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Enhancing phase balance in electric vehicle clusters: a smart charging approach using phase mode switching

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Abstract—European low voltage distribution systems are primarily three-phase four-wire networks, where the three phases have uneven load connections. With the rising number of electric vehicles (EVs) in the market, the charging behaviors of the single-phase EVs are inevitably leading to a more severe phase unbalance issue in the grid. To address such concerns, this paper proposes a smart charging control scheme that utilizes phase mode switching functions of electric vehicle supply equipment (EVSE). The connected three-phase EVs can be switched to single-phase charging mode by charging only at the first phase, hence alleviating the congestion on the other phases of the cluster. A case study using charging data from a real-world situation in a public working place in Athens is conducted, to demonstrate the functionality of the proposed phase mode switching method. The simulation outcomes reveal that the phase mode switching scenario reduces the collective charging time by 8.4% and improves maximum phase power unbalance by 31% compared to the benchmark scenario. The results indicate that the smart charging control manages to effectively mitigate the phase power unbalance issues among three phases and allows the cluster to charge with more flexibility.

Index Terms—electric vehicle, phase unbalance, smart charging, distribution system

I. INTRODUCTION

As the power system undergoes a progressive transformation towards greater sustainability, the adoption of electric vehicles (EVs) is pivotal in this transition, particularly within the distribution system, as EVs charge at low voltage levels. However, with the substantial charging demands associated with a high penetration rate of EVs, the system is anticipated to experience significant load congestion [1].

Among the EVs, there are three-phase EVs capable of charging across three phases and single-phase EVs restricted to charging only on one phase. The integration of single-phase EVs into charging clusters has exacerbated phase unbalance issues, adversely affecting the power grid [2]–[4]. System phase power unbalance, indicating the power difference between two phases, causes problems such as capacity waste, nuisance tripping, motor overheating and damage, as well as increased investment costs [5]. Calearo *et al.* [6] conclude that uncoordinated EV charging can severely increase the phase power unbalance level even with low penetration rate,

further decreasing the effective utilization of charging capacity. For example, only 45% of charging capacity usage rate is achieved with uneven EV charging in [7], due to phase power unbalance.

Therefore, dedicated management control algorithms are necessary to keep the charging power within the cluster capacity while also limit the system phase power unbalance to an acceptable level. Vega-Fuente *et al.* [8] introduce a coordination strategy for single-phase EVs, in which electric vehicle supply equipment (EVSE) connects those EVs to the less loaded phase of the cluster at the beginning of the charging process to mitigate the unbalance issues, likewise, similar methods have been proposed in [9] and [10] that enable EVSE to actively select the charging phase for EVs. Simolin *et al.* [11] present two solutions for power unbalance alleviation via EV charging, phase reconfiguration and phase-specific control, the former one also allows single-phase EVs to charge on the preferred phase, while the second strategy assumes that the three-phase EVs are capable of varying the charging level on each phase separately. However, the above-mentioned methods require levels of controllability which are not achieved by common EVSE and EVs technology as well as communication standards.

On the other hand, three-phase EVs can charge in single-phase mode by only utilizing the first phase in the EVSE connection. This capability offers the potential for dedicated smart charging control aiming at minimizing the phase power unbalance within the cluster, without requiring cutting-edge technology or advanced components for the EVSE. To the best of our knowledge, the proposed approach of phase mode switching has not yet been explored in the literature.

This paper proposes a smart charging control for EV charging cluster considering phase mode switching functionality that enables three-phase EVs to shift between three-phase mode and single-phase mode. The algorithm manages to achieve power sharing among the EVs while also mitigate the cluster power unbalance issues. This paper is organized as follows: the physical layout of the cluster as well as smart charging methodology are explained in Section II. The case study results and charging behaviors analysis are showcased

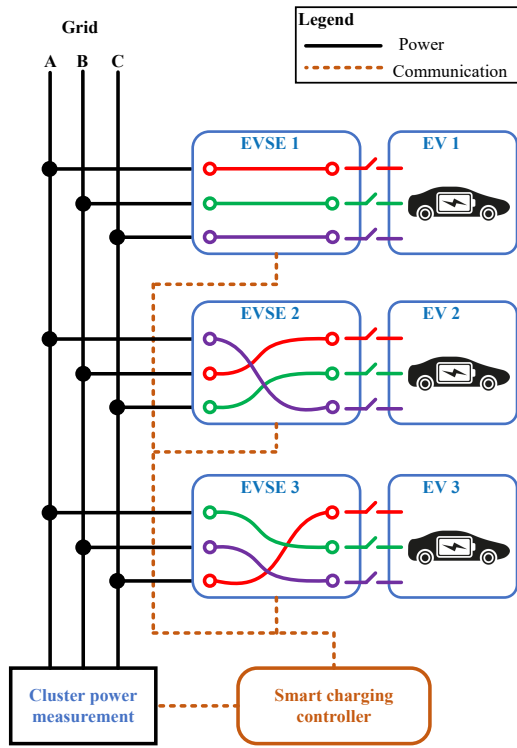


Fig. 1. EV charging cluster layout - the connection phase is wired in a rotational way to avoid charging congestion on one phase

in Section III, and Section IV concludes the paper.

II. METHODOLOGY

A. Cluster layout and phase wiring

The charging cluster layout is presented in Fig. 1, where the cluster connects directly to the external grid and enables three EVs to charge simultaneously via individual EVSE. Each EVSE charges the connected EV based on the received demand signal from the smart charging controller through the communication channel. On the other hand, the controller also receives information from each EVSE regarding the connection status and the charging type of its EV, the charging type of the EV indicates if it is a three-phase EV or a single-phase EV. Moreover, the cluster local measurement meter also sends the detected phase charging power of the whole cluster to the controller for smart charging management.

It is worth highlighting that the wire connection of each phase inside the EVSE employs rotation techniques, resulting in rotated connection phases from the EVSE to the EVs when interfacing with the grid. Since single-phase EVs only charge at the first phase (primary phase), EVSE without phase rotation could cause significant congestion on phase A in the cluster when a large number of single-phase EVs request to charge. In addition, it results in a low capacity usage rate as the other two phases are not utilized. Therefore, phase rotation in EVSE makes sure that the primary phase of each connected EV can be evenly distributed across the whole cluster, hence reducing

the risk of overloading one phase. For example, a single-phase EV connecting to EVSE2 in Fig. 1 will lead to the charging power on phase B in the cluster instead of phase A.

B. Smart charging control mechanism

The smart charging controller collects the information of the cluster charging power from the local power measurement as well as the information of each EV from every EVSE, and sends the demand signal to the EVSE to manage the charging session. The adopted strategy is shown in Fig. 2. The four blocks are activated consecutively during each decision-making process.

The first block determines whether a three-phase EV needs to charge in single-phase mode. Since a three-phase EV can also be charged in single-phase mode, active phase mode switching gives the controller more flexibility for conducting load management when there is potential charging conflicts among the EVs. To better clarify the switching logic, an example is provided in Fig. 3, using phase i EVSE as an example, which connects to phase i as the primary phase. P^{i+1} , P^i and P^{i-1} respectively represent the cluster charging power at phase $i+1$, i and $i-1$, while $P_{diffmax}$ denotes the maximum allowed phase power unbalance. If the cluster charging power of phase i is less than that of either the counterpart outside the allowable range, the corresponding connected three-phase EV will be switched to single-phase mode to increase the charging power of phase i , hence reducing the gap among the phases in the cluster. The same strategy applies to the EVSE with other phases as the primary phase.

However, whenever there is a change in the connection profile, indicating disconnection or new connection of EVs, the charging mode will be reset to the original status to avoid the misbehavior of the controller caused by the connection variation. Moreover, the switching action only happens if there is no idle primary phase in the cluster. For instance, if EVSE3 has no EV connected, even if EVSE2 can switch its three-phase EV to single-phase mode, such action will not occur. This is because having two single-phase EVs charging in the cluster creates more severe phase unbalance issues than having one single-phase EV and one three-phase EV in the cluster. It is crucial to emphasize that the decisive factor is an idle primary phase, not an idle EVSE. The appearance of idle EVSE in this study is due to the use of a simplified three-EVSE cluster. In larger clusters with more than three EVSE, idle EVSE does not prevent phase mode switching.

After the charging mode of each EV is settled, the second block calculates the number of participants of each phase in the cluster. A three-phase EV counts as one participant to each phase, while a single-phase EV serves only as a participant to its primary phase. The calculation is carried out based on equation (1),

$$N^i = \sum_j \sigma_j^i \cdot \delta_j, \quad \forall i \in (A, B, C) \quad (1)$$

where i represents the specific phase (A, B, C) in the cluster, hence N^i depicts the number of participants of phase i , j

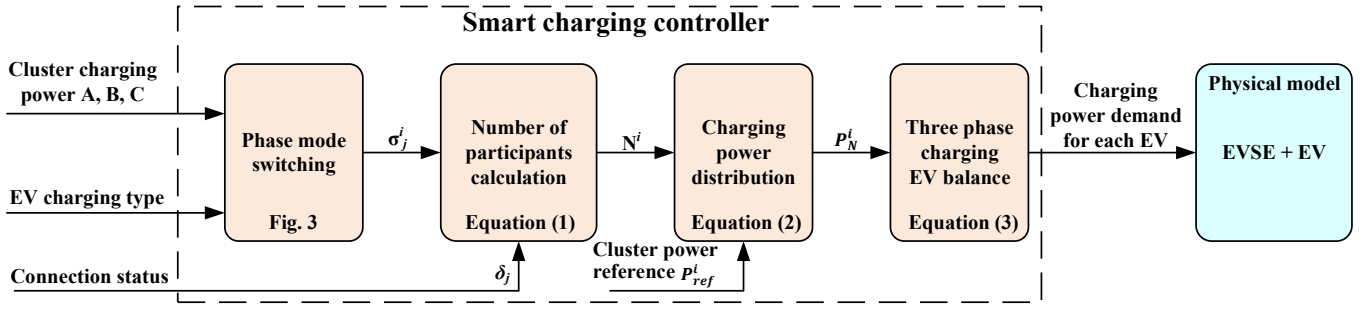


Fig. 2. Smart charging control logic - four blocks take place consecutively for power sharing in each phase

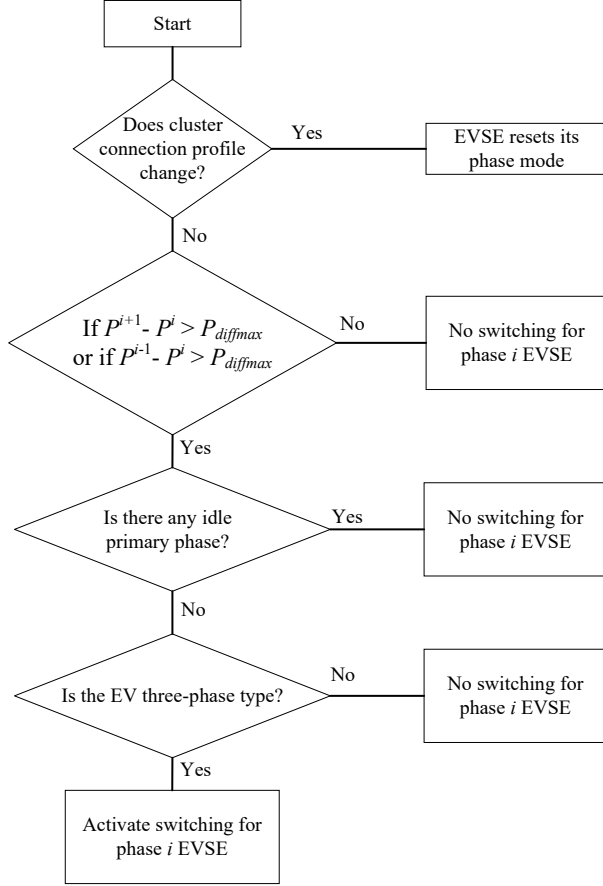


Fig. 3. Phase mode switching logic - this diagram gives an example of the switching logic for EVSE with phase i as primary phase.

indicates the j th EVSE. Binary variables σ_j^i and δ_j specify the charging mode information and connection status respectively. If the j th EVSE is charging its EV in single-phase mode but without phase i as the primary phase, then σ_j^i is 0, otherwise it is 1. Connection status δ_j turns to 1 if the j th EVSE has an EV connected.

The charging power distribution block implements power sharing techniques on each phase, according to equation (2), where P_N^i is the shared power for each participant on phase i , and P_{ref}^i represents the power reference of phase i which

sets the maximum charging level of the cluster.

$$P_N^i = \frac{P_{ref}^i}{N^i} \quad (2)$$

The last block balances out the charging power for EVs charging in three-phase mode, as the shared power on each phase might vary according to the different number of the participants, shown in equation (3).

$$P_j^s = \min(P_N^A, P_N^B, P_N^C) \quad (3)$$

where P_j^s is the charging power on each phase provided for the j th EVSE, P_N^A , P_N^B , and P_N^C are the shared power for each participant on phase A, B and C. It is of vital importance to mention that this block only applies to the EVs that charge in three-phase mode.

C. Case study

A case study is conducted in MATLAB/Simulink environment to investigate the functionality of the switching techniques. The simulation takes real-world charging data on 8th January 2024 for a whole day, recorded in public work places of Athens, Greece, consisting of the time of connection and the charged energy. The connection profile and charging information of each EV is presented in Table I.

TABLE I
EVs CONNECTION PROFILE AND CHARGING INFORMATION

EV no.	Charging type	Connection time	Charged energy (kWh)	EV maximum power (kW)
EV1	three-phase	07:53:34	20.1	7.34 per phase
EV2	single-phase	07:37:43	13.5	7.34
EV3	single-phase	08:31:27	25.5	7.34

In the simulation, the charged energy serves as the target, the EVs will be disconnected when reaching this specified energy goal. The utilized maximum charging power of EVs is collected in lab testing presented in [12]. The cluster transformer fuse limit of 22 kW is set as the power reference, which only allows one three-phase EV in Table I to charge to its maximum, this level is settled by the supply contract of the experimental system setup in the lab at Technical University of Denmark, Risø campus [13]. The allowed maximum phase

power unbalance level is set to 12 A, which translates to 2.76 kW in the system. This threshold is established at 75% of the maximum unbalanced level for connection to the low-voltage distribution system in Denmark (16 A) [14], [15]. To better demonstrate the results, a benchmark scenario that operates the smart charging algorithm without phase mode switching function is also conducted for comparison.

Maximum phase power difference is utilized to quantify the cluster phase power unbalance, the calculation is indicated in equation (4), where P_{diff} is the maximum phase power difference that represents the power difference between the highest phase power and the lowest phase power, P_{phA} , P_{phB} and P_{phC} are the cluster power on each phase.

$$P_{diff} = \max(P_{phA}, P_{phB}, P_{phC}) - \min(P_{phA}, P_{phB}, P_{phC}) \quad (4)$$

III. RESULTS ANALYSIS

Fig. 4 demonstrates the cluster charging power as well as the phase mode of EV1. As the only three-phase EV, EV1 is the second one to connect to the cluster after EV2, hence a charging conflict is created as both EVs are the participant of phase B. Therefore, each EV gets 50% of the phase power capacity of 3.67 kW. Meanwhile, since EV1 is a three-phase EV, its charging power on the rest two phases is limited to 3.67 kW due to power balance. Thus, charging power at phase A and C keeps at 3.67 kW while charging power at phase B reaches 7.34 kW.

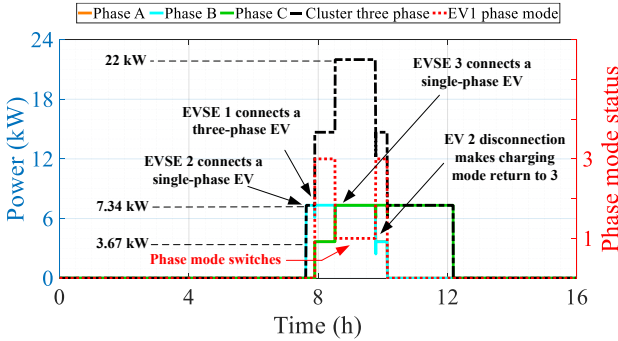


Fig. 4. Cluster charging power and the phase mode of EV1 - mode switches from three-phase to single-phase to reduce phase power unbalance

The phase mode switching takes place when the third EV, EV3 connects to the cluster. EV3 connects to EVSE3, which has phase C as primary phase, hence it also brings charging conflict to phase C, and results in a power sharing as well. However, the phase power difference would be 3.67 kW without intervene (7.34 kW on phase B & C, 3.67 kW on phase A), which breaches the aforementioned allowed maximum power difference of 2.76 kW. Therefore, the smart charging controller switches the charging mode of EV1 from three-phase to single-phase to decrease the number of the participants on phase B & C. As a result, each participant is granted with the maximum phase power capacity of 7.34

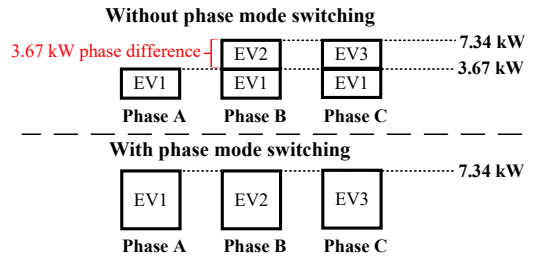


Fig. 5. Controller logic of cluster phase power between scenarios with and without phase mode switching

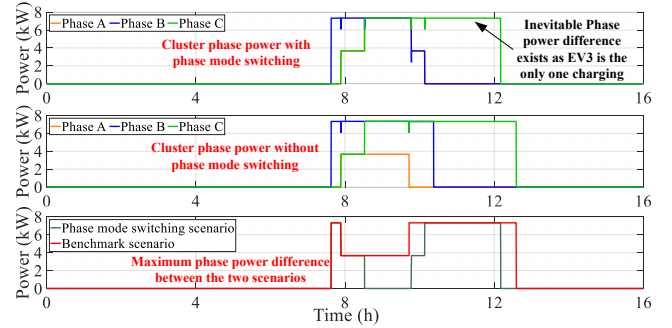


Fig. 6. Simulated results of cluster phase power between scenarios with and without phase mode switching as well as the maximum phase power difference comparison

kW because every individual phase only serves one participant after the switching action. It can be observed that the power of three phases stabilizes at 7.34 kW once the phase mode of EV1 change from three-phase to single-phase, and the overall cluster power reaches the fuse limit of 22 kW. Fig. 5 compares the the controller logic between the phase switching and benchmark scenario.

Fig. 6 presents the simulated results of cluster phase power for the two scenarios and also the maximum phase power difference comparison according to equation (4). In the benchmark scenario, the charging power of EV1 is limited to 3.67 kW per phase after EV3 connects, leading to phase A lower than the other two phases. However, for the phase mode switching scenario, EVSE1 manages to eliminate the unbalance issue by activating the phase mode switching for its three-phase EV.

It is worth mentioning that the switching action only takes effect when there is no idle primary phase, as described in Fig. 3. Therefore, phase mode switching is not triggered before EV3 connects, otherwise the switching would make phase A & B fully occupied and phase C idle, which leads to a more severe phase unbalance issue. This also explains the charging mode of EV1 returning to three-phase after EV2 disconnects.

Fig. 7 shows the charged energy of each EVSE and compares the results between the two scenarios. As the EVSE disconnects its EV when the energy target is met, the eventual charged energy levels are the same between the two scenarios. However, both EVSE2 and EVSE3 achieve an earlier completion of charging in the phase mode switching scenario. EVSE1

finishes the charging session at a later stage due to a reduction of charging power, caused by the switch of phase mode from three-phase to single-phase.

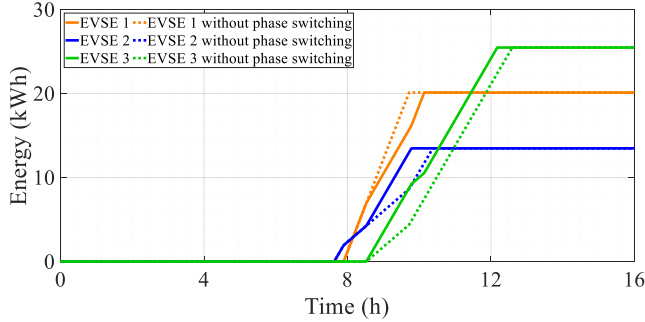


Fig. 7. Charged energy of each EVSE between scenarios with and without phase mode switching

The findings are also supported by Table II, it can be observed that even though the charging time is extended for the three-phase EV, the rest EVSE are capable of charging their single-phase EVs in a much shorter time period as the cluster gets more flexibility for charging. Since the whole cluster manages to complete the charging with more available capacity, the phase mode switching scenario outperforms the benchmark scenario by reducing the collective charging time by 8.4%.

TABLE II
EVSE CHARGING TIME STATISTICS IN DIFFERENT SCENARIOS

	Switching scenario	Benchmark scenario
EVSE1	135 minutes	110 minutes
EVSE2	129 minutes	165 minutes
EVSE3	219 minutes	244 minutes
Whole cluster	273 minutes	298 minutes

When comparing the maximum phase power difference, the phase mode switching scenario also outperforms the benchmark scenario by 31%, as indicated by the average value. This improvement arises not only from the mitigation of phase power unbalance during the phase mode switching activation, but also from the resultant early completion of charging session. The enhancement in maximum phase power unbalance and overall charging duration underscores the efficacy of the phase mode switching function in addressing the three-phase unbalance issue within the charging cluster.

IV. CONCLUSION

In this study, we have addressed the significant issue of phase power unbalance in EV charging clusters caused by the participation of single-phase EVs. The proposed smart charging control scheme effectively utilizes the phase mode switching functionalities of the EVSE to dynamically manage the distribution of charging loads. By enabling three-phase EVs to switch to single-phase mode and draw power exclusively from the primary phase, the algorithm mitigates the congestion and reduces the power disparity among phases

within the charging cluster. Moreover, the power sharing logic makes sure that the collective charging power is within the cluster capability on each phase. Our case study, based on real-world charging profiles from a public workplace in Athens, demonstrates the effectiveness of the smart charging control. Simulated results reveal that the maximum phase power unbalance is decreased by 31% on average compared with the benchmark scenario, and the collective charging time is also shortened by 8.4%. The findings highlight the potential of phase mode switching as a viable solution for achieving balanced load distribution in EV-dense environments.

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