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A Novel Demand Control Policy for Improving Quality of Power Usage in Smart Grid

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***Abstract*—Smart grid has emerged as a promising technology for enabling bi-directional communication between the power company and its users to facilitate intelligent, robust, and resilient next generation power grid systems. Through this technology, both the power company and its subscribers can be equally benefited, not only from economic point of view, but also in terms of environment-friendly quality of power usage. One important challenge for the smart grid designers is the demand side management, which can lead to avoiding the peak hours and reducing the cost for the consumers. In this paper, we address the power balancing challenge for the smart grid and discuss different solutions including game theoretic methods and demand control policies. Also, we present our novel demand control policy for achieving an effective management of the power consumption. Computer simulations demonstrate the effectiveness of the proposed policy compared to existing ones.**

***Keywords*-Smart grid, power balancing, Demand Side Management (DSM), Direct Load Control (DLC), Quality of Power Usage (QoPU).**

I. INTRODUCTION

Recently, smart grid has emerged as a hot research topic offering a promisingly robust communication infrastructure toward an intelligent power grid where minimal human interaction is required [1]–[4]. The smart grid presents flexible and reliable energy distribution through a bi-directional dialog between the supplier control center and the smart meters on the user-side. In addition to the main power supplier, additional energy generation sources (that may also comprise green energy) are included in smart grid, such as batteries, backup devices, Plug-in Hybrid Electric Vehicles (PHEVs), solar cells, and so forth. This aspect of the smart grid is expected to contribute to a quite complicated real-time consumer power demand management.

The power utility operator should employ an appropriate demand load management scheme to balance the power supply and demand profiles in a cost-effective fashion [5]–[9]. By doing so, the demand load control allows the operator to smooth the distribution of the overall power-consumption over time. For example, the peak loads, at busy times, can be alleviated if an appropriate demand management scheme is adopted to shift non-urgent power demands from the regular peak load to off-peak load durations. The operator may also exploit real-time pricing to give the option to users to reduce electricity bill by transferring a part of the demand to off-peak durations. In addition, the use of the distributed power generation sources/storage in the smart grid may also be exploited to alleviate peak loads. Therefore, appropriate demand load management schemes help the smart grid to be more reliable by reducing the likelihood of power outage due to unexpected rise in customers demand.

While it is important to design an efficient demand load management scheme in smart grid, it is equally important to allow the utility company to take into account the various power requirement levels associated with the requests coming from customer-appliances. In this paper, we present two contributions. First, we introduce the Quality of Power Usage (QoPU) concept to effectively assign different grades to incoming requests. Second, we develop a policy to take into account the incoming power demand requests for scheduling power distribution in a system-wide balanced fashion. While the work in [5] presented an inspiring concept for an online dynamic demand scheduling policy for efficient power distribution, it adopts a deadline-based scheduling for power distribution, which may not be practically viable. In our work, we address this issue and propose a practical control policy for power scheduling in smart grid.

The rest of the paper is structured as follows. Section II presents relevant research works on smart grid demand load management schemes. Section III describes the considered smart grid system and also formulates the problem of designing control policy for power balancing. Our novel control policy for power distribution in smart grid is proposed in Section IV. The performance evaluation of the proposed control policy is validated in Section V through computer-based simulations. Finally, the paper concludes in Section VI.

II. RELATED WORK

A communication protocol based on residential electrical appliances connected over the smart grid's home area networks is proposed in [10]. In this work, two categories of in-home equipment are considered, namely real-time and schedulable appliances. In this power scheduling protocol for smart grid system, a time-slotted system is assumed, which consists of power update, request, and scheduling phases. In a similar vein, the work conducted by Koo *et al.* [11] proposed a multilayer device control algorithm for the home area network based on Zigbee. When sufficient electricity supply is not available, the control algorithm is executed at the smart grid control center according to the least necessary (i.e. prioritirized) home appliances. The shortcoming of these approaches consists in the fact that they focus on controlling power allocation only for inside the residences. The overall smart grid power balancing issue is, however, not at all, considered in these works.

In [12], a general operating method to combine power procurement and demand response in smart grid was proposed. This work aims at maximizing the social welfare by considering the effect of the renewable energy and the multistage feature of the power procurement process. To model the social welfare, the work also introduced the notion of quality of power usage guarantee given by the utility company to its customers. The social welfare maximization algorithm performs joint power procurement and dynamic pricing. However, it does not address the smart grid system power balancing issue in terms of smoothing the peak power usage distribution.

Most contemporary demand-side management approaches primarily focus on the interactions between a utility provider and its consumers. For example, the authors in [9] present an autonomous and distributed demand-side energy management system by exploiting an automatic Energy Consumption Scheduler (ECS), deployed in the smart meters at the customer-residences. The ECS in each smart meter contacts with the utility provider as well as with other smart meters to find the optimal energy consumption schedule for the user. The work suggests game theory as a means to perform the optimal scheduling. The schedule is done on either an hourly or a day-ahead (i.e., for the next twenty-four hours) basis. This may not be applicable in many situations, especially when the users might want to change their power usage demands at any point of time during the day.

Instead of using game theoretic approaches as suggested in [9], a major trend in residential load management is Direct Load Control (DLC) [5]. The DLC methodology is based on a contract between the utility provider and customers. The contract states that the utility provider may remotely control the operations and energy consumption of certain residential appliances. In the work conducted by Koutsopoulos *et al.* [5], a taxonomy of methods for DLC is described, and two of the delineated approaches are adopted for smoothing the power demand profile in order to minimize the operational cost of the smart grid. The work considers online scheduling of power demand tasks, which have time-flexibility before activation of the appliance. One of the most important assumptions of the work is the deadline-based scheduling for power distribution. In other words, queued demands are processed when their deadline expires, or when the consumption drops below a specific threshold.

While the aforementioned work [5] serves as a motivation for our own research in DLC for balancing power consumption level in smart grid, it is not without its shortcoming due to the deadline-based scheduling concept. The term, deadline, refers to the time duration until which the users may wait (i.e., sacrifice) for activation/use of a specific appliance. Note that this deadline concept may be difficult to implement in practice since the users would always want to request for a "zero" deadline, in order to activate their appliances immediately. In our work, we aim to overcome this shortcoming by proposing a novel power distribution scheduling policy for smart grid.

In the next section, the system model, along with the problem of effectively scheduling power distribution in smart grid is described in detail.

III. SYSTEM MODEL & PROBLEM STATEMENT

Before delving into our proposed solution, it is essential that the readers become familiar with the considered smart grid system model from a practical view point. The system model, which is presented in this section, is also important to identify the problem statement regarding power distribution in smart grid.

A. *Smart Grid System Architecture*

The smart grid is a cyber physical system, i.e., a combination of power grid and communication system. Note that the communication system is not the main focus in our considered system model. For detailed information of the smart grid communication architecture, interested readers are referred to our earlier work [13], [14].

On the other hand, in the power side of the smart grid, for sake of practicality, we consider a wholesale power market, as depicted in Fig. 1. The wholesale power market comprises the main power source (i.e., geo-thermal/hydro-electric/nuclear power plants) and the renewable power generation sources (e.g., solar panels, wind turbines, PHEVs, and so forth), which produce the primary (base) and secondary power, respectively. Our consideration, thus, reflects the multi-vendor power market in practice.

There is a number of power retailing companies, which are commonly referred to as "retailers". A retailer, usually, belongs to a specific area in order to supply power to the customers residing in that area. The retailer buys power, based on the forecast of customer-demands for the following day, from one (or a number of) power source(s), and sells this power to its subscribed users. As depicted in Fig. 1, every retailer has a control center. The control center has a number of operational components, including authentication, billing, data aggregation, and direct load control. The customers' smart meters, subscribed with the retailer, are able to communicate (bi-directionally) with the control center over wireless technology [1]. The control center is responsible for providing power demanded/requested by the customers. In the figure, also notice that the residential appliances (i.e., in the customer side) are connected, over wireless links, with the smart meter of the residence.

Based upon the afore-mentioned system architecture, the problem of power distribution in smart grid is explained in the remainder of this section.

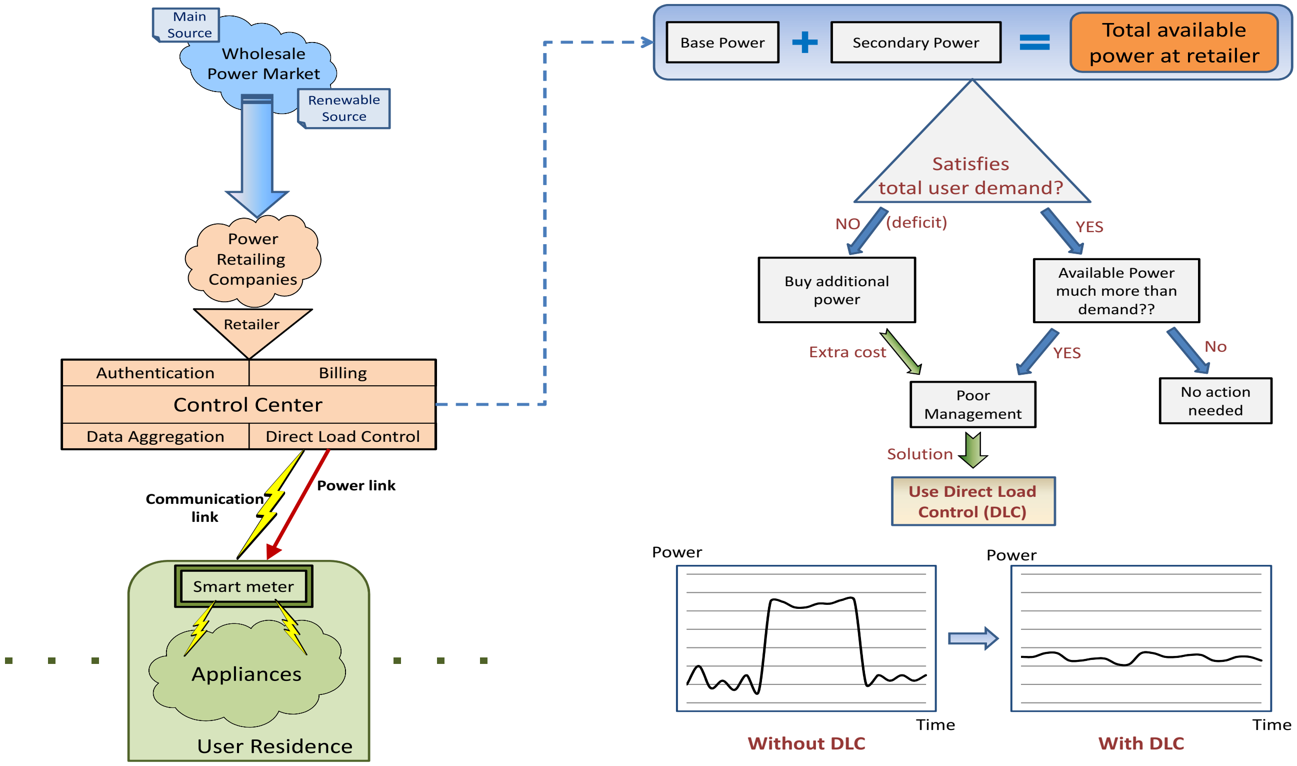


Fig. 1. Considered smart grid architecture and problem formulation.

B. Problem Formulation

Let us consider the total power available at a specific retailer from the scenario depicted in Fig. 1. Let P_{max} denote the total available power at the retailer that is the combination of the base and secondary power purchased from the wholesale market, as shown in the figure. Let P_{demand} represent the demand from the entire population of customers, served by the retailer. If P_{max} satisfies the demand requests coming from all the customers for servicing their appliances, (i.e., when $P_{max} \geq P_{demand}$), the control center does not need to take any action.

On the other hand, in the case where ($P_{max} >> P_{demand}$) (e.g., during low-demand usage periods), this condition refers to the scenario in which the retailer has purchased an excessive amount of power that would be wasted, thereby incurring financial loss on the retailer. This situation is represented as one of the "poor management" cases in Fig. 1.

The other "poor management" case arises when there is a deficit (i.e., $P_{max} < P_{demand}$). In this case, the retailer is forced to buy additional units of power from the wholesale market. This may be more expensive since this purchase is to be made immediately, and immediate purchases are usually more expensive than those made on forecast/day-ahead basis. Also, during peak hours, if a number of retailers require purchasing additional power at the same time, the primary source may reach its full capacity. As a consequence, the retailers would be forced to buy the extra power from the secondary sources, which are even more expensive.

Indeed, by this way, the retailer may be subject to higher cost in both of the afore-mentioned situations. A traditional way to solve this problem is by buying day-ahead additional power to counter the pressure during the peak hours, and less power during the non-peak/night hours. However, note that the price of the power during the peak hours is expensive (even if it is a day-ahead purchase) while that during non-peak hours is comparatively cheaper. Therefore, each unit of additional price to be paid during the peak hours forces the retailer to impose extra price on the customers.

DLC can be exploited to mitigate these problems by shifting some portion of the power consumption during the peak to non-peak hours. This is depicted on the bottom right of the figure using the power versus time plots. The usual case (i.e., without applying DLC) is shown on the left, where during the middle of the day, the retailer experiences the peak hours while other periods have significantly low levels of usage. On the other hand, the plot on the right side demonstrates that the application of DLC substantially balances the power consumption over time. This can be attributed to the fact that DLC-based system encourages the users to subside some of their power-hungry appliances during peak hours by projecting that price plans during peak-hours are more expensive.

It is worth stressing that the broader definition of DLC enables the utility provider/retailer to control the electrical appliances in the customer-residences. Indeed, this is a practical problem, and as a consequence, additional policies are required to overcome the privacy concerns associated with

DLC. For example, instead of controlling all residential appliances, the utility company could be given access to control few appliances, which are power-intensive and non-urgent. This problem also arises the need for differentiating various types of appliances with different grades of power usage requirement that will be addressed in Section IV-A. Also, to avoid further privacy-centric complications, DLC may be applied to only those customers, who express their interest to avail themselves of cheaper electricity.

Therefore, in the next section, we propose an effective DLC scheme, with adequate control policies, for balancing power distribution in smart grid.

IV. PROPOSED SCHEME: A DLC-BASED SOLUTION

In this section, we first present our envisioned Quality of Power Usage (QoPU) grades for differentiating appliance-demand requests. Then, we propose an adequate control policy for facilitating DLC for smoothly distributing power in smart grid.

A. Multi-level Quality of Power Usage

From the operational point of view, usually, the residential devices belong to either two types, namely non-schedulable and schedulable. Non-schedulable devices require immediate operation, e.g., a light-bulb, television, personal computers, and so forth. On the other hand, the operation of a schedulable appliance can be planned to commence at a later time. We further catergorize the schedulable appliances into two types: interruptible (e.g., air conditioner, heaters, and PHEVs) and non-interruptible (e.g., washing machine and dish washer). Since the non-schedulable appliances require immediate attention, they do not fall into the scope of our DLC-based policy.

Each request from a schedulable device, i, is considered to have a number of attributes $\{a_{i,1}, a_{i,2}, ..., a_{i,n}\}$. Here, n is the total number of attributes considered in the system. By combining the different attribute values of an appliance, we construct the notion of power usage grade, $G_p \mid p \in \{1, \mathcal{P}\}$, where $\mathcal{P}$ denotes the total number of grades in the system. In order to compute the appropriate grade to be assigned to the i^{th} device-request, the following equation is used:

$$\eta^i = \sum_{j=1}^{n} w_{i,j} \cdot a_{i,j}, \tag{1}$$

where $w_{i,j}$ refers to a weight corresponding to the j^{th} attribute value of the i^{th} device-request, and η^i denotes the weighted attribute value of the i^{th} device-request. We relate η^i to one of the system power usage grades, G_p, as follows.

$$if\ \left(G_{p_{min}} < \eta^i < G_{p_{max}}\right),\ \eta^i \rightarrow G_p, \tag{2}$$

where, $G_{p_{min}}$ and $G_{p_{max}}$ indicate the lower and upper bounds of a considered power usage grade G_p, respectively.

The value of η^i depends on the nature of attributes considered in the system. Accordingly, the weights will also be estimated by the system. Throughout the remainder of the paper, we consider that the smallest values of η^i will be mapped to G_1, while other values of η^i are to be assigned with G_p values in an ascending order. Also, we consider G_1 to be of the highest priority grade.

The system should attempt at assuring the required grade of power usage as per the appliance-request, i.e., maintaining the quality of power usage. This is why, we refer to the proposed multi-level quality of power usage framework as QoPU. Next, we present our envisioned policy to maintain power usage quality while effectively balancing the power distribution in the smart grid.

B. Proposed DLC-based Scheduling Policy

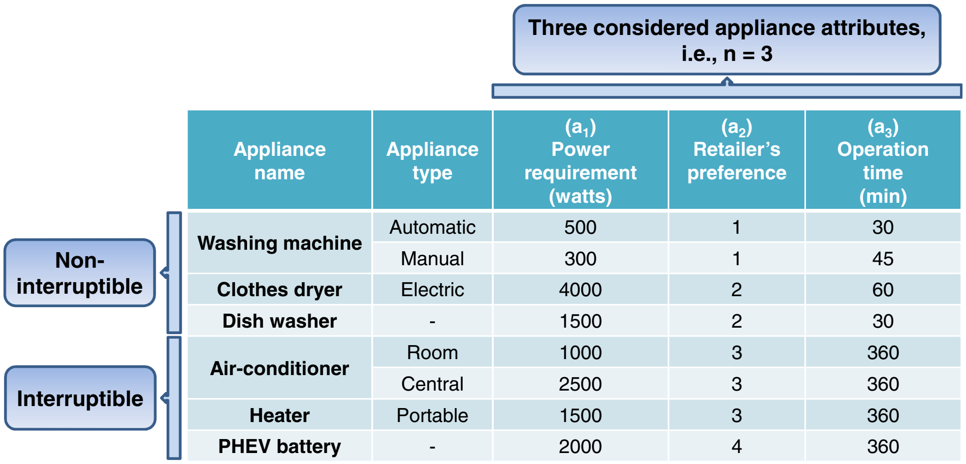
Assume that P_{th} and P_{usage} are two system parameters, which denote the retailer's total power (initially allocated/purchased) for serving the customers, and the current level of usage, respectively. $P_{request}$ indicates a quantity of power level associated with a request from a schedulable appliance that requires a certain QoPU grade, G_p. Based on these parameters, we present our proposed DLC-based scheduling policy in the following steps.

1. If $(P_{usage} + P_{request}) \leq P_{th}$, then activate the appliance immediately.
2. If $(P_{usage} + P_{request}) > P_{th}$, the request is placed in a queue.
3. A queued request will be handled according to the priority of its QoPU grade.
4. The request to be activated is the earliest arriving one, which has QoPU grade, G_p, such that p is the smallest amongst the queued requests, and it will be activated when $(P_{usage} + P_{request}) \leq P_{th}$.
5. Since its activation, an interruptible appliance, i, is allowed to remain active without any interruption for a time window, T. Upon expiration of T, the request of appliance i is queued and assigned a relatively lower priority than those of the other appliances, which were activated fewer times than the number of activations of appliance i.

In the next section, through a case scenario, we demonstrate the performance of the proposed QoPU-oriented DLC-based scheduling policy.

V. PERFORMANCE EVALUATION

We present a case scenario in this section to illustrate the effectiveness of our proposed DLC policy. The considered residential schedulable appliances, in this example, are demonstrated in Fig. 2, whereby non-interruptible and interruptible devices are shown with their attribute-values. For simplicity, $n = 3$ is considered in this example, i.e., three attributes are chosen, and the attribute-values of the different appliances are listed in the figure. Based on these attribute-values, the grade of an appliance-request can be computed by using Eqs. 1 and 2. The power requirement (watts) attribute a_1 values for the various appliances are obtained from [15]. We also assume that the smart meter is able to learn the operational time of some appliances from the usage history. As an added option,



Three considered appliance attributes, i.e., n = 3

	Appliance name	Appliance type	(a_1) Power requirement (watts)	(a_2) Retailer's preference	(a_3) Operation time (min)
Non-interruptible	**Washing machine**	Automatic	500	1	30
		Manual	300	1	45
	Clothes dryer	Electric	4000	2	60
	Dish washer	-	1500	2	30
Interruptible	**Air-conditioner**	Room	1000	3	360
		Central	2500	3	360
	Heater	Portable	1500	3	360
	PHEV battery	-	2000	4	360

Fig. 2. A scenario illustrating different QoPU attributes of a number of schedulable appliances.

the customers are also considered to be able to manually input the operational time into their smart meters.

We setup our computer simulations using Matlab [16]. We consider a single retailer serving electricity to a small town-block comprising one thousand residential customers. The customers are assumed to have both schedulable and non-schedulable appliances. The schedulable appliances are considered to be the same ones as shown in Fig. 2 with the same attribute-values. On the other hand, the non-schedulable appliances (e.g., television, computer, lights, microwave, toaster, coffee maker, refrigerator, and freezer) having specific power requirements (as per [15]) are modeled to be immediately activated upon request. The requests originating from any residential appliance are distributed randomly in specific ranges of time to closely simulate reality. In our simulations, $T = 1$ hour (i.e., the interruptible appliances are activated for at least one hour without interruption), $\mathcal{P} = 6$ (i.e., number of QoPU grades is six), the weights $w_{i,1}$, $w_{i,2}$, and $w_{i,3}$ are arbitrarily set to 1, 500, and 10, respectively. It is worth mentioning that the arbitrary values of these weights do not affect the fundamental results observed in the conducted simulations.

Fig. 3 demonstrates the power drawn from the retailer in a one day interval (starting from 7:00 am until 7:00 am of the following day). For this simulation, P_{th} is set to 1.6 Megawatts. The results depicted in the figure comprise three elements, namely (i) the overall non-schedulable appliances usage (highlighted in dashed green color), (ii) the overall power drawn in the normal situation where the schedulable appliances are getting electricity immediately upon their request (plotted in red), and (iii) the overall power drawn while applying the proposed policy (plotted in blue). The figure illustrates that in normal situations, the retailer suffers from a peak period during the mid-day. This is effectively avoided by applying the proposed DLC scheduling policy, in which a tolerable threshold of power is set and schedulable requests are scheduled in a later time.

With our proposed policy, and various settings of P_{th}, Fig. 4(a) demonstrates the average waiting time for non-interruptible appliances until their activation, and Fig. 4(b) shows the average waiting time between the running periods of one hour for the interruptible appliances. In Fig. 4(a), by applying the proposed QoPU grades, we can see that the average waiting time is low for the appliances requiring low power requirement and low operating time, and having high preferences from the retailer (e.g., washing machines). On the other hand, the average waiting time is higher for appliances, which require higher power requirement and longer operating time, and have lower preferences from the retailer (e.g., clothes dryer).

In Fig. 4(b), the average waiting time between the running periods of each of the interruptible appliances is plotted. As evident from the figure, the average waiting time is comparatively higher, in case of a central air conditioner, than that of a room air conditioner/portable heater. This basically results from the higher power requirement of a central air conditioner. On the other hand, even though the PHEV battery requires more power, it experiences a lower waiting time in

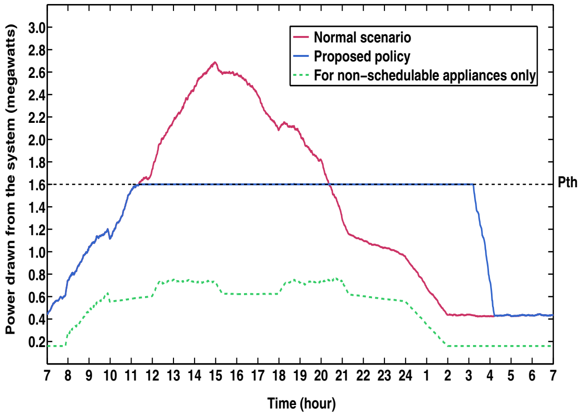
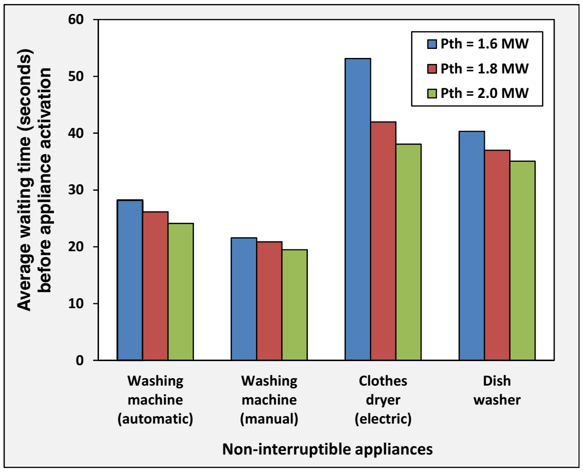
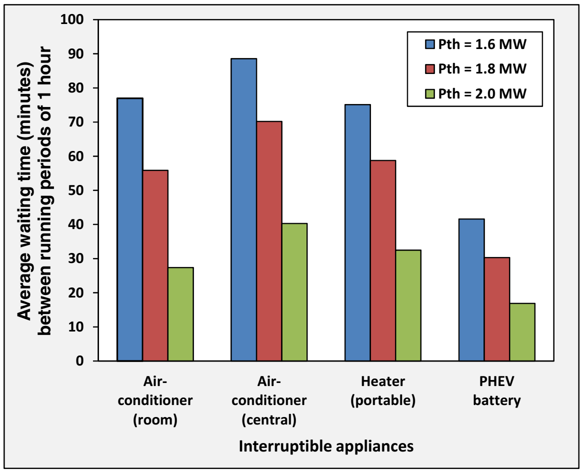


Fig. 3. The overall power drawn from the retailer (in Megawatts) with and without the proposed policy in a time duration of twenty four hours (starting from 7:00 am of a day until 7:00 am of the following day).



(a) Average waiting time for different non-interruptible appliances until they are activated.



(b) Average waiting time for different interruptible appliances between running periods of 1 hour.

Fig. 4. Average waiting time for various schedulable appliances.

contrast with those associated with the air conditioners and heaters. This better performance in terms of the PHEVs lower waiting time can be attributed to the actual time of placing the corresponding PHEV requests to the system. Because, the PHEV requests may be placed at any time of the day while the air conditioners and heaters usually demand power during daytime, especially during the peak hours. With these results, we may conclude that the appliances, which need short time and low power, are activated first (not to wait for a long time), and the other power-intensive appliances requiring long operating time are scheduled with lower priority. In addition, since the interruptible appliances usually operate over a long duration, our proposal uses a policy to interrupt them periodically, and gives chances to higher priority appliances to operate.

VI. CONCLUSION

In this paper, we reviewed the shortcoming of contemporary demand-side management approaches in smart grid and pointed out the need for an effective power balancing scheme to distribute the power appropriately on a daily basis. We also proposed a novel multi-level Quality of Power Usage (QoPU) concept, in which different grades are assigned to demand requests. In correspondence with these grades, we proposed a novel DLC-based scheduling policy for balancing the power distribution. Through computer simulations, the performance of the proposed policy is evaluated. The simulation-results clearly demonstrated the effectiveness of the proposed policy for leveling the power distribution during peak hours. It is also worth noting that the proposed QoPU grades can also be adopted by other control policies in order to ensure a priority-based scheduling of electrical appliances.

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