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Electric Vehicle Charging Management with Droop Control

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***Abstract*—Increasing residential electricity demand due to simultaneous charging of multiple electric vehicles (EVs) on the same feeder might lead to overloading of the distribution transformers as well as under-voltage at remote terminals of the feeder. In this paper, two different droop control techniques have been proposed for EV charging management to mitigate such problems by reducing the charging load on the basis of droop factors corresponding to the terminal voltage deviation or transformer loading level. Such a control strategy reduces the feeder congestion and improves the terminal voltage at the feeder end. However, since the voltage drop increases as the distance from the substation is increasing, the customers located at the far end of the feeder will suffer from higher curtailment of the charging power in comparison to the customers who are connected closer to the sub-station. Thus, there will be disparity among the customers depending upon their distance from the sub-station and the customers at the far end of the feeder will face more restrictions, thereby limiting their benefit from the dynamic pricing of electricity. On the other hand, when the droop control is based on transformer loading level, a common factor will be applied to all the EV charging loads on the feeder, so everybody will be equally affected.**

Keywords—droop control, EV charging, transformer loading, under-voltage.

I. Introduction

Electric Vehicles (EVs) have recently gained popularity in the Danish market to overcome greenhouse emissions from the transportation sector. According to Danish statistics, a total of 88720 vehicles were registered, in households (60%) and industry (40%), in the last six months of 2023 [1]. Out of these registered vehicles, 41% are EVs and 9% are plug-in hybrid electric vehicles (PHEVs). Considering only household vehicles, which are used privately, 49% are EVs and 9% are PHEVs. These statistics on vehicle registration justify the popularity of EVs and PHEVs and their rapid growth in the Danish transportation sector, implying an increase in the electric load on the distribution network.

Nowadays, the EV home chargers are available in different capacities, viz. 2.3, 7.4, 11 and 22 kW. In Denmark, households are equipped with a 3-phase 32 A power supply. Technically, this will allow 22 kW charger installation. However, considering other household loads 11 kW chargers are popular. In Denmark, besides a subsidy for EV charging, household chargers are subjected to hourly dynamic pricing which is fixed the previous day. This dynamic pricing structure motivates users to charge EVs during low electricity prices with the help of smart chargers whereby the customers can specify the desired charging schedule in advance. This is further facilitated by the chargers which can be accessed by mobile apps. Consequently, a large number of EVs might get connected for charging simultaneously, especially during periods with low electricity price, and eventually overloading the low voltage distribution feeder. Therefore, appropriate charging management approach is necessary to accommodate a large number of EVs in the distribution network .

In recent years, many studies in the literature have addressed intelligent energy management of charging stations. Home energy management system, which reduces energy demand during the peak periods, to optimise the charging of EV is presented in [2]. A bilevel model is proposed in [3], where the distribution system operator minimizes the total operational cost of the active network in the upper level, while in the lower level EV owners tend to minimize their charging cost . In [4], an optimization methodology was suggested for different EV charging stations, e.g., workplaces, residences, and shopping centers, considering both the EV charging behavior and its impact on power systems. Day-ahead electricity price was discussed as a mechanism to unlock the flexibility potentials of charging stations [5]. Hereby, the EV demand flexibility was optimized to improve power flow in the distribution lines and control carbon intensity. In [6], an approximate dynamic programming-based energy management system was suggested for the EV charging stations equipped with multiple types of chargers to reduce the operation cost. The study used fuzzy logic to allocate each EV an appropriate charging spot based on its charging urgency. A bi-level optimization model was proposed for EV charging to design dynamic charging prices based on the regional grid load [7]. The key objective of the study was to optimize the charging costs of EV users and provide peak shaving and valley filling for the local grid. In [8], a model predictive control-based algorithm was

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developed to unleash the flexibility of coordinated EVs for voltage regulation.

An EV controller was developed and tested in the Danish distribution grid to provide ancillary services including congestion management, voltage regulation, and primary frequency regulation [9]. Hoque et al proposed a novel framework [10] which offered price flexibility alongside the market prices to encourage the demand response from the EV owners while satisfying their own preferences. Consequently, high-quality congestion management was achieved, thereby improving voltage regulation. In [11], dynamic power tariffs were proposed through two control loops, viz. the power flow and voltage controls, to provide local support for distribution grids with high EV penetration. A novel three-stage flexibility provision framework was proposed in [12]. Firstly, priced-based demand response from the EVs was scheduled on a day-ahead horizon in response to flexibility requirement of the grid. Secondly, the EV charging schedule was re-optimized based on the latest intraday predictions of renewable generations and demands. Finally, the EVs provided real-time frequency control to mitigate frequency variations and power imbalances. In [13], the stochastic behavior of EV's charging patterns was modeled and the EV charging was coordinated to provide voltage support to the local distribution grid with the adaptive deployment of controllable loads, e.g., batteries and combined heat and power loads. A three-stage stochastic model was proposed to integrate the flexibility potentials of large-scale public parking lots into the local distribution network [14] to provide local grid support for voltage regulation and congestion management. The proposed model enabled the utilization of EVs' flexibility in response to electricity prices in the day-ahead, intraday, and balancing markets. In [15], model predictive control was employed to utilize EV charging control, both unidirectional and bidirectional, to enhance the flexibility potential of building demands in response to renewable power availability.

Ireshika et al [16] analyzed the impact of voltage based droop control for EV-charging upon the local grid voltage. For lower penetrations, this method facilitated the compliance to voltage regulation standards, while simultaneously reducing the peak loading of the transformer. However, the voltage regulation standards could not be complied with under high penetration of EVs in the distribution grid. While the study concludes the improvement of compliance to EN50160 voltage standards, it does not comment upon the poor voltage regulation and subsequent higher curtailment of EV charging power, which affect the customers connected at the far end of the feeder. This paper analyzes the unfair distribution of EV-charging power curtailment among the customers based upon their point of connection in the distribution network. Such a problem could be addressed if a common parameter, like the transformer loading, is used for estimating the droop-based power curtailment factor for all the customers in the local distribution grid.

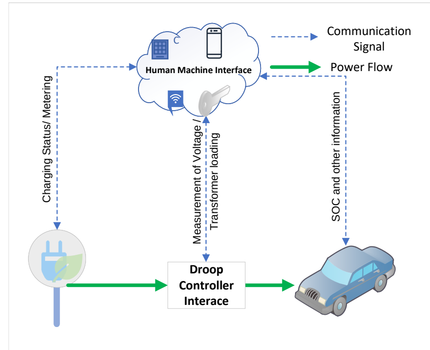

Fig. 1. Control Architecture.

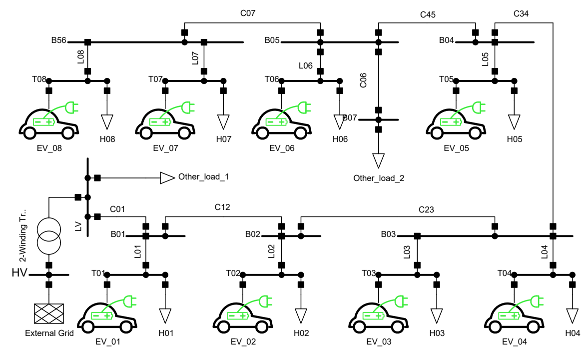

Fig. 2. Low Voltage Distribution Grid network.

II. System Set up

The control architecture of the EV charging with droop control is presented in the Fig. 1. The droop controller determines the factor for the reduction of EV charging power on the basis of the voltage measured at the point of connection of EV charger or loading of transformer. The droop controller is interfaced between the EV and the charging point. All the devices are capable of communicating information through human machine interface using appropriate technologies, eg. mobile applications, hard wire, cloud, key pad, card reader etc.

A test grid of eight households in a radial feeder, representing the neighbourhood of a low voltage distribution grid, is considered here as shown in Fig. 2. Along with the controller, it is modelled and simulated in DIgSILENT PowerFactory. The network consists of a 0.1 MVA, 10/0.4 kV transformer. The rated charging capacity of EV (P_{rated}) is 11 kW. The EV battery size is assumed to be 62 kWh. All the lines and cables are assumed to be 100 m in length. Other load 1 represents the bulk load connected to the respective terminal as part of other radial feeders. The hourly load profile of individual households is obtained from their daily energy demand data (table I) and transformer loading profile obtained from the substation metering data.

III. Modelling of System

The behaviour of EV as an electrical load, when connected to the charging station, is modelled as the battery unit of specific size. The depth of discharge (in %) of EV (DOD) at the beginning of charging appropriately resembles the dynamics of driving profile and distance travelled. The initial

TABLE I
HOUSEHOLD ELECTRIC ENERGY DEMAND PER DAY

HH	Load (kWh/day)	HH	Load (kWh/day)
HH_01	15.42	HH_05	9.23
HH_02	14.03	HH_06	5.68
HH_03	11.70	HH_07	12.13
HH_04	11.42	HH_08	8.75
Other_load_1	474.2	Other_load_2	124.8

state of charge (SOC_{ini}) of an EV is related to its DOD by the equation,

$$SOC_{ini} = 100 - DOD \ [\%] \tag{1}$$

After charging the EV for t hours, its SOC is determined using Coulomb count method as follows,

$$SOC(t) = SOC_{ini} + \frac{\int_0^t P_{char}(t)dt}{C_{bat} \times 3600} \quad [\%] \tag{2}$$
$$0 \leq SOC(t) \leq 100 \quad [\%],$$

where C_{bat} is the battery capacity in kWh and (P_{char}) is charging power in kW. P_{char} is proportional to the droop coefficient, $k_t(t)$, and it is given by,

$$P_{char}(t) = k_t(t) \times P_{rated} \quad [kW]. \tag{3}$$

Two types of droop control approaches for curtailing the charging power of EVs are discussed in this paper:

1) voltage droop, and
2) loading droop.

As shown in Fig. 3(a), voltage droop is based on the measurement of terminal voltage, $V_{poc}(t)$, at the point of connection of the EV charger. It is then compared with the specified high and low voltage levels, V_h and V_l, respectively. When $V_l < V_{poc}(t) < V_h$, the voltage droop factor, $k_v(t)$ is given by,

$$k_{droop}(t) = k_v(t) = 1 - \frac{V_h - V_{poc}(t)}{V_h - V_l} \tag{4}$$

The droop factor is unity when $V_{poc}(t) > V_h$ and it is zero when $V_l > V_{poc}(t)$. In this study, it is arbitrarily assumed that $V_h = 0.98pu$ and $V_l = 0.92pu$. These levels can be adjusted according to the specific feeder requirements and characteristics.

Similarly, the loading droop control is based on the measured value of transformer loading $I_{xmer}(t)$ as shown in Fig. 3(b). When the transformer loading exceeds the critical level (i_{crit}), i.e. $I_{xmer}(t) > i_{crit}$, the loading droop factor, $k_l(t)$ is given by,

$$k_{droop}(t) = k_l(t) = 1 - \frac{1 - I_{xmer}(t)}{1 - i_{crit}} \tag{5}$$

Here, the critical level is arbitrarily selected to be 0.5 pu. The droop factor is filtered using a first order low pass filter to avoid rapid changes in the droop factor.

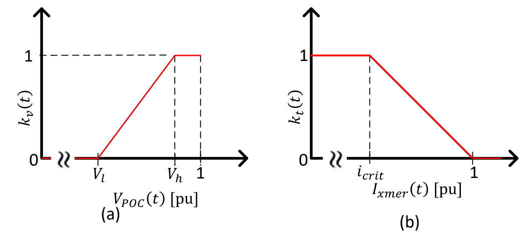

Fig. 3. Droop Control coefficients for EV charging (a) Droop based on terminal voltage of EV charging, (b) Droop based on loading of transformer.

TABLE II
SIMULATED TEST CASES

Case No.	Case Study	*EV*	*Voltage Droop*	*Loading Droop*
1	Base Case	x	x	x
2	No Droop	✓	x	x
3	Voltage Droop	✓	✓	x
4	Loading Droop	✓	x	✓

A. Simulation

Four different case studies are carried out with variation in choice of droop control as presented in table II. There is no EV in the base Case #1. The EVs are present but no droop control is applied in Case #2. Voltage droop is applied in Case #3 and Loading droop is applied in Case #4.Dynamic simulation is carried out for the 24-hour period to evaluate the variation in the feeder terminal voltages $V_{poc}(t)$ at different terminals and transformer loading, $I_{xmer}(t)$.Furthermore, the EV charging is scattered based on their assumed arrival times after 15:00 hr.

B. Results and Discussions

The simulated results are compared for feeder voltage profile and transformer loading as well as the charging power of the selected households.

In order to assess the feeder loading level and voltage profile in cases #2, #3 and #4, all EVs are connected for charging at 00:00 hr when the 24-hour simulation begins.

The daily load profile of the eight houses in the base case when no EV is connected is shown in Fig. 4(a). The transformer loading for all four cases are presented in Fig. 4(b). The maximum transformer loading is 56.3% for base case at 18:00 hr. The transformer loading increases from 25% to 108% at 00:00 hr when all the EVs are charging without any droop control. With the implementation of voltage or loading droop for charging EVs, the maximum transformer loading is limited to 70.5% and 72% respectively. This reductions is attributed to reduction in the EV charging power as a result of the droop control.

The voltage dip at terminal T01, which is close to the secondary of transformer, is well above 0.96 pu for all case studies as seen from Fig. 4(c). However, the voltage dip is significantly low, up to 0.9 pu at 00:00 hr, for the terminal T08 at the far end of the radial feeder while no droop control (case #2) is implemented as seen from Fig. 4(d). The voltage at T08 is significantly improved to 0.95 pu and 0.93 pu considering voltage or loading droop control for EV charging

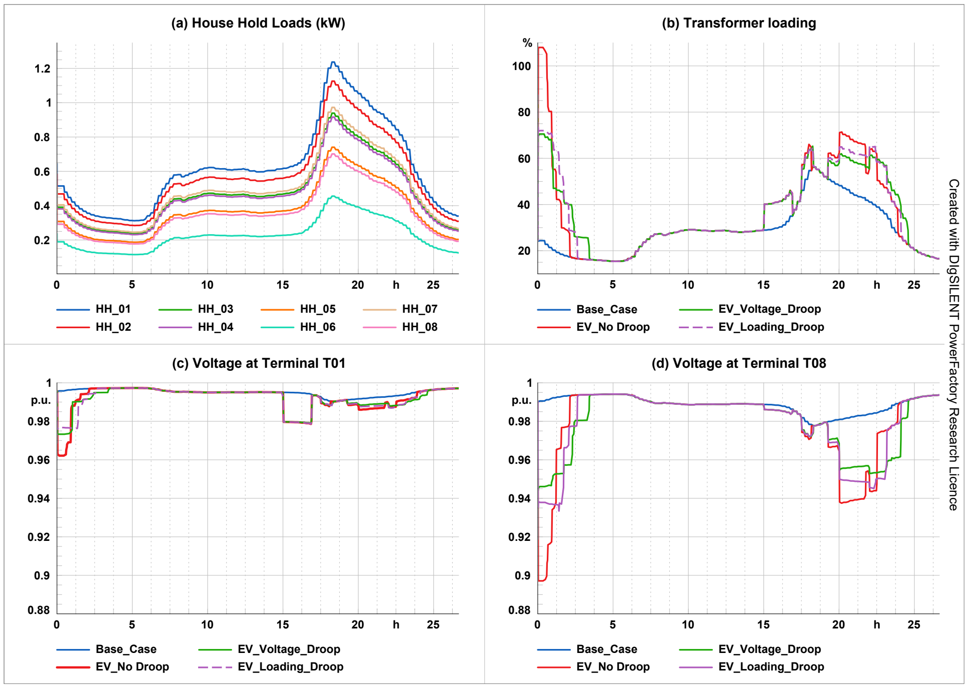

Fig. 4. Comparison of simulation results for all case studies: (a)House holds load profile;(b) Transformer loading (%); (c)Terminal voltage at the beginning of feeder (T01); (d) Terminal voltage at the far end of feeder (T08).

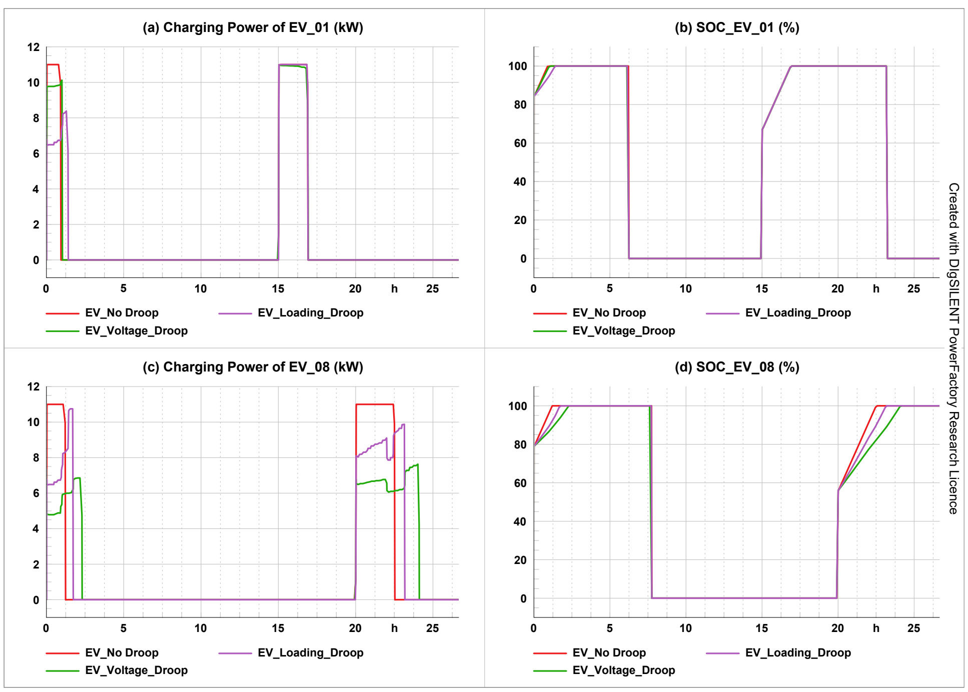

Fig. 5. Comparison of simulation results for all case studies: (a) and (b) Charging power and SOC of EV_01 respectively; (c) and (d)Charging power and SOC of EV_08 respectively.

respectively. Thus, the simulation study clearly indicates that using the droop control for power regulation of EV charging, the problem associated with overloading and voltage dip in long radial feeder in distribution grid can be minimised.

The charging power of EV corresponding to case studies, are compared in Fig. 5(a) and (c) for EV_01 and EV_08 respectively, while battery SOC is shown in Fig. 5(b) and (d). With no droop control in Case #2, all EVs are charged with rated power level of 11 kW. In case #4 all EVs are charged with 6.5 kW. Hence the same cost benefit of the dynamic electricity prices are applicable to all the EVs in no droop control and loading droop control. However, with the voltage droop control, EVs at the far end of the radial feeder are charged with lower power level (4.8 kW) compared to 6.5 kW at 00:00 hr for EV_01 which is closer to the transformer. As a result EV_08 takes longer charging time. Thus, voltage droop approach is unfair for the consumers at the far end of the feeder in terms of economic charging although the improvement in termianl voltages is better than in loading droop concept. Fig. 5(b) and (d) illustrates that all EVs are fully charged with 100% SOC despite any control method, but with longer time for droop controls.

Considering shattered arrival times of different EVs (EV_01 arrives home at 15:00 hr, while EV_08 at 20:00 hr) their charging rates will depend upon the grid condition at those instants. Thus the loading of transformer is flattened and the coltage profile is improved.

The transformer loading, and minimum voltage profile of terminal T01 and T08 for all case studies are summarised in Fig. 6. The transformer loading decreases significantly by 36% nder Loading droop control and to 37.5 % under Voltage droop control. The terminal voltage at the far end of the feeder is improved to 0.95 pu by voltage droop control and 0.93 pu by the loading droop control. However, due to the voltage droop control, there is unequal curtailment of power among the consumers based upon their distance from the transformer substation. The problem is alleviated by Loading droop control, whereby all the charging power of all the EVs in the distribution network is reduced by the same factor. On the other hand, this method needs a communication between the transformer substation and all the EV chargers. Moreover, this method would avoid any overloading of the transformer.

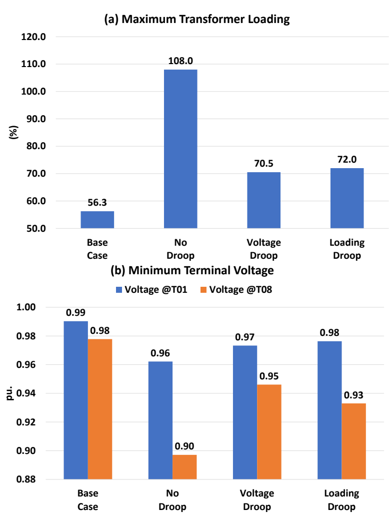

Fig. 6. Summary of case studies results (a) maximum transformer loadings, (b) terminal voltages at T01 and T08.

IV. Conclusion

This paper highlights the effect of droop control in EV charging and its impact upon the EV charging capacity available to the different users based upon their point of connection and feeder loading level. In general, both the droop control techniques decrease the maximum transformer loading level, improve the feeder voltage profile. It thus solves the problem of transformer overload and severe under-voltage observed when all the EVs are charging at nominal power.

Under voltage droop control, the feeder voltage profile is improved and the transformer loading is decreased. However, the customers at the far end of the feeder is at a disadvantage as they have to suffer from a higher power reduction during peak loading conditions. Under severe feeder loading conditions, if the terminal voltage falls below the low voltage limit, they might even be forbidden from charging.

The transformer loading based droop control is justifies as it affects equally to all the customers and there is no location based bias. However, this method needs continuous communication from the transformer substation to all the EV chargers.

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