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Novel Soft-Constrained Distributed Strategy to meet high penetration trend of PEVs at homes

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ABSTRACT

This paper shows that the Demand Response Program is not sufficient to solve the problem of high penetration level of Plug-in Electric Vehicles (PEVs), even when energy management systems are used in homes. In the presence of Time-varying electricity price, PEVs tend to charge during low price periods. The problem starts when the number of PEVs exceeds a certain threshold. A total load of all homes on a transformer may exceed its capacity and create high peak-demand during low-electricity price. To overcome this situation, we propose a novel Soft-Constrained Distributed Strategy. The novelty consists of defining a new distributed information exchange between Power Utility and end-users, new constraints are developed at home level taking into account the transformer and Distribution Network's technical limits, and a new optimization model is proposed to implement the strategy. A case study is conducted using data provided by Hydro-Quebec. Simulations and comparative results show the validity of our approach. The proposed strategy reduces the peak–demand, energy loss, depreciation cost, transformer's Loss Of Life, and voltage deviations. Lastly, our study shows that it is not necessary for the power utility (e.g. Hydro-Quebec) to upgrade all Distribution Transformers on the network and the infrastructure during the increasing penetration of PEVs.

1. Introduction

In recent years, the integration of PEVs into the Distribution Network has been studied intensively [1–4]. According to [5], the total sold PEVs worldwide in 2015 is 565,668. In China, the sales were trebled compared to 2014, and the overall world growth of selling PEVs is 79% in 2015 compared to the previous year. China set a goal to reach 5 million PEVs by 2020, the same for India in which the target is 6 million PEVs by 2020. The good news about the future of PEVs is announced by Norway and Germany in which the first one banned the gas-powered cars by 2025 and the second one announced that all new cars must be Electric Vehicles by 2030. The penetration level of PEVs is increasing every year [5–6]. Studies have demonstrated that a high penetration level could create problems on the Distribution Transformer (DT) and the network such as overload, overheat, voltage deviations [7], and blackouts which may cost billions of dollars [8]. Therefore, different charging control strategies were suggested to schedule the charging of PEVs.

1.1. Control strategies

In the literature, there are four main control strategies for the load management: (i) Centralized [9–11], (ii) Hierarchical [12,13], (iii) Multi-Agent [14], and (iv) Decentralized [15,16]. Under Centralized Strategy (CS), a central controller makes decisions and controls the power flow of all its optimized loads (Fig. 1a). It is mostly used in Parking Lots, [9,10,12] and Charging Stations [17–19] when a small number of PEVs is presented. If the number of loads and constraints increases [12,19], this strategy becomes slower and impractical to be used. Also, it introduces security and privacy concerns to the end-users [14]. An alternative strategy is used on a larger scale, which is the Hierarchical Strategy (HS) [12,14]. It is composed of different levels of control; each local controller controls its loads and sends the optimal solution to the controller of a higher level (Fig. 1b) [20]. If the higher level is the central controller, therefore, it gathers and analyzes the data of all local controllers. Based on that, it orders them to modify their optimal target to obtain an acceptable global solution. The problem with this strategy is that it is complicated and not very efficient compared to other strategies. Bidirectional communication is required which may cost lots of money for the power utility. More-

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Abbreviations

BSS	Battery Storage System at home
DN	Distribution Network
DRP	Demand Response Program
DT	Distribution Transformer
EWH	Electric Water Heater
LC	Local Controller
LOL	Loss Of Life of the Distribution Transformer
PEV	Plug-in Electric Vehicle
PV	Photovoltaic
RTP	Real Time Price of Electricity
SDS	Soft-Constrained Distributed Strategy
SHEMS	Smart Home Energy Management System
SN	Serial Number of the DT
SOC	State Of Charge of the battery in pu
TOU	Time Of Use Electricity Price

over, it has many problems regarding controlling and managing the power flow in the presence of energy storage systems [14]. Another strategy was proposed which is Multi-Agent Strategy (MAS) [14]. In this strategy, each local controller optimizes its loads and exchange data with its neighbors to achieve cooperative objectives (Fig. 1c) [14]. The problem with this strategy is that communication infrastructure is needed between the local controllers that may cost a fortune to the power utility. All the three mentioned strategies are less common to control loads at homes, while in this paper, our interest is to optimize home appliances. For this purpose, only Decentralized Strategy (DS) can be used [21,22]. In DS (Fig. 1d), each local controller tries to manage its internal loads without communicating to external agents or units [14,21–23]. The problem with this strategy is that householders do not take into account external factors and constraints on the network into their optimization [15,16]. Obtaining an optimal local solution for each householder does not necessarily contribute to an optimal global solution for the Distribution Transformer (DT) and the network. Therefore, many end-users can have high peak demands in the same period causing problems on the DT and the network. Demand Response Programs (DRP) were introduced to solve the problem [24]. Householders can use smart algorithms to optimize their electrical loads in a way to minimize their electricity cost, [25].

DRP can be price-based and incentive-based [15]. One or both of them could be used depending on the strategy of the utility or the aggregators [26]. The main goal of the DRP is to provide a time-varying electricity price and incentive prices, to shift the power consumption of some loads to an off-peak time when the consumption is lower [27]. Usually, Time Of Use (TOU), Real Time Price (RTP), and Dynamic Price are mostly used [24,28]. DRP has limitations; papers [23,29] show that DRP works appropriately until the number of PEVs exceeds a particular limit. Because of the DRP, the PEV charging time in all homes will be shifted to off-peak time, which may produce an undesired peak on the DT. The question is, shall the power utility provide different time-varying electricity prices for all end-users, for each group of end-users, or for individual end-users to solve the problem?

1.2. Home energy management system: related works

To apply the Decentralized Strategy, an energy management system is needed at home level. The home energy management is a hot topic of research in which many studies were done to improve the management of energy at homes using smart algorithms. For example, paper [22] used convex programming to minimize the electricity cost at home. It is relatively faster than other methods and more efficient. The cost of the battery and the charger are considered in the objective function, and the optimized elements are PEV, Photovoltaic (PV) and Battery Storage System (BSS). However, the objective function in [22] is missing parameters related to DRP such as energy-based, price-based and incentive-based programs. Moreover, it did not consider the supplied energy to the grid. Therefore, it may not be implemented on a larger scale where many homes are connected to the same DT. In [16], the objective function includes the generation and maintenance cost of the

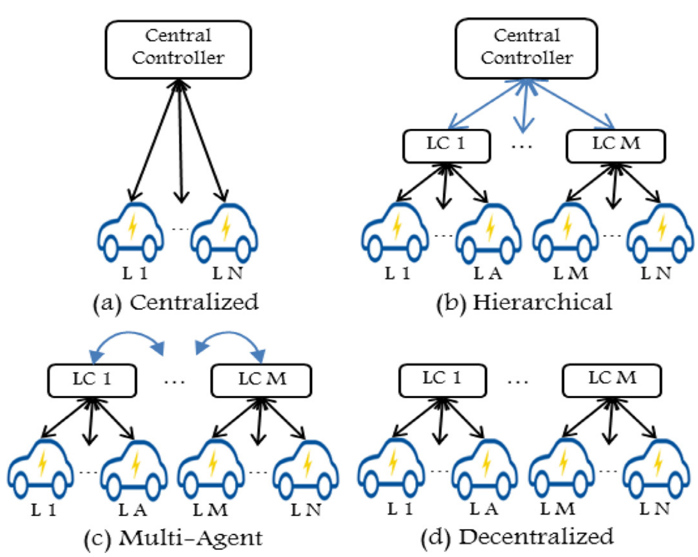

Fig. 1. Control strategies for the same number of loads: (a) centralized, (b) decentralized, (c) hierarchical, and (d) multi-agent. Black arrows represent direct control, while blue arrows represent the communication between controllers and indirect control. L: load, LC: local controller. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)