Real-time Grouped Management of Electric Vehicle Battery Chargers (EVBCs) for Voltage Profile Improvement in Radial Distribution Networks

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***Abstract*—Voltage limit violation is one of the main factors that impact large-scale integration of electric vehicles in distribution networks. In order to improve voltage profiles, active charging management techniques can be deployed in real-time, considering voltage sensitivities of customer buses. The study in this paper investigates a real-time charging management approach for electric vehicles, clustered according to voltage sensitivities among the customer buses, in a local network. Constant power (CP) and constant current (CC) models, representing a range of electric vehicle battery chargers (EVBCs), are used in simulations with high-resolution stochastic EV charging and residential demand profiles. The paper quantifies the performance of the proposed management approach in a local network model based on real data and IEEE European Low Voltage (LV) Test Feeder.**

***Index Terms*—Battery charger, electric vehicle, power distribution, sensitivity analysis, voltage limit.**

I. INTRODUCTION

Electric vehicles (EV) have been on the rise globally in the last decade with annual market growth rate mostly above 50% [1]. The main drivers are increasing feasibility of EVs due to reduced battery costs, technological advancements that increase driving range and national policies to reduce carbon emissions in the road transportation sector [2-3]. Currently, it is not clear how the aging power networks will integrate the anticipated massive increase in EV charging load in the following years. A new report that overviews the electricity distribution systems in Europe highlighted that the number of plug-in EVs per charging station is the highest in Ireland (around 60), while it is above 20 in Belgium, more than 10 in the UK and below 10 in the other surveyed countries [4]. A recent project pointed out that LV network voltage performance is the critical factor in determining how many EVs can be accommodated in a local network [5].

There is a diverse range of electric vehicle battery chargers (EVBCs) in the field. Charging systems are mainly categorized as on-board and off-board, with unidirectional or bidirectional power flow [6]. In the study presented in this paper, Level 2 chargers are considered in the analysis due to their common usage in EU. Level 2 on-board chargers can be 1- or 3-phase, with 4-20 kW charging rates, usually requiring a dedicated supply equipment, with a charging period of 1 to 6 hours.

In network impact analysis studies, it is important to make use of realistic models that correctly reflect the behavior of charging systems. Considering continuous increase in computational power and related reducing costs in research and field applications, it is becoming possible to use more detailed device models in quasi-dynamic analysis. The vast majority of the related studies in the literature use constant power (CP) load model to simulate the impacts of EVBCs on distribution networks [8-13]. However, a number of EVBCs also behave as constant current (CC) load.

In studies with EV charging profiles, deterministic scenarios [8, 10, 14] are increasingly replaced by probabilistic approaches [9, 11-13]. Time-series metering data is usually directly used to take into account residential building consumption [8, 10-11]. For mitigating the negative impacts of new assets integrated into local networks, sensitivity-based management has gained popularity in recent years, especially for photovoltaic systems [16]. However, this approach has not been explored for EV charging management in a European local network case with stochastic scenarios.

The presented study explores grouped management of EVBCs according to voltage sensitivities of customer buses in a local network. CP and CC load models for EVBCs are used in stochastic daily residential customer scenarios implemented in IEEE European LV Test Feeder. Several performance indicators are used to quantify the impact of the proposed coordination approach on bus voltage profiles.

II. METHODOLOGY

This section explains the EVBC model, residential load model, related demand profiles that are adopted from the past studies and presents the grouped EVBC management methodology in separate subsections.

A. EVBC Modelling and Implemented Charging Profiles

In order to represent EVBCs in power system simulation software, CP and CC model of three selected EVBCs were used. The details of the selected EVBCS are provided in Table 1. The EV charging data was taken from an actual vehicle charging field study, "Test-an-EV", which claims to be one of the Europe's largest EV research project [17]. In this project, driving and charging patterns of more than 180 full EVs (Peugeot Ion, Mitsubishi i-MiEW and Citroen C-Zero) owned by families in Denmark were monitored for 3 months period. The data has five-minute resolution. For stochastic simulation in this paper, the EV harging profiles for the residential nodes in the test system are randomly selected from the dataset. The selected data was converted to one-minute interval data via Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) interpolation, in order to match the resolution of the available load data (Figure 1). Stochastic profile selection is done based on equation (1), where $P_{e_{n,m}}$ is the active power demand of a customer owned EVBC at node n and at minute m of the day; N is the total number of load busses in the investigated distribution network (in this study, 55) and r is the index of a dataset with R_e profiles.

$$P_{e_{n,m}} = P_{e_{r,m}} \qquad 1 \leq n \leq N, 1 \leq r \leq R_e, 1 \leq m \leq 1440 \qquad (1)$$

B. Residential Load Modelling and Demand Profiles

The component-based residential load model used in this paper was developed in [18] and used in several studies [19-23]. Measured mean demand profile of aggregated residential customers in a UK urban LV network presented in [21] was firstly decomposed into corresponding load mixes based on the statistical information about contribution of different load types.

TABLE I. SPECIFICATIONS OF THE SELECTED EVBCS

Code Name	Number of Phases	Rated Power (kW)	Max Current (A)	Full Charge Time (h)	Battery Type	Capacity (kWh)
EVBC1	1-ph	7.7	32	4.16	Li-ion	32
EVBC2	1-ph	7.4	32	2.97	Li-ion	22
EVBC3	1-ph	3.3	16	4.85	Li-ion	16

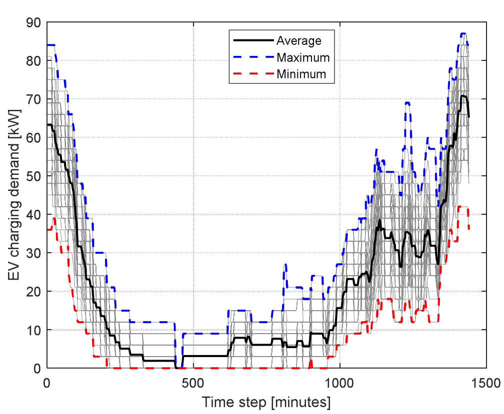

Fig. 1. Sample of 55 individual EV profiles with average, maximum and minimum envelopes

In the next step, they were clustered under related load categories (such as power electronic loads, resistive loads, energy efficient lighting loads, etc.), with coefficients for each load model derived. The exponential load model has two general equations, (2) and (3), defining the relationship between active and reactive power demands and system voltage. P_0 and Q_0 are the nominal active and reactive power demands at the nominal voltage V_0, respectively. V is the actual supply voltage at the considered bus.

$$P = P_0 \left(\frac{V}{V_0}\right)^{n_p} \qquad (2)$$

$$Q = Q_0 \left(\frac{V}{V_0}\right)^{n_q} \qquad (3)$$

In (2)-(3), $n_p = n_q = 0$ is used to represent constant power (CP) loads, while $n_p = n_q = 1$ reflects the behaviour of constant current (CC) loads and $n_p = n_q = 2$ is used for constant impedance (CI) loads. Other values can also be given to the coefficients.

C. Voltage Sensitivity-Based Grouping and EVBC Management Methodology

The voltage sensitivity matrix represents the impact of the changes in power demands at each bus based on its own voltage and the voltages of all the other buses. Briefly, the management system collects bus voltage data, makes a step change in the power demand of one of the buses and collects bus voltage data again. Calculating the difference between the two collected values for each bus, one row of the matrix is filled out. The same process is repeated by changing the power demand of another bus, to determine another row of the matrix and the process continues until all the matrix values are derived. Based on the sensitivity values, the EVBCs at customer buses with similar impact on other customer buses are categorized under a number of groups (Table II). These groups are used to select which EVBCs should be managed during low voltage periods.

TABLE II. IDENTIFIED EVBC GROUPS

Phase	Group	Related Customer Nodes
A	A.1	1, 3, 4, 5, 9
	A.2	9, 14, 21
	A.3	20, 22, 25, 29, 30, 31, 34
	A.4	46, 48, 49
	A.5	51, 52, 54, 55
B	B.1	2, 6
	B.2	7, 10, 11
	B.3	13, 15
	B.4	23, 35, 36, 37
	B.5	26, 38, 40, 41, 45, 50, 53
	B.6	44
C	C.1	8, 12
	C.2	16, 17, 24
	C.3	18, 33
	C.4	19, 27, 38, 32, 39, 42, 43, 47

The proposed EVBC management methodology is explained in the steps listed below:

Step 1: Get each customer bus RMS voltage measurement

Step 2: Check if the lowest voltage among the measured ones is lower than 0.93 pu

Step 3a: If it is lower than 0.93 pu, go to Step 4

Step 3b: If it is higher than or equal to 0.93, do nothing, go back to Step 1 and wait for the next run

Step 4: Find the corresponding EVBC group of the bus with minimum voltage lower than 0.93 pu

Step 5: Check if EVBC at that bus is currently in charging mode

Step 6a: If it is in charging mode, stop it and do not allow charging until minimum bus voltage is above 0.96 pu, go back to Step 1 and wait for the next run

Step 6b: If it is waiting idle, check the currently charging EVBCs in the other buses that belong to the same group and continue to Step 7

Step 7: Select one of the other detected EVBCs from the same group that are currently in charging mode, stop it and do not allow charging until minimum bus voltage is above 0.96 pu, go back to Step 1 and wait for the next run

In the proposed control, 0.93 pu is selected to take precaution for prospective undervoltage issues below a 0.90 pu limit. On the other hand, 0.96 pu threshold is selected for allowing a curtailed EVBC to continue charging, considering that some EVBCs can cause voltage drops up to 3% together with increase in residential demand, so as to not cause minimum bus voltage to drop below 0.93 pu again, requiring another intervention to an already curtailed and shifted EVBC charging regime. The management approach is designed to operate in real-time, without requiring any load predictions, by only evaluating gathered data at each 1-minute step throughout a day. Due to the non-existence of any predictions, the management can only shift charging times forward in time.

III. CASE STUDY

The effectiveness of the proposed approach in a distribution network with residential customers and EVs is explored through simulations. Each of the three selected EVBCs is simulated in its own scenario to make a comparative analysis of the findings. IEEE European Test Feeder is used, as it is a typical LV secondary network based on actual measurements in Northern England [24] (Figure 2). It is a three-phase 400 V (nominal phase-to-phase voltage) radial system that represents typical LV feeders in the UK. The network has a total of 55 single-phase (230 V nominal phase-to-neutral voltage) residential users, which are nearly equally distributed to three phases of the feeder (21 users on phase A, 19 users on phase B and 15 users on phase C). The stochastically selected residential demand and EV charging profiles were applied in network simulations. It was assumed that each of the 55 load points in the LV feeder has an EV charger installed. Simulation time is one day with a 1-minute resolution. Occurrence rates of the lowest bus voltage in certain ranges, in cases without and with management throughout a day for each selected EVCB model, are provided in Table III. Grouped management approach reduced voltage occurrence below 0.90 pu by 0.5% to 4.7% in daily average. Accordingly, 39% to 87% of the undervoltage problems were eliminated. Additionally, occurrence of minimum voltage between 0.90 pu and 0.95 pu is reduced up to 19.8 %, while occurrence in the range of 0.95pu and 1.00 pu increased by 0.1% to 7.5 %. Daily voltage profiles for the lowest bus voltage in each case for CP model are provided in Figures 3, 4 and 5. The difference in voltage profiles are due to intervened charging cycles that are postponed from times when the lowest bus voltage is below 0.93 pu to the times when it is above 0.96 pu based on the methodology described in section 2.c. The CC model results are not plotted, since they are quite close to the CP model results. CC model results are comparatively numerically provided in Tables 3 and 4.

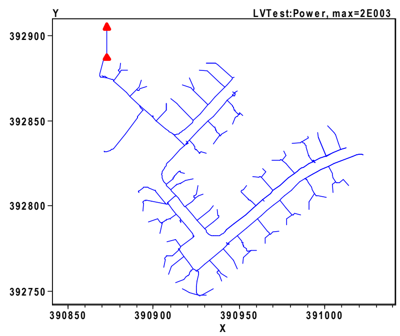

Fig. 2. European LV Test Feeder [23]

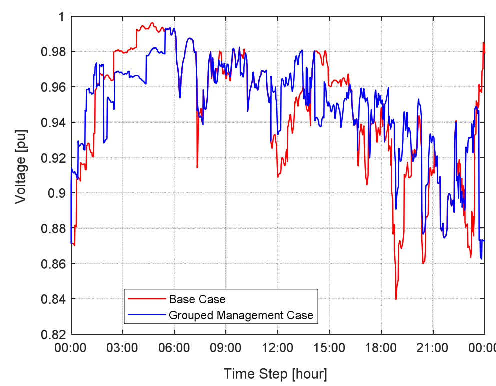

Fig. 3 Daily voltage profile for the scenario with EVBC1, CP model

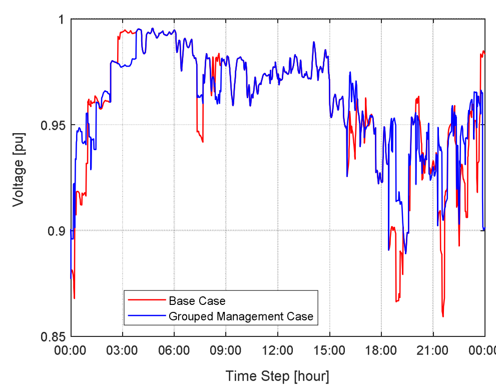

Fig. 4. Daily voltage profile for the scenario with EVBC2, CP model

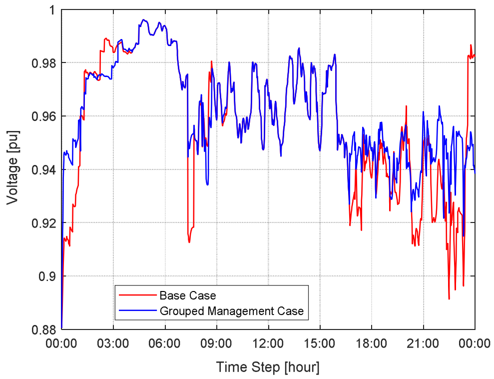

Fig. 5. Daily voltage profile for the scenario with EVBC3, CP model

The maximum, minimum and average time shifting for the interrupted charging cycles are given in Table IV. The times with voltages below 0.90 pu are 00.00, 18.00, 19.00, 22.00. Due to the fact that simulations only cover one day and charging demand is high close to the end of the day, there is less available time window for the interrupted charging cycles in EVBC1 and EVBC2 scenarios with high rated power (7.4 kW) during charging, compared to EVBC3 with lower rated charging power (3.3 kW). The number of intervention events decided by the management logic was 24, 17 and 24 for EVBC1, 2 and 3 scenarios, respectively. 62, 65 and 71% percent of these events were intervened respectively. For the rest of the detected events, there were no EVs at charging mode at the busses in the same group with the bus facing voltage lower than 0.93. Intervention numbers for each group in each case are listed in Table V. Although there are slight differences among voltage occurrence rates in case of using CP and CC model, the percentages of performed charging cycle interventions for each groups are found the same.

TABLE III. DURATION OF THE LOWEST VOLTAGE IN SPECIFIC RANGES

Scenario	Occurrence (%)		
	Below 0.90 pu	***Between 0.90 and 0.95 pu***	***Between 0.95 and 1.00 pu***
EVBC1 without management (CP)	12.0	33.1	54.9
EVBC1 with management (CP)	7.3	33.5	59.2
EVBC1 without management (CC)	11.2	33.8	55.0
EVBC1 with management (CC)	6.2	35.8	58.0
EVBC2 without management (CP)	5.7	24.3	70
EVBC2 with management (CP)	1.9	25.8	72.3
EVBC2 without management (CC)	4.8	25.3	69.9
EVBC2 with management (CC)	0.9	29.0	70.1
EVBC3 without management (CP)	0.8	35.2	64.0
EVBC3 with management (CP)	0.1	29.0	70.9
EVBC3 without management (CC)	0.6	35.3	64.1
EVBC3 with management (CC)	0.1	28.3	71.6

TABLE IV. TIME SHIFTING VALUES FOR THE INTERRUPTED CHARGING CYCLES

Scenario	Time Shifting Values		
	Minimum (min)	***Average (min)***	***Maximum (min)***
EVBC1 (CP)	37	221	421
EVBC1 (CC)	26	209	421
EVBC2 (CP)	13	92	203
EVBC2 (CC)	13	87	203
EVBC3 (CP)	11	87	197
EVBC3 (CC)	11	88	197

TABLE V. THE PERCENTAGE OF PERFORMED CHARGING CYCLE INTERVENTIONS FOR EACH GROUP

Phase	Group	Percentage of Interventions for Each Scenario (%)		
		EVBC1 (CP & CC)	**EVBC2 (CP & CC)**	**EVBC3 (CP & CC)**
A	A.3	20	34	18
	A.4	12	7	18
	A.5	12	13	18
B	B.4	12	13	18
	B.5	20	13	28
C	C.3	12	-	-
	C.4	12	20	-

IV. CONCLUSIONS

The study in this paper has investigated grouped management of EVBCs in local network based on voltage sensitivities of customer nodes. The impact of the proposed approach is analyzed in three scenarios, each with a different EVBC model allocated to 55 residential customer in IEEE European LV Test Feeder. For each EVBC, scenarios explored using CP and CC models. Promising results observed by considerable improvement of voltage in all cases, with a wide range of time shifting of interrupted charging cycles. In daily stochastic simulations, there were EVBCs at charging mode available for intervention in most of the times when voltages below the defined limit. This is mainly due to high contribution of EVBCs to the occurrence of the detected voltage problems and their high potential as a dispatchable loads to mitigate most of the negative impacts.

Future work will explore grouped management for longer time periods than a day, in different networks with diverse characteristics, together with other flexible units, such as PVs with energy storage, heat pumps and other distributed energy resources.

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