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Mitigating the Impacts of EVs Charging Infrastructure on Dutch Residential Grids

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***Abstract*—With the enforcement of governmental regulations and incentives, the share of electric vehicles (EVs) in the mobility sector is on the rise, impacting significantly the grid and its operation. This paper aims to investigate and find solutions to mitigate the impacts of EV charging on Dutch residential grids, namely the impacts of voltage magnitude regulation and distribution transformer loading. This paper proposes a decentralized coordinated charging strategy with local voltage control at its essence. The proposed charging strategy effectively allocates the charging power by prioritizing users based on their current State-of-Charge (SOC) and/or Time of Departure (ToD), or the current loading on the distribution transformer. These parameters are communicated to the charge controller through an Internet-of-Things (IoT) platform. The proposed charging strategy was simulated on a real Dutch residential grid that serves 86 household users, assuming every household has its own controllable EV charger. Based on the obtained results, the proposed charging strategy has eliminated all voltage magnitude violations, reduced the loading on the distribution transformer, while also achieving a SOC that is 2.5% less than that of the uncontrolled charging strategy.**

***Index Terms*—Voltage magnitude regulation, distribution transformer loading, decentralized control.**

I. INTRODUCTION

The Dutch government is fully committed to prolonging its position as the European leader in electric mobility and has set clear goals in the so-called Mission Zero. This commitment includes the selling of only zero-emission vehicles from the year 2030 and onward. As a result, projections estimate an average of 400.000 electrical vehicles (EVs) to be deployed every year, as well as the need for 1.8 million EV chargers (public or private), for the year 2030 [1].

Typically, EV users charge in the evenings and late-night using residential charging stations [2]. A charging EV requires a significant amount of power when compared to the average household consumption, which often translates into lower voltage magnitudes at the charging node. As a result, undervoltage is proven to be a predominant issue factor when compared to any other type of technical problems [3]. From a regulatory perspective, the operating voltage should be between 90% to 110% of the nominal voltage, as defined in EN 50160 standard [4]. Another common impact from the EV loads may be observed in the distribution transformer supplying the low voltage (LV) grid. Overloading a transformer can rapidly increase the amount of energy losses and the amount of heat generated, consequently, damaging its internal components and reducing its lifetime [5]. Other impacts include harmonic distortion, voltage unbalance, and poor power quality [6].

Unfortunately, it is estimated that the current grid capacity can withstand a considerably low EV penetration rate with an uncoordinated charging routine [7]. Therefore, coordinated charging among EV users can help maximize the utilization of the existing grid capacity while also adhering to the gird limits and preventing abnormal costs with regards to grid upgrades. EV charging can be coordinated using centralized, decentralized, and market-based approaches. Centralized methods are more prominent and rely on one central entity to dispatch EV charging either on a day-ahead basis, for example, or by relying on an EV aggregator as demonstrated in [8]. Apart from being very expensive, centralized methods are very complex due to the interaction of many measurement devices and communication infrastructures [9]. On the contrary, decentralized methods asses the problem on a local level and act accordingly. Decentralized methods not only take into account the constraints set by the Distribution System Operator (DSO), but also adapt to the current circumstance of the distribution grid in order to effectively and autonomously schedule and dispatch EV charging [10]. In addition, they are easier to implement and are economically more attractive when compared to centralized methods. The similarity between centralized and decentralized control is that both methods solely operate on minimizing and distributing load from a DSO's perspective rather than just relying on minimum charging costs. The minimum load method assumes the presence of incentive regulations, as in the case of many European countries, in order to minimize the EV charging load when the corresponding household consumption is high and vice-versa [11]. The resulting load curve is an effective shift in the EV charging load to off-peak hours, while respecting the grid capacity limits [12]. The third approach, however, is to use a market-based approach to alter the EV users' charging behavior by giving monetary incentives. Control strategies that follow this approach generally determine a physical factor that would set the charging price in a specific time-period, as presented in [13]. Consequently, EV users are expected to change their consumption patterns in response to the time-dependent prices.

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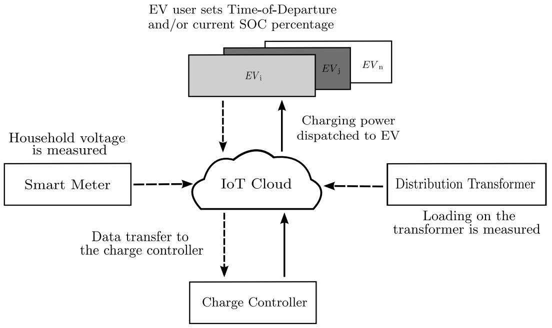

Fig. 1. User's SOC and/or ToD, along with the smart meter measurements, are communicated to the charge controller via the IoT cloud. The charging decisions are also communicated to the EVs via the IoT cloud.

II. Proposed Decentralized Control Method

The proposed decentralized control approach aims to mitigate the impacts of EV charging on Dutch residential grids, while also allowing users to participate in the coordinated charging routine. This control method inherently assumes an interactive Internet-of-Things (IoT) platform has been developed and deployed as shown in Fig. 1. The purpose of this platform is for users to communicate their current State-of-Charge (SOC) and/or Time of Departure (ToD) to the charge controller, which will then autonomously set a priority level to the respective user. The essence of the proposed control method lies in its ability to dispatch EV charging, for a specific user, based on the current voltage magnitude measurement of the household connection. Assuming the distribution transformer is able to provide the charging power decided upon by the charge controller, the charging power is set as a function of the household voltage magnitude. Consequently, the lower the household voltage magnitude, the lower the charging power that would be dispatched and vice-versa. In this sense, one of the main features of this strategy lies in its ability to prioritize users based on their inputs without interrupting the charging process. Before exploring the three regions of interest in Fig. 2, the six variables of focus are defined below:

- $V_{\mathbf{i,t}}$: represents the household voltage for user, i, at time-step, t.
- $\hat{V}_{\mathbf{i,t}}{}^{\mathbf{min}}$: represents the cumulative moving average of the household voltage magnitude. This is calculated by taking the average of the household voltage for user, i, of all previous time-steps within a pre-defined time window.
- $V_{\mathbf{th}}$: represents the voltage threshold.
- $P_{\mathbf{min}}$: represents the minimum limit for charging power dispatch.
- $P_{\mathbf{max}}$: represents the maximum limit for charging power dispatch.
- $P_{\mathbf{i,t}}{}^{\mathbf{char}}$: represents the dispatched charging power for user, i, at time-step, t.

The three main regions of the dispatch curve are highlighted below:

1) **If $V_{\mathbf{i,t}} \geq \hat{V}_{\mathbf{i,t}}{}^{\mathbf{min}}$, then $P_{\mathbf{i,t}}{}^{\mathbf{char}}$ = $P_{\mathbf{max}}$.**

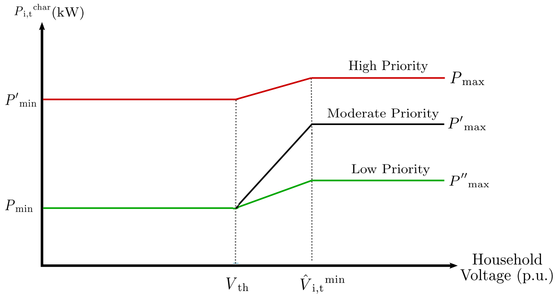

Fig. 2. Once a user has been given a certain priority level, the $P_{\max}$ and $P_{\min}$ limits are set and $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ can be dispatched according to the user's household voltage magnitude.

This usually indicates that the household is not heavily loaded (i.e. the voltage magnitude is high) and the EV can charge at the maximum power.

2) **If $V_{\mathbf{th}} \leq V_{\mathbf{i,t}} < \hat{V}_{\mathbf{i,t}}{}^{\mathbf{min}}$, then $P_{\mathbf{i,t}}{}^{\mathbf{char}}$ is curtailed.**
This means that

$$P_{\mathrm{i,t}}{}^{\mathrm{char}} = m \cdot V_{\mathrm{i,t}} + c, \tag{1}$$

where m and c are defined as follows:

$$m = \frac{P_{\max} - P_{\min}}{\hat{V}_{\mathrm{i,t}}{}^{\min} - V_{\mathrm{th}}} \tag{2}$$

$$c = P_{\max} - (m \cdot \hat{V}_{\mathrm{i,t}}{}^{\min}) \tag{3}$$

The purpose of this region is to gradually decrease $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ as the household voltage magnitude drops and gradually increase $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ as the household voltage magnitude increases.

3) **If $V_{\mathbf{i,t}} < V_{\mathbf{th}}$, then $P_{\mathbf{i,t}}{}^{\mathbf{char}} = P_{\mathbf{min}}$.**
This usually indicates that the household is heavily loaded (i.e. the voltage magnitude is low) and the EV can charge at the minimum power.

Note that regardless of the household voltage magnitude, EV charging resumes but at a lower $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ value. Additionally, every household user has a unique charging power dispatched at every time-step (where charging occurs) depending on which of the three aforementioned regions the household's voltage magnitude corresponds to. Therefore, the household voltage magnitude does not only reflect the dispatched charging power, but also reflects the respective household consumption and that of the other users connected to the same phase.

Three charging strategies are proposed in which users can qualify for priority based on their current State-of-Charge (SOC) percentage, Time-of-Departure (ToD), or both. The fourth proposed charging strategy, however, qualifies users for priority based on the current loading on the distribution transformer supplying the LV grid. Within each charging strategy lies three levels: high, moderate, or low priority level. As a result, users who qualify for a high priority level, for example, are allocated more charging power than that of the users with a moderate or low priority level. Consequently, $P_{\mathrm{i,t}}{}^{\mathrm{char}}$ is effectively allocated to users who urgently require charging, instead of overloading the distribution grid by allowing all users to have the ability to charge at $P_{\max}$. In Fig. 2, the three distinct priority levels that will be used by the four proposed charging strategies are defined as follows :

- **High priority level:** Users who qualify for high priority will charge with an adjusted minimum power, $P'_{\min}$, that is higher than the original minimum charge power, $P_{\min}$.
- **Moderate priority level:** Users who qualify for moderate priority will charge with an adjusted maximum power, $P'_{\max}$, that is lower than the original maximum charge power, $P_{\max}$.
- **Low priority level:** Users who qualify for low priority will charge with a furtherly adjusted maximum power, $P''_{\max}$, that is lower than both, the original maximum charge power, $P_{\max}$, and the previously adjusted maximum charge power, $P'_{\max}$ (in moderate priority).

A. Strategy I: Priority based on SOC

As the name suggests, this strategy sets user priority depending on the initial SOC percentage, $SOC_{\text{i,t}}^{\text{initial}}$. Users with a low $SOC_{\text{i,t}}^{\text{initial}}$ percentage will be given higher priority than users with a high $SOC_{\text{i,t}}^{\text{initial}}$ percentage. The three priority levels are defined as follows:

- A user qualifies for **high priority** if the user's $SOC_{\text{i,t}}^{\text{initial}} \leq 40\%$.
- A user qualifies for **moderate priority** if the user's $40\% < SOC_{\text{i,t}}^{\text{initial}} \leq 70\%$.
- A user qualifies for **low priority** if the user's $SOC_{\text{i,t}}^{\text{initial}} > 70\%$.

B. Strategy II: Priority based on Time-of-Departure (ToD)

The second charging strategy sets user priority depending on the time a user intends to leave. The earlier the ToD is, the higher the priority level and vice-versa. The three priority levels are defined as follows:

- A user qualifies for **high priority** if the user's ToD is within one hour.
- A user qualifies for **moderate priority** if the user's ToD is more than one hour but within two hours.
- A user qualifies for **low priority** if the user's ToD is more than two hours.

Since residential EV chargers are considered, the power rating of these chargers is considerably lower than that of the commercially available fast and ultra fast chargers; consequently, EVs connected to residential chargers need longer periods of time to charge. Therefore, the constraints that define the priority levels for this charging strategy are set on the basis of one-hour intervals rather than 15-minute intervals. In that way, users who qualify for high or moderate priority can benefit from a considerable amount of added SOC percentage as they approach their respective ToDs.

C. Strategy III: Priority based on SOC & ToD

To further extend the idea of priority-based charging, this charging strategy sets priority levels based on both, the $SOC_{\text{i,t}}^{\text{initial}}$ percentage as well as the ToD of the respective EV. Accordingly, EV users with a low SOC percentage and earlier ToD are allocated more charging power than EV users with a higher SOC percentage or later ToD. The three priority levels are defined as follows:

- A user qualifies for **high priority** if the user's $SOC_{\text{i,t}}^{\text{initial}} \leq 40\%$ **and** the user is leaving within two hours.
- A user qualifies for **moderate priority** if the user's $40\% < SOC_{\text{i,t}}^{\text{initial}} \leq 60\%$ **and** the user is leaving within two hours.
- Else, a user qualifies for **low priority**. That essentially means the user is either leaving in more than two hours or leaving in the coming two hours but with an $SOC_{\text{i,t}}^{\text{initial}} > 60\%$.

D. Strategy IV: Priority based on Distr. Transformer Loading

In the previous charging strategies, setting priority levels is directly related to the users' inputs. This means users were provided with the maximum and minimum charging power limits as a result of their EVs' SOC and/or ToD. In this charging strategy, however, the minimum and maximum charging power limits are defined and set based on the current loading on the distribution transformer regardless of the EV's SOC and ToD. Yet again, the three priority levels employed in the aforementioned charging strategies are used here and are defined as follows:

- All users qualify for **high priority** if the current loading on the transformer is less than or equal to 80%. This threshold represents the normal operational limits of a typical distribution transformer and therefore users can charge at high power rates.
- All users qualify for **moderate priority** if the current loading on the transformer is greater than 80% but less than or equal to a 100%. Users at this priority level can charge at a considerably lower charging power than that of the high priority level as the transformer is heavily loaded in this region of operation.
- All users qualify for **low priority** if the current loading on the transformer exceeds 100% and therefore indicates the transformer is overloaded.

III. CASE OF STUDY

The most prominent residential chargers in the Netherlands adopt the so-called *Mode 2* charging technique, which can normally provide a maximum charging power between 2.3 kW and 3.7 kW using a one-phase connection as per the RVO guidelines [14]. As a result, this scenario is developed on the basis of providing the most likely scenario to occur in the near future. Table I presents the values for the $P_{\max}$ and $P_{\min}$ limits introduced in Fig. 2. Furthermore, the residential network used in this study is depicted in Fig. 3. This represents a real LV distribution grid provided by a Dutch DSO at a certain location in the Netherlands. The grid serves 86 households using a single distribution transformer with a voltage rating of 11 kV/400 V and a nominal power rating of 150 kVA. The voltage magnitude of the reference bus is set at 1.0 p.u. Every feeder contains a different number of households and each

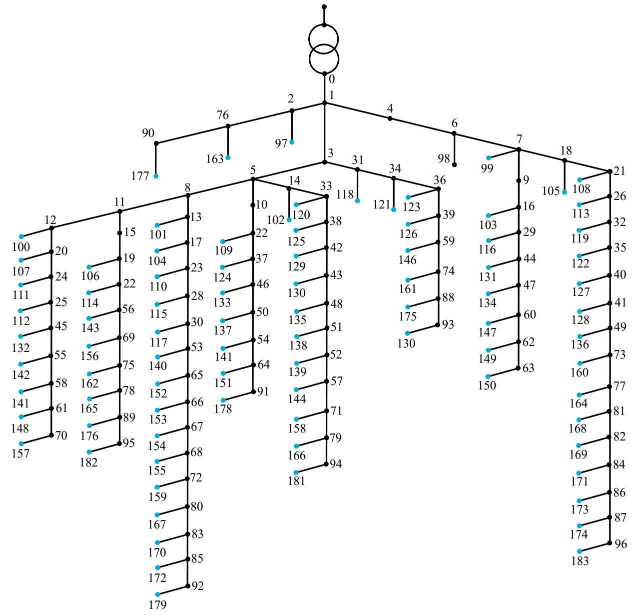

Fig. 3. Dutch residential grid serving 86 households. Each blue dot represents a household user and their corresponding user number.

TABLE I
THE POWER RATING OF EACH OF THE PARAMETERS PRESENTED IN FIG 3.

Parameter	Power Rating (kW)	Prioirty
P_{max}	3.7	High
P'_{max}	2.5	Moderate
P''_{max}	1.7	Low
P'_{min}	3.0	High
P_{min}	1.2	Moderate & Low

household is connected to one-phase. Furthermore, the EV load profile has been obtained from [15], where 86 EVs were selected randomly and assigned to every household. Finally, the battery pack considered in this research is similar to that of a Nissan Leaf with a battery pack capacity of 40 kWh.

IV. SIMULATION RESULTS

This section presents the results of the proposed charging strategies, evaluated with respect to the amount of voltage magnitude violations mitigated. The simulation ran for a period of 672 time-steps which translates to one week of operation (in time-steps of 15 min). The control parameter V_{th} is set at 0.95 p.u. for all scenarios. Unless stated otherwise, the EV penetration rate is set to 100% and each household has one EV. Finally, the number of voltage magnitude violations associated with every control strategy is a global variable and indicates the total number of voltage magnitude violations in the whole residential grid, and not only in the voltage profile of the presented user (if applicable).

A. Impacts on Voltage Magnitude Regulation

The residential grid has been simulated under six strategies: household consumption without EVs, uncontrolled EV charging, and the four charging strategies discussed earlier in Section II. Household consumption without EVs resulted in no voltage magnitude violations and a voltage profile between approximately 0.97 p.u. and 1.0 p.u which reflects the normal day-to-day consumption. Uncontrolled EV charging has resulted in 112 voltage magnitude violations; therefore, one would expect the charging strategies to mitigate the impacts of under-voltage. Consequently, SOC-based priority control, ToD-based priority control, Transformer Loading priority control, and SOC & ToD Combined priority control resulted in 8, 14, 12, and 0 voltage magnitude violations, respectively, as shown in Table II. To prove that uncontrolled EV charging can result in voltage magnitude violations, the voltage profile of User 179 (located at the end of the longest feeder) is presented in Fig. 4. Although User 182 has not shown any voltage magnitude violations with uncontrolled EV charging, User 182 is more interesting to our final evaluation due to its extensive EV charging profile when compared to the other users located at the bottom of the other feeders. The voltage profile of User 182 is plotted in Fig. 5.

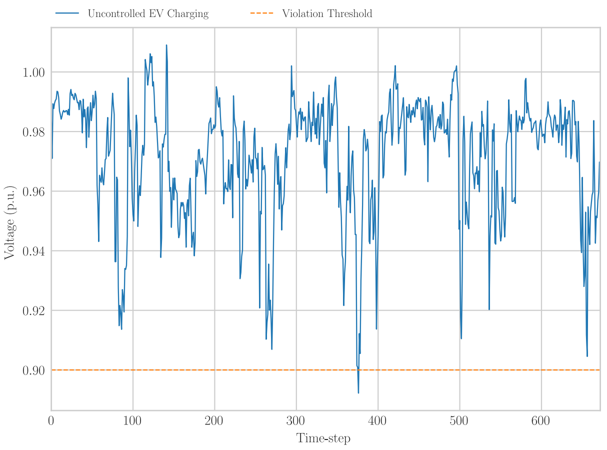

Fig. 4. Voltage profile of User 179 with uncontrolled EV charging.

While some strategies mitigated most of the impact, the results in Table II prove that formulating a control strategy based on only one factor will not fully mitigate the resulting impacts. If the SOC-based charging strategy is considered, for instance, EVs are prioritized in terms of their SOC percentages without taking into account when their respective ToD is scheduled. As a result, if two EV users had the same SOC percentage, both would be assigned the same level of priority even if one of the users is leaving in a time step far ahead. The same conclusion can be extended to ToD and Transformer Loading priority controls as they both set priority based on one factor. However, SOC & ToD Combined priority control has eliminated all voltage magnitude violations and also provided a better voltage profile than that of the other control strategies. This is because users who do not urgently require charging are prioritized at a lower level; therefore, relieving the grid from any extra stress.

B. Evaluation at Different EV Penetration Rates

To further extend this evaluation, the residential grid was simulated again at an EV penetration rate of 26.7%, 50%, and 74.4%. Assuming each household can have up to one

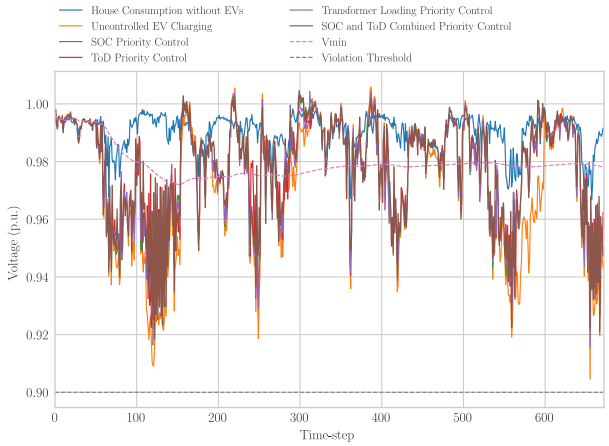

Fig. 5. Voltage profile of User 182 under six strategies. The voltage profiles have been improved under the four charging strategies, specifically when employing SOC & ToD Combined priority control.

TABLE II
THE TOTAL NUMBER OF VOLTAGE MAGNITUDE VIOLATIONS PER CHARGING STRATEGY AT A 100% EV PENETRATION RATE.

Charging Strategy	***Voltage Magnitude Violations***
Household Consumption Without EVs	0
Uncontrolled EV Charging	112
SOC Priority Control	8
ToD Priority Control	14
SOC & ToD Combined Priority Control	0
Transformer Loading Priority Control	12

EV, the EV penetration rate is the ratio of households with EVs to the total number of households in the residential grid. The resulting voltage magnitude violations corresponding to each EV penetration rate has been plotted in Fig. 6. With exception to the SOC & ToD Combined priority control, voltage magnitude violations are present in all other charging strategies with an EV penetration rate of 50%, 74.4%, and 100%. Yet, no voltage magnitude violations were recorded across all strategies with an EV penetration rate of 26.7%, which indicates the extent to which the current grid capacity can handle uncontrolled EV charging in this scenario.

C. Impacts on the Distribution Transformer

The regions of interest for transformer loading are shown in Fig. 7. A transformer loading up to 80% of its capacity is considered as in normal operation, while a loading between 80% and 100% is considered as heavy loading operation. If the transformer loading is greater than 100%, the transformer is overloaded and the load must be curtailed immediately to avoid any damage [16]. Under normal household consumption, the transformer loading barely exceeds 40% as shown by the dashed-blue line in Fig. 7. It also shows that the highest transformer loading occurs during the peak hours of consumption towards the end of every day. Additionally, Fig. 7 shows that most of the loading is owed to EV charging, which indicates the importance of employing a coordinated charging strategy. For this scenario, however, the uncontrolled charging strategy has not resulted in an overload, but has heavily loaded the distribution transformer to approximately 90% of its power loading capacity. In this case, all charging strategies have successfully brought down the loading percentage from the heavy loading to the normal loading operation, as the power drawn by the EVs is curtailed to adhere to the minimum voltage magnitude threshold of every household connection. Finally, the resultant impacts on the distribution transformer loading in this scenario suggests no upgrades are needed with regards to the transformer capacity.

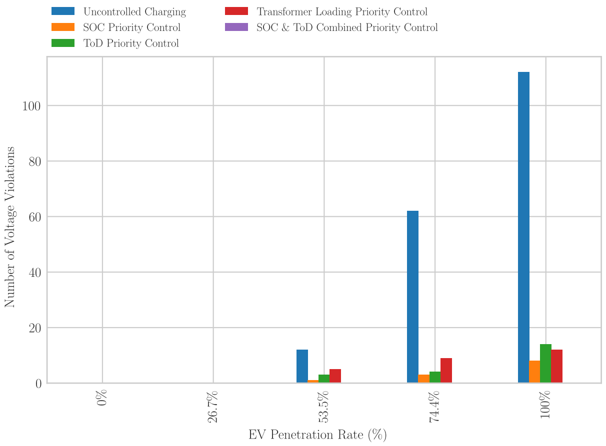

Fig. 6. Number of voltage magnitude violations per charging strategy per EV penetration rate. As the number of EV users increases, the impact on the grid gradually increases as evident in the uncontrolled charging strategy.

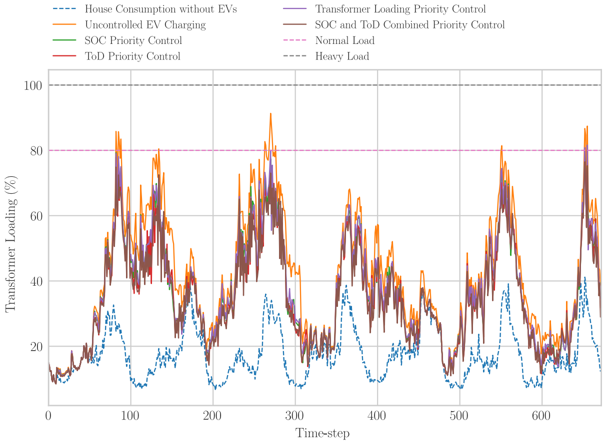

Fig. 7. Transformer loading percentage for all of the tested EV charging strategies.

D. Impacts on EV Users

The promising results of this scenario suggest that the current grid capacity can handle an EV penetration rate of 100% without causing any voltage violations (given the SOC & ToD Combined priority control is employed). However, it is of utter importance to investigate the extent in which the EVs' SOC percentages are being charged, with respect to uncoordinated charging and all four charging strategies. Since uncoordinated charging simply applies the maximum charging power, one would expect the charging strategies to achieve a SOC that is lower than that of uncoordinated charging, hence

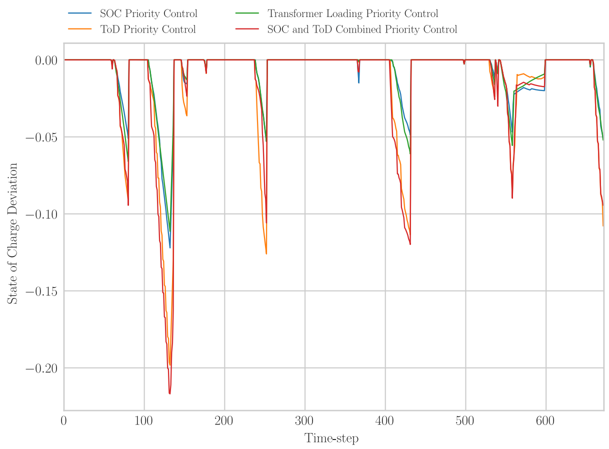

Fig. 8. The difference in SOC between all charging strategies compared to the uncontrolled strategy, for EV User 182.

the negative SOC deviations for EV User 182 in Fig. 8. Please notice that a SOC of 0% indicates the EV is disconnected from the charging point and thus data is not available. As can be seen, the maximum difference in SOC between the coordinated and uncoordinated charging strategies is between 10% to 23% (depending on the charging strategy employed). However, it can be concluded that the longer the charging period, the lower the SOC difference between the uncontrolled and controlled strategies. To put this into perspective, let's consider the ToD priority control strategy for a 12.5-hour charging period. At the beginning of the charging period, EV 182 will be prioritized at a low level and therefore more power will be allocated to other users who are leaving shortly. As the EV approaches its ToD, the priority level will be increased (i.e the charging power rate is increased) in order to charge the EV as much as possible before its ToD. This is why the SOC deviation from that of the uncontrolled strategy increases to nearly 9% at the beginning of the charging period but diminishes to less than 2.5% at the end of the charging period. Additionally, all the other coordinated charging strategies showed nearly similar SOC deviations from that of the uncontrolled strategy in long charging periods. This proves that approximately the same SOC percentage can be achieved at the end of a long charging period suggesting that EV users may be highly inclined to participate in a coordinated charging program.

V. CONCLUSION

In this paper, a decentralized charging strategy has been proposed in which users set their current State-of-Charge (SOC) and/or ToD (Time-of-Departure) using an Internet-of-Things (IoT) platform to communicate with the charge controller. The charge controller then sets the priorities for charging by allocating more charging power to users who urgently require it while also taking into account the voltage magnitude of the household node. Four strategies are proposed in this paper in which priorities either depend on the EV's SOC, ToD, a combination of SOC & ToD, or current loading on the transformer. The SOC & ToD Combined priority control has fully mitigated the impact on voltage magnitude regulation and considerably decreased the loading on the distribution transformer. The difference in SOC between the proposed control strategy and the uncontrolled one is high in the beginning of the charging period but starts to decrease as the charging period approaches its end. This is because the coordinated strategies prioritize the charging power to users in need of charging, while also respecting the grid requirements and limits. The resulting SOC difference at the end of a long charging period is equal to 2.5%. Therefore, users could be inclined to enroll into a coordinated charging routine, if the right incentives are given. As a future work, coordination of the proposed strategy at the medium voltage (MV) level will be tested.

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