The performance of the proposed reactive power allocation algorithm presented in Fig. 5 is validated in this section. For simplicity, the coordination of reactive devices in a single home to support an LV grid is considered, assuming that the home has received a reactive request from the cloud server. Each home contains a PV inverter, EV and several basic home appliances (A/C, Washing Machine, Dishwasher and Microwave). The solar power produced onsite is simulated by the System Advisor Model (SAM) [23] with temperature data from Sydney Airport station (Station Id. 066037). The real-time tariff for the day-ahead schedule is taken from [24]. For the real-time RPS, the cloud server runs the optimization algorithm and generates the set of candidate appliances and their rank according to the device prioritization strategy. The

TABLE II: Simulation parameters of reactive devices

Devices	Power rating (VA)	Type	Usage (hr)
EV	5000	1	350
PV	6200	1	452
AC	1800	1	365
IH	3000	1	300
WM	400	0	100
DW	500	0	200
MW	1200	0	220

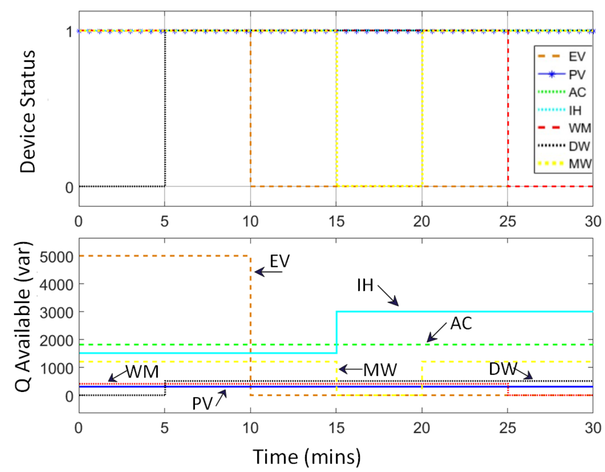

Fig. 6: Device status with their reactive power capability

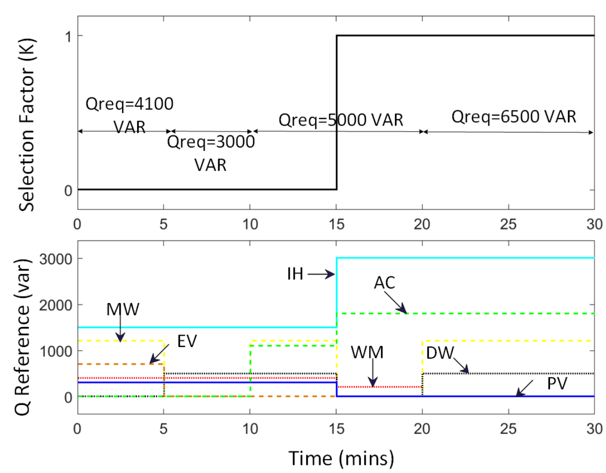

Fig. 7: Reactive power reference allocation to devices based on selection factor

corresponding reference reactive power for each device is then forwarded to the device via the home aggregator and EMCU. The local controller in the devices is assumed ideal and can provide the requested support instantaneously. Moreover, the communication delay is assumed to be negligible and is not considered in the simulation study. Table II presents the simulation parameters of the devices in the reactive support pool. Fig. 6 depicts the device status and their corresponding available calculated reactive power capacity over a period of 30 mins starting from 12 AM. As discussed the available reactive capacity is a function of the device type and spare power processing capacity. For the first five minutes, DW being in use is not available for reactive support. Similarly, MW when it comes into operation from 15-20 minutes shows nil available reactive power. Also, the available reactive support from EV drops to zero at 10 minutes due to its changed location. PV, AC and IH present relatively constant and large reactive support capability while other home appliances show an intermittent nature in reactive power capability.

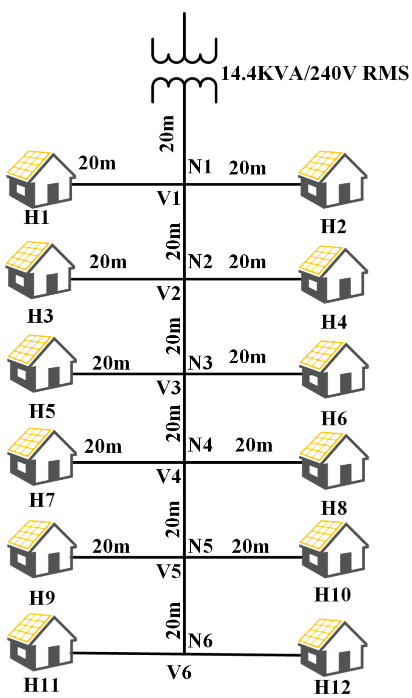

Fig. 8: Residential LV distribution test feeder

Fig. 7 illustrates the allocation of reactive power references for the devices in accordance to the requested reactive power support from the cloud server. For the first 15 minutes, the selection criteria is based on reliability (device usage) which ranks the devices in the order as $\{WM, DW, MW, IH, EV, AC, PV\}$. The latter fifteen minutes employs management complexity criteria to determine the appliances and their order to minimize the number of devices in the support. The order keeps updating because of the changes in the operation of various devices. Moreover, to illustrate how the algorithm smoothly adapts to any change in reactive reference, a step change in VAR support is applied at 5,10 and 20 minute. The algorithm accordingly recalculates the

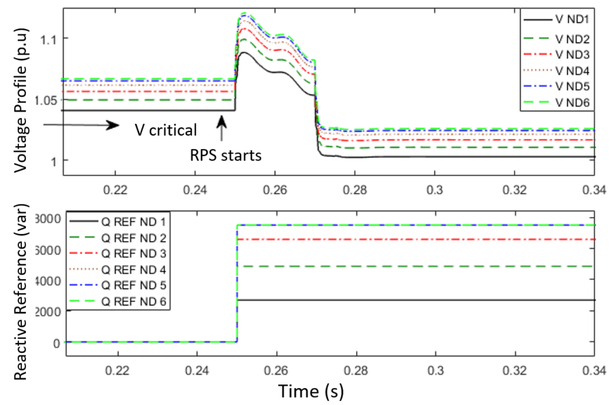

Fig. 9: voltage profile along with the reactive power reference before and after RPS from home devices at each node

new references for each device and assigns them immediately. For instance, at t=15 mins, the reactive allocation mechanism switches from device usage to management complexity. Accordingly, all the requested reactive power (5 kVAR) is now provided using only IH, AC and WM. While before the selection factor was changed, IH, PV, WM, DW, MW and AC were supplying the same amount of reactive power i.e. $5kvar$.

B. RPS in LV Network

A case study is presented here to illustrate the role of the proposed method in addressing the over-voltage problem in a low voltage distribution feeder with high PV penetration. In this setup, the residential feeder consisting of 12 homes powered by a 75 kVA transformer as shown in Fig. 8 is implemented. The backbone feeder is 120m long and the corresponding distribution line and transformer parameters are provided in detail in [10]. Each home is equipped with a PV inverter system with generating capacity of 6.2 kW and other electrical loads and reactive power support capable devices. The maximum export to the grid is limited at 75 kW from 12 homes while each home has a maximum reactive support capacity of 7 kVAR. In the daytime, when the PV generation is at a maximum and the load consumption is at a minimum, the grid voltage may experience an overvoltage problem as shown in Fig. 9. Through proper coordinated reactive power consumption among reactive capable devices at each home, activated at t= 0.25 s, the voltage profile of the grid is brought back to the normal range. The required reactive support at each node is generated through droop control, whereby the reactive support is initiated when the grid voltage exceeds 1.03 pu. It is also evident that the homes farther from the distribution transformer require more RPS to lower the node voltage. The required reactive power support from each node is also shown in ~~the~~ Fig. 9.

The voltage at a particular node in the LV network depends on the power flows to/from that node and the impedance of the adjacent line segments. The node voltages can be calculated as:

$$v_n = v_{n-1} - \frac{r_n P_n + x_n Q_n}{v_1} \tag{11}$$

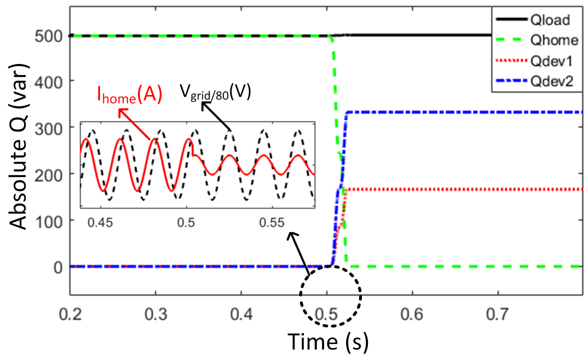

Fig. 10: RPS for unity power factor home

where, v_1 is the voltage at the initial node (i.e. the secondary side of the distribution transformer), whereas P_n and Q_n are the net power flows to/from the node n.

C. RPS for unity power factor home

In another case study, the role played by the reactive capable devices in realizing near unity power factor home is exemplified. Fig. 10 shows the reactive power requirement of the reactive load in the home and the corresponding reactive power drawn from the grid. Before devices are commanded to provide the local reactive needs, the required reactive power is drawn from the grid. This degrades the power factor, and if this scenario is present in numerous homes, the voltage profile of the grid may fall below the nominal value if proper support is not activated by the utility such as capacitor banks. At t=0.503s, the free and available reactive capable devices at homes are commanded to provide the reactive requirement of the residential load, thus reducing the reactive power drawn from the grid to zero. Two devices are used, which in total provide the required 500 var of reactive power to the local load. Hence, through proper employment of reactive capable devices, the power factor of the home can be improved as well as the network losses associated with the flow of reactive power from distant reactive sources.

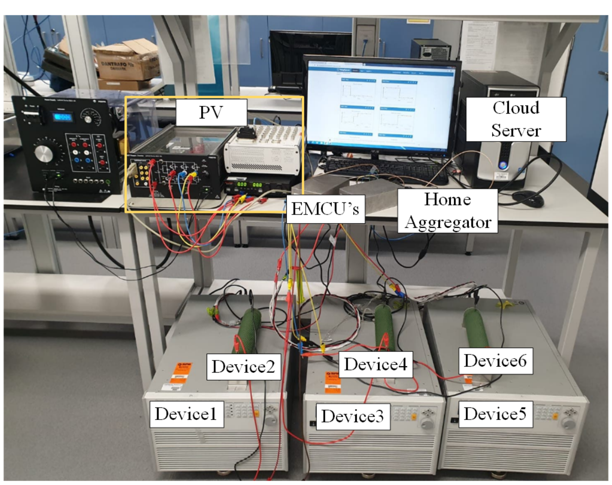

Fig. 11: Experimental setup for cloud server implementation

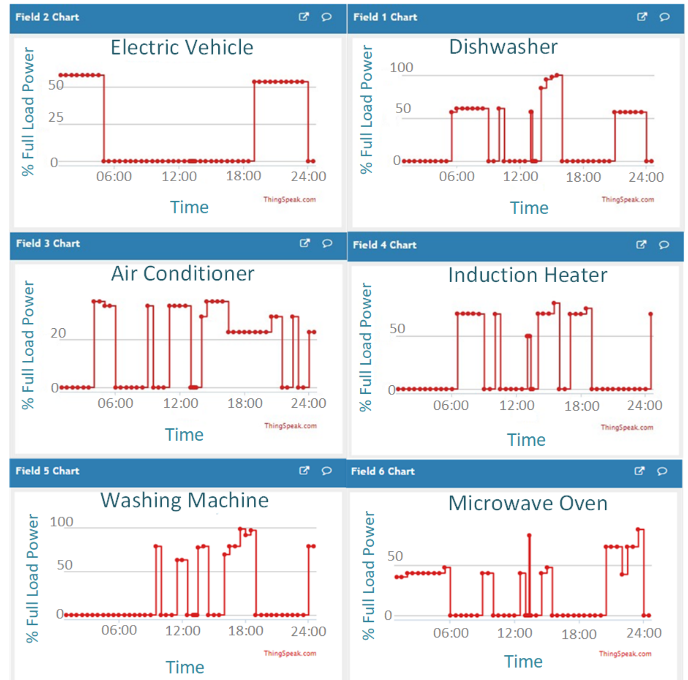

Fig. 12: Day ahead active power profile of the devices

D. Cloud Server Implementation

Fig. 11 shows the hardware prototype platform for implementation of the proposed system. The system is composed of two programmable loads and a PV system, which are all connected to the EMCU and linked to ThingSpeak® through a home aggregator. The programmable loads are modeled to generate particular patterns of active power consumption. The home aggregator is designed using a Raspberry PI, and it bridges the communication link between the ThingSpeak® server and the EMCU. Fig. 12 depicts the day ahead anticipated usage pattern of the devices as set by the user. Based on day ahead power consumption patterns, the cloud server can calculate the available reactive capacity at any time of day. Upon receiving the request for reactive support, the cloud server runs the algorithm and nominates the devices for grid support from the pool of candidate devices on the basis of selection factor (k). A scenario similar to that presented in the simulation of Fig. 7 has been implemented using the ThingSpeak® server. Thus, the obtained reactive reference for each of the seven devices for a zoomed in period of 30 mins starting at 9:00 AM is illustrated in Fig. 13. The reactive support provided by each is exhibited as a percentage of the spare reactive power capacity.

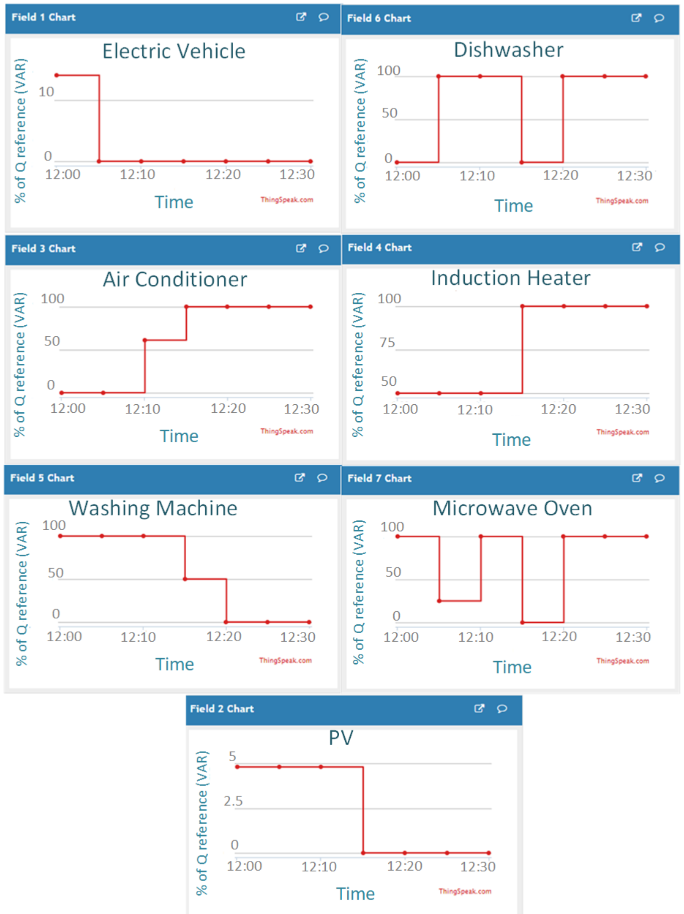

Fig. 13: Reactive power reference allocation based on selection factor by the cloud server

VI. Economic Analysis

This section establishes the economic benefit that can be attained from the proposed approach. Traditional methods of voltage regulation such as using capacitor banks have been deemed economically unfavorable in previous studies [25]. In addition to being a non-profitable approach, there are also several technical glitches when using capacitor banks that can be effectively addressed by the approach proposed in this paper. The technical benefits of the proposed method over capacitor bank are summarized in Table III. Hence, the proposed approach for voltage regulation is compared with another popular method, active power curtailment (APC), for grid voltage regulation. For simplicity, only the operation cost of both approaches is considered, and the installation and maintenance costs are ignored here. A low voltage radial distribution network consisting of 12 homes, as shown in Fig. 8, is used. These are also referred to as net-zero energy solar houses as they have an identical energy generation and consumption in one year. Each home consists of a rooftop PV system, local load and several reactive support capable devices. The maximum power export is restricted to 75 kW from 12 houses with each home's PV generation limited to 5 kW. The net reactive support capacity available from the pool of reactive devices from each home is set to 7 kVAR. The common issue of overvoltage is replicated in this residential feeder arising from peak PV generation and minimum local demand. Two droop control based approaches are then applied to address the overvoltage issue, and the corresponding cost associated with each is calculated:

TABLE III: Pros and Cons of reactive support realized using capacitor bank and proposed method

Features	**Capacitor**	**Proposed method**
Support resolution	Discrete	Continuous
Response speed	Slow	Fast
Maintenance cost	High	Low
Network loss	High	Low
Lifetime	Low	High

- Curtailing the active power of the PV inverters (APC)
- Consuming reactive power from reactive capable devices (RPS)

In APC, the active power production of each inverter is reduced linearly when the node voltage exceeds 1.03 pu with complete stoppage at 1.06 pu. If the cost of 1 kWh of feed-in energy is billed at S_{RP}, the economic loss encountered by the PV operator is given as:

$$C_{APC} = S_{RP} \times \Delta P_{cur} \tag{12}$$

In RPS, the reactive support capable devices are commanded to absorb reactive power in accordance with the deviation of the node voltage from nominal high voltage, which is again 1.03 pu. The cost for RPS can be broken down into three components: the price of reactive power, the cost due to additional power loss in the RCD and the cost arising from the reactive power flow in the network (network loss). Each of these components are calculated as:

$$\begin{aligned} C_{RPS} &= S_{RQ} \times \Delta Q_{\text{supp}} \\ C_{NPL} &= C_{RP} \times \Delta P_{Nloss} \\ C_{DPL} &= C_{RP} \times \Delta P_{Dloss} \end{aligned} \tag{13}$$

where, S_{RQ} is the buying price of the reactive power by the grid operator and C_{RP} is the cost of active power consumption. ΔP_{Nloss} and ΔP_{Dloss} are the active power loss in the devices and network owing to the additional reactive power consumed in RCDs.

From the simulation study, it was observed that around 25.7 kW of active power curtailment was required to bring the voltage profile within the nominal range. Similarly, using RPS 28.5 kVAR of reactive power was required for eliminating overvoltage in the network. Moreover, 5.26 kW of power was wasted as network loss due to reactive power flow and around 0.57 kW (at 98% efficiency) power was lost in reactive capable device itself. The total financial cost associated with each method assuming 3 hrs/day of peak PV generation for a period of 1 week is shown in Fig. 14. The costs of active and reactive power are based on the price provided in [26]. It can be concluded from the figure that the proposed method is economically attractive for both grid operators as well as PV owners. One of the major advantages of the proposed solution

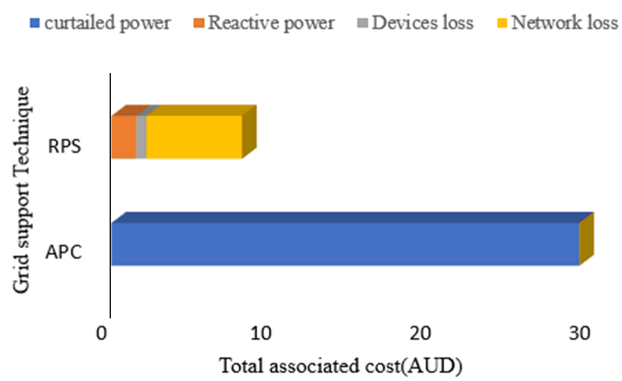

Fig. 14: Financial cost/week for the two techniques of voltage regulation

over APC is the enhancement of the PV hosting capacity of the distribution grid [13]. This implies that more PV generated active power can be injected into the grid while maintaining the voltage profile. However, with APC, the active power has to be reduced causing financial loss for the PV owners.

VII. Conclusion

This paper proposes a coordination algorithm for employing multiple reactive power support capable devices present in a low voltage distribution system for grid voltage regulation. The algorithm considers two criteria: first is improving the useful lifetime of candidate devices, and second is reducing the management complexity while availing the RPS from them. A framework supporting such a realization is simulated in MATLAB/Simulink and implemented with a laboratory prototype. The results illustrate the applicability of the proposed solution either to maximize devices' reliability or reduce management complexity. The prominence of the proposed method was also established by describing the economic benefits it brings. The study showed that the proposed method is less expensive to APC by 68%. Despite the effectiveness, the current research has not delved into lifetime improvement or management complexity improvement qualitatively, which will be part of future research.

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