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Increasing charging energy at highly congested commercial charging sites through charging control with load balancing functionality

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HIGHLIGHTS

- Load balancing at highly congested charging sites is studied.
- A novel phase-specific control is developed to mitigate load unbalance.
- The developed control method outperforms the previously proposed solution.
- The control method increases the charging operator's profits up to 6%
- The control method achieves higher benefits in case of higher congestion.

ABSTRACT

It is expected that a notable share of charging sites will face significant congestions in the future, and thus, an effective utilization of the available charging capacity will be highly needed. It has been shown that unbalanced electric vehicle (EV) charging loads may reduce the charging energy, which can lead to a reduced quality of charging service and charging site operator's profits. To overcome the issue, this paper considers two solutions that allows the charging site to control the phase load balance: phase reconfiguration and a novel phase-specific control. Extensive simulations are carried out to investigate the benefits of the solutions. The results clearly indicate that the control methods have a notable potential in increasing the charging energy and quality of the charging service in highly congested charging sites. According to the simulation results, the phase-specific control leads to up to 5.9% higher revenue whereas the phase reconfiguration increases the revenues by up to 4.1% when compared with the baseline scenario without any load balancing functionality. The results also show that the more congested the charging site is, the higher benefits of the phase-specific control can be seen. Furthermore, the results show that assuming perfectly balanced three-phase loading yields unrealistically high charging energy in the congested charging sites, and thus, it is discouraged to use this assumption in future studies.

1. Introduction

Due to their various benefits, the number of electric vehicles (EVs) on the road is increasing rapidly. As the EVs are becoming more popular, more pressure is put on the charging solutions. According to a cost-effectivity analysis [1], the costs of electricity grid reinforcements often outweighs the benefits of improved charging circumstances in case the charging site is connected into an old electricity network. Furthermore, charging sites are assumed to be subject to notable demand charges in the future [2] which further discourages investments into a potentially unnecessarily high charging capacity. This leads to a situation in which charging sites will likely have to deal with a very limited charging capacity [3], and thus effective utilization of the available charging capacity is of great importance.

It is commonly assumed that charging loads are perfectly balanced on the three phases, for example as in [4–7], and unbalanced three-phase networks are rarely considered [8]. However, in reality, there are single-phase EVs, and the charging load of three-phase EVs can be unbalanced as well [9]. Therefore, the charging loads are expected to be unevenly balanced between the three phases, and thus, the available charging capacity may not be fully utilized if this issue is not taken into account. For example, in [10] only up to 88 % capacity usage rate was temporally achieved due to unevenly balanced EV charging loads. This means that phase load balancing could notably improve the capacity usage and thus increase the quality of charging service and the profits of the charging site. Therefore, it can be in the interests of charging site operators to find a way to balance the charging loads efficiently.

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1.1. Related research

In the scientific literature, there are studies that consider unbalance together with EV charging. In [11], it is shown that the phase voltage unbalance is expected to increase at residential areas due to more EVs and photovoltaic (PV) systems are being connected to the grid. The study also shows that the phase voltage unbalance could be reduced by a smart charging scheme that aims to maximize the PV self-consumption and minimize the peak consumption at household level. In [12], load balancing using off-board EV chargers and balancing inverters for PV systems is studied. In the study it is shown that PV and EV hosting capacity of the distribution network can be improved using the off-board EV chargers and the balancing inverters. However, the use of off-board EV chargers (including fast-charging stations) could increase the investment costs of the charging site infrastructure notably, as typical commercial EV supply equipment (EVSE) in Europe relies on on-board chargers of the EVs (according to *mode 3* charging, IEC 61851 standard). Additionally, the use of PV systems may not always be feasible, or the power may not always be available at the needed time. In [13], load balancing through charging control of single-phase EVs with vehicle to grid properties is studied. The results indicate that the proposed control method is able to significantly reduce load unbalance while bringing cost saving for the EV users. Since the study assumes relatively long plug-in durations compared to the energy requirements, the charging sessions include notable flexibility for the vehicle to grid control. This kind of situation is typical for home charging. However, according to [14], around 77 % of the charging sessions have idle time of less than 5 min in a commercial charging site within the premises of a shopping mall. This means that there may be a very limited amount of flexibility for vehicle to grid control in these kinds of locations. In [15–18], a phase-reconfiguration method to mitigate load unbalance is studied. The studies consider only single-phase charging loads from the distribution system perspective. The method is shown to reduce voltage unbalance [15–18] neutral current [15,17,18], and energy losses [18] and increase EV hosting capacity [16].

According to the authors' knowledge, there are no studies that focus on load balancing to increase charging energy within a charging site. The phase-reconfiguration method [15–18] could also be used to increase charging energy through load balancing in case of limited charging capacity, and thus, it is considered also in this study as one of the potential load balancing solutions. However, since the charging energy aspect was not included in the studies, their results are not comparable to this study. More research related to the voltage unbalances can be found, e.g., in [12,15–18].

1.2. Contributions and structure

To fill the gap in the scientific literature, this paper assesses the load unbalance mitigation to increase charging energy within a commercial charging site. To enable load balancing through EVSEs, two different solutions are considered: phase reconfiguration and a novel phase-specific control. The phase-specific control exploits the advanced power electronics inside of the EV to control charging loads. Consequently, it has two notable advantages over the phase reconfiguration: it does not require any additional hardware and it is able to adjust the charging currents of three-phase EVs more flexibly.

To examine the potential benefits of the solutions, extensive simulations are carried out using a validated simulation model and real charging data of commercial charging sites. The main contribution of this paper is to find answers for the three following research questions:

1. How much the charging energy of a commercial charging site can be improved with a load balancing functionality? This question is addressed by developing a novel phase-specific control (Section 3.4.3) and analysing the simulation results obtained by using it (Section 4.1). For comparison, the phase-reconfiguration method, proposed in the literature, is also considered. The simulations are repeated with different amount of congestion to determine the correlation between the load balancing benefits and the congestion (Section 4.2 and 4.3).

2. What are the applications and future aspects of the load balancing solutions? This question is discussed based on the simulation results and the assumption of the simulations (Section 5).

3. What is the influence of assuming a perfectly balanced three-phase network on the charging energy of a charging site? To address this question, simulations are carried out with the said assumption and the results are analysed (Section 4.1).

The remainder of the paper is organized as follows. In Section 2, the two considered load balancing solutions are presented. Section 3 describes the setup for the simulations. The simulation results are presented in Section 4 and discussed in Section 5. The paper is finalized in Section 6 with conclusions and answers for the research questions.

2. Options for load balancing functionality

In this paper, two solutions to enable more controllability for the charging system are considered: phase reconfiguration and phase-specific control. As mentioned in the related research [15–18], loads could be switched from one phase to another by using a phase-reconfiguration module. One simple way to implement this kind of phase reconfiguration would be a parallel use of power relays that are connecting the phases of the grid in different orders to the EVSE output. This enables the control system to decide which phase a single-phase EV will be connected to.

The digital communication defined in charging standard IEC 61851 does allow an EVSE to set separate current limits for each phase in *mode 3* charging. This digital communication could be used to take advantage of the complex power electronics that already exists in the EVs. From the EVSE point-of-view, this would enable load balancing functionality without any additional hardware requirements. Therefore, for the control system to be able to control phase current limits separately, it is only required that the charge controller in the EVSE and the connected EV supports the functionality. However, it is currently uncertain how widely this functionality is supported by the EVs. Additionally, it is worth keeping in mind that there exist non-ideal charging characteristics (realized charging currents sometimes deviate from the current limit set by the EVSE) in the existing charging control solutions already [9]. An EV may choose to charge with a lower current than the current limit indicated by the EVSE, e.g., to protect the battery or due to the internal limitations of the EV. Therefore, it is not realistic to assume that the current drawn by each EV could be perfectly controlled in the future regardless of whether a load balancing functionality is used or not. For more information about the non-idealities, see [9].

To achieve more balanced loading, the control system could prioritize charging sessions differently. For example, prioritizing three-phase charging sessions over single-phase sessions could potentially reduce unbalance. However, this would be unfair from the EV users' perspective, it might not lead to optimal capacity usage rate in a long term, and it could prevent the efficient usage of other prioritization principles. Therefore, further consideration of this kind of solution is excluded from the paper.

3. Investigation

In this paper, the focus is on load balancing potential in highly congested commercial charging sites. Other potential applications for the developed control method are discussed in Section 5.2. In the following subsections, the data used in the simulations, studied cases, examined scenarios, used control methods and simulation model are described separately.

3.1. Used data

This paper uses real charging session data from REDI and Tripla, which ensures realistic setups for the study while avoiding the typical pitfalls caused by utilizing synthetic charging loads [19]. Both REDI and Tripla are shopping centers located in Helsinki, Finland, and they have around 300 and 200 EVSEs, respectively. The EVSEs support 22 kW charging powers (3 × 32 A, 230 V), and the charging is uncontrolled. There are 48,264 and 39,160 charging sessions for REDI and Tripla, respectively, which are recorded between 10/2019 – 2/2022. However, due to the influence of COVID-19 on the EVs' usage behavior and the increasing number of EVs in use, a subset of the data is selected to be used in the simulations of this paper. The subset includes all charging sessions recorded during the last five months (10/2021–2/2022). The data include plug-in time, connection time, active charging time, charged energy, average charging power, and peak power for each charging session.

To improve the data quality, the data is preprocessed. In the preprocess, charging sessions are deleted if connection time is below 5 min, active charging time is below 1 min, charged energy is below 0.1 kWh or above 100 kWh, average charging power is above 25 kW, peak power is below 0.5 kW or above 25 kW, or active charging time is longer than connection time. If the average charging power is greater than the peak charging power, the peak charging power value is replaced by the average charging power value. Additionally, all charging sessions with over five-hour connection time are excluded as they are assumed to be either work or home related charging, which both are possible in the considered locations. After preprocessing, there are 10,508 and 10,702 charging sessions for REDI and Tripla, respectively.

3.2. Studied cases

In addition to the case REDI and case Tripla, a third case is created by combining all charging sessions of both locations. This case (RT) represents a hypothetical larger charging site, and it can be used to give insights on how the load balancing potential correlates with the size of the charging site.

To investigate highly congested areas, we assume that the number of EVSEs is lower than the highest number of simultaneously plugged in EVs seen in the data. This also means that there will not be available EVSEs for every EV. Four different magnitudes of plug-in congestion are investigated: there is enough EVSEs for 99, 95, 90, or 80 % of the time. The persistence curves for REDI, Tripla, and RT are presented in Fig. 1 and the key numbers of the persistence curve are shown separately in Table 1. As an example of Table 1, 10 % of the time there is $\geq$ 13, $\geq$11, and $\geq$ 23 EVs plugged in at REDI, Tripla, and RT, respectively.

In each case, the available total charging capacity is assumed to be (3 × 6 A) × N_{EVSE}, where the N_{EVSE} denotes the number of EVSEs. The

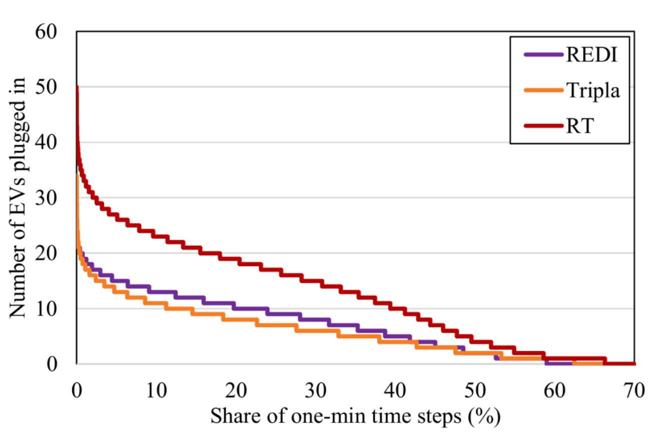

Fig. 1. Persistence curve for the number EVs that are plugged in.

Table 1
Number of EVs plugged in.

Persistence	REDI	Tripla	RT
Peak	26	34	50
1 %	19	18	33
5 %	15	13	27
10 %	13	11	23
20 %	10	8	19

capacity of 3 × 6 A per EVSE is the minimum non-zero three-phase capacity that can be allocated to an EV in *mode 3* charging (IEC 61851). This selection is made so that the available capacity would be as low as possible, but high enough so that there is never a need to temporally disable the charging sessions to prevent overloading. The details of the examined cases are presented in Table 2 in terms of the charging infrastructure and in Table 3 in terms of EVs. In Table 3, the subscript of N denotes the phase usage and the maximum charging current drawn.

This paper considers cases where the phases of the three-phase EVSEs are connected to the grid in different order to promote phase load balance. This is a common practise in real-life implementations. The three different ways to connect EVSEs are illustrated in Fig. 2. The connection order alternates so that EVSE 1, EVSE 4, EVSE 7… are similar, EVSE 2, EVSE 5, EVSE 8… are similar and so on. It is also assumed that single-phase EVs always draw charging current from the phase that is in the left side of the EVSE in Fig. 2. This means that if the EVSE connection method is "ABC", "BCA" or "CAB", a single-phase EV would draw the current from phase A, B, or C from the grid perspective, respectively. The simulation also assumes that the arriving EVs choose randomly the EVSE from the available EVSEs.

3.3. Examined scenarios

This paper examines four different scenarios. The first scenario (1) does not utilize any phase load balancing. This scenario is used as a reference point to determine the benefits of the load balancing functionalities. The second scenario (2) utilizes phase-reconfiguration modules on each EVSE, and thus, the control system can decide which phase a single-phase EV will be connected to. In the third scenario (3), the developed phase-specific charging control is in use. The third scenario is further divided into four subscenarios in which different shares of three-phase EVs (25, 50, 75, or 100 %) support the phase-specific control. In case an EV does not support the phase-specific control, the EV considers only a single current limit and adjust the current drawn in each phase according to it. The fourth scenario (4) assumes perfectly balanced loading. This scenario represents a theoretical upper limit for the load balancing potential and can be used as a reference point to determine how well the phase load balancing functionalities are executed. Additionally, the scenario can be used to assess how the assumption of perfectly balanced three-phase network influences the charging energy of the charging site. The subscenarios are presented in

Table 2
The charging infrastructure of the examined cases.

Case	Subcase	N_{EVSE}	Capacity
REDI	"99"	19	3 × 114 A
	"95"	15	3 × 90 A
	"90"	13	3 × 78 A
	"80"	10	3 × 60 A
Tripla	"99"	18	3 × 108 A
	"95"	13	3 × 78 A
	"90"	11	3 × 66 A
	"80"	8	3 × 48 A
RT	"99"	33	3 × 198 A
	"95"	27	3 × 162 A
	"90"	23	3 × 138 A
	"80"	19	3 × 114 A

Table 3
The number of EVs of the examined cases.

Case	$N_{1\times16\ A}$	$N_{1\times32\ A}$	$N_{3\times16\ A}$	$N_{3\times32\ A}$
REDI	5885	2100	2067	456
Tripla	7193	1314	2193	2
RT	13,078	3414	4260	458

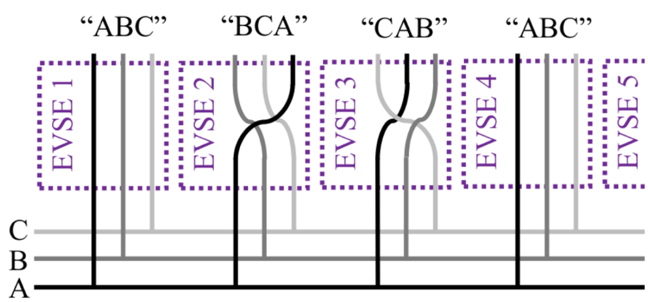

Fig. 2. Connections of the EVSEs.

Table 4
The examined scenarios.

Scenario	Description
1	No phase load balancing
2	Utilizing phase-reconfiguration modules
3–25	Phase-specific control supported by 25 % of the three-phase EVs
3–50	Phase-specific control supported by 50 % of the three-phase EVs
3–75	Phase-specific control supported by 75 % of the three-phase EVs
3–100	Phase-specific control supported by 100 % of the three-phase EVs
4	Perfectly balanced loading

Table 4.

3.4. Control algorithm

Within this paper, the charging control algorithm structure is divided into three components for the sake of clarity: *Capacity determination*, *Capacity allocation*, and *Capacity usage rate correction*.

The *Capacity determination* determines the available total charging capacity of all EVs. The available total charging capacity limits are fixed based on the fuse size but case-dependent and can be found in Table 2. The *Capacity allocation* component decides how the capacity will be allocated between the EVs while respecting the maximum allowed capacity limit. This paper considers the fair sharing principle presented in [20] as the *Capacity allocation* principle. This benchmark principle divides the available charging capacity evenly between the EVs that request energy at each time step. The fair sharing principle is illustrated in Eq. (1), where I_L is the allocated current limit for each EV at time step t, I_t is the available total capacity of each phase in amperes, and n_a is the number EVs actively requesting energy.

$$I_L(t) = \frac{I_t}{n_a(t)} \tag{1}$$

Due to the non-ideal charging characteristics, the realized charging currents may deviate from the current limit set by the EVSE. This means that each EV may not draw the current I_L from each phase intended by the fair sharing principle and charging capacity could be wasted if this is not taken into account. To ensure that control algorithm is able to effectively allocate capacity despite the non-idealities, *Capacity usage rate correction* is needed. In the scientific literature, four different solutions for *Capacity usage rate correction* are presented: Battery tail capacity reclamation [21], EV belief function [22], regression model-based approach [23], and charging characteristics expectation (CCE) feature [24]. However, the battery tail capacity reclamation considers only single-phase charging whereas the EV belief function considers only three-phase charging. Therefore, they are not applicable in this situation that includes both single-phase and three-phase EVs. To train the regression model, a large dataset of each EV (including variables such as state-of-charge (SoC)) is required. Yet, commercial EVs do not widely support data transfer (such as SoC) to the charging station in case of *mode 3* charging. Therefore, it may be difficult to obtain data of the SoC over the charging session, and thus, the use of this solution is problematic. Since the CCE feature does not require any preliminary knowledge about the EVs and is suitable for single-phase and three-phase charging, it is considered in this paper.

The CCE feature enables the control algorithm to track each EV's charging characteristics and is shown to perform well [24]. It uses measurements to track the realized charging currents and memorizes the correlation between the current limits and the realized charging currents using a separate matrix for each EV. This enables the control algorithm to estimate what kind of charging currents EVs will draw with certain current limits. Additionally, the CCE feature tracks which phases are used by the EVs. For more detailed description of the CCE feature, see [24].

3.4.1. Baseline control algorithm

In the baseline scenario (1) without phase load balancing, the three algorithm components are combined in the charging control algorithm using an iterative approach similarly as in [24]. A block diagram of the control algorithm is presented in Fig. 3. The algorithm operates in real-time. Every time step, the algorithm starts by reading the charging current measurements, and these measurements are then used to update the CCE matrix so that the algorithm is able to track the charging characteristics of each EV. Then, the charging status of each EV is examined in order to form a list of EVs actively requesting energy. The charging status is read from the *mode 3* (IEC 61851) compliant charge controllers located in the EVSEs.

After forming the list of active EVs, the algorithm starts an iterative loop. In the loop, the algorithm considers increasing the capacity allocation of a single EV with 1 A at a time. The algorithm considers 1 A increments because this is the minimal available increment in the commercially available EVSEs considered in e.g. [24]. The algorithm uses the CCE feature to estimate whether the capacity allocation increment would cause peak load violation. If the increment is not estimated to cause a violation and the current limit is not already at maximum, the increment is accepted. Each EVSE is assumed to support current limits up to 32 A. However, it is worth emphasizing that due to the non-ideal charging characteristics, EVs may not be able to draw such high charging currents. To implement fair sharing principle, the algorithm moves to the next EV after every increment. In case the increment is expected to cause a peak load violation, the increment is rejected, and the EV is removed from the list. The iterative loop is run as long as there are EVs in the list. Only after the iterative loop is finished, the considered current limits are applied by sending them to the corresponding EVSEs. The run time of a single iterative loop is a faction of a second [10], and thus, the solution does not require an unnecessarily high computational capacity.

3.4.2. Phase reconfiguration

In case of phase reconfiguration, the control algorithm operates similarly as the baseline algorithm. However, after an EV arrives, the control algorithm detects whether the EV draws charging current from a single-phase or from the three-phases. If the newly arrived EV is single-phased, the phase-reconfiguration function assigns it to the phase that is currently least congested (if the EV is not already assigned to it). This solution is essentially the simplest greedy partition algorithm called list scheduling. More complex multiway number partitioning algorithms could also be used to achieve more balanced loading throughout the considered time periods. However, the list scheduling is suitable for online algorithms and minimizes power relay wear as only up to one

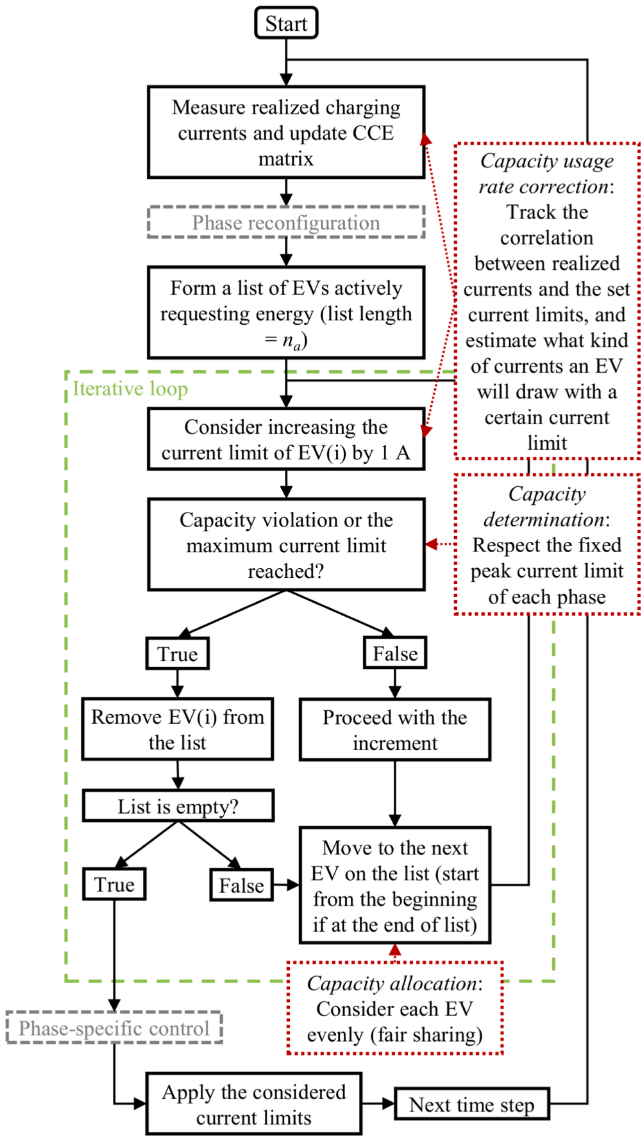

Fig. 3. Block diagram of the control algorithm for the baseline scenario where the load balancing functions (shown in grey dotted line) are not being used.

phase-reconfiguration action is done for each charging session. Therefore, it is considered in this study. A block diagram of the additional functionality of the phase reconfiguration is illustrated in Fig. 4.

3.4.3. Phase-specific control

In case of phase-specific control, the algorithm exploits the phase specific current limits made possible by the digital communication defined in the standard IEC 61851. The phase-specific control is an extension of the baseline algorithm presented in Fig. 3 and does not utilize the phase-reconfiguration functionality. The additional phase-specific control functionality (shown in grey dotted line in Fig. 3) is executed at the end of the baseline algorithm.

The additional functionality of the phase-specific control is illustrated in Fig. 5. The algorithm of the phase-specific control consists of two loops. The outer loop ensures that each of the three phases are considered whereas the inner iterative loop ensures that the capacity of the phase under consideration is used effectively. The inner iterative loop (shown in purple dotted line in Fig. 5) is very similar to the iterative loop in the baseline algorithm (shown in green dotted line in Fig. 3), except that it considers only the three-phase EVs that support phase-specific control and it considers each phase separately.

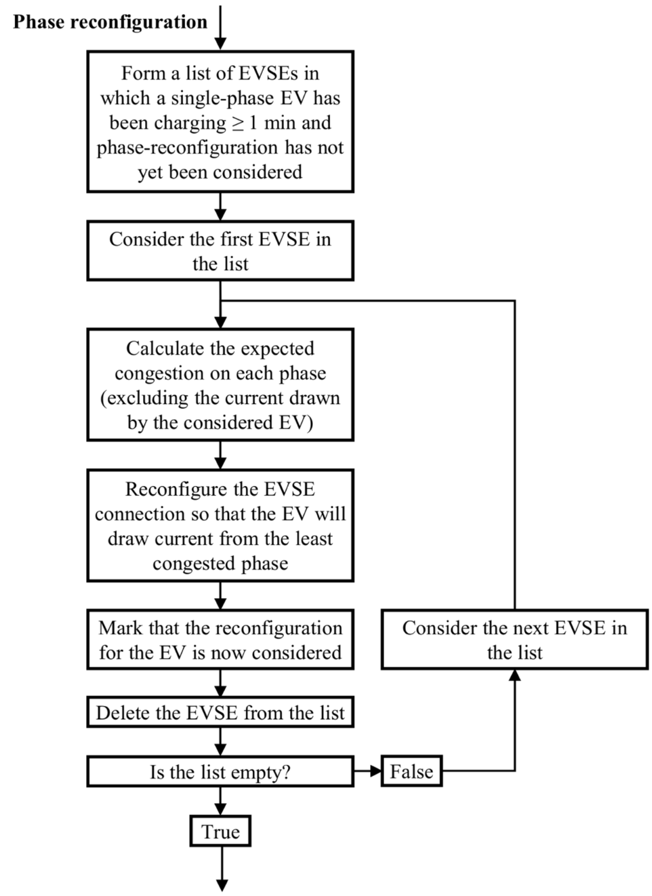

Fig. 4. Block diagram of the additional functionality of the phase reconfiguration.

This novel solution can be used to control the charging currents of each phase separately. In this paper, the functionality is used to maximize the charging capacity usage rate of each phase while respecting their capacity limits. Without the functionality, the available charging capacity for three-phase EVs would be limited according to the phase that is the most congested. This could lead to a situation where the charging capacity of the other phases are not effectively used. Consequently, the revenue and the quality of charging service of the charging site would be reduced.

3.5. Simulation model

The simulation model considers each phase current separately to model phase load balance. Since the standard IEC 61581 sets limitations to the charging currents (e.g., minimum current limit set by an EVSE is 6 A), it is considered more practical to model currents instead of powers. To determine the related powers or energies, the simulation model assumes constant 230 V phase voltage. The simulation model uses a temporal resolution of 60 s. This is shown to be reasonable accurate resolution to model EV charging loads in case of peak load management [25].

To model realistic EV charging current behavior, the simulation model utilizes charging profile modelling method presented in [10,14]. In the method, preliminary measurements with an IEC 61851 compliant charging station (Wirelane Doppelstele 2 × 22 kW) are conducted and used to determine how the charging currents correlate with the energy missing from the battery of the EV and the current limit set by the EVSE. These correlations are used to form a two-dimensional lookup table for each EV model. By using these lookup tables, the simulation model can determine charging currents that depend on the EV model, the current

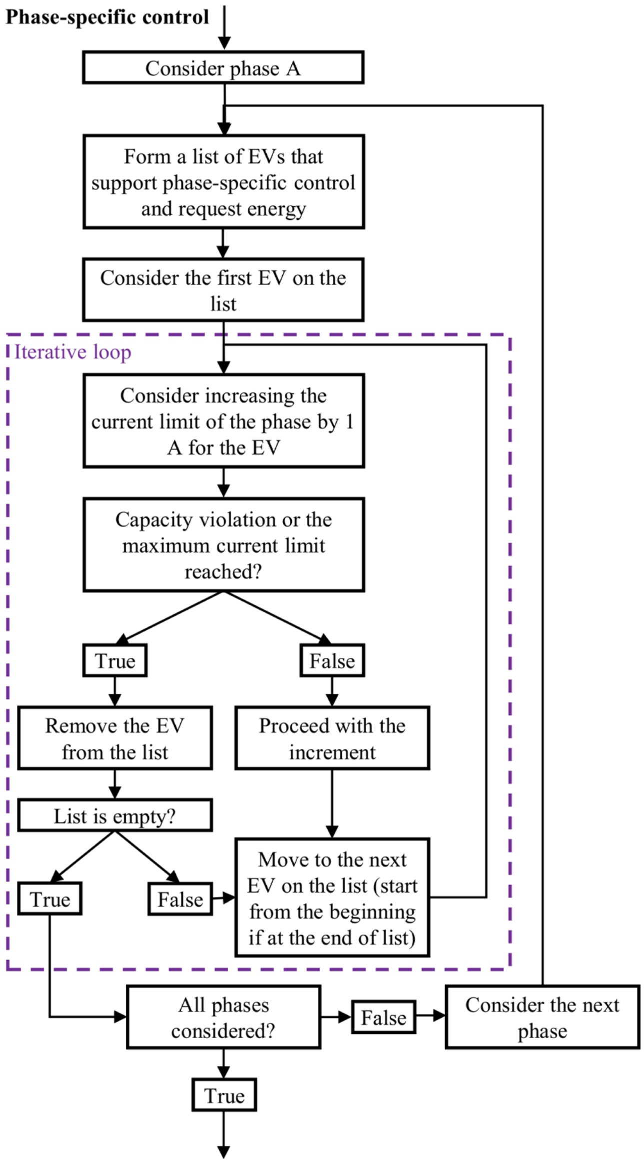

Fig. 5. Block diagram of the additional functionality of the phase-specific control.

limit set by the EVSE, and the energy that is missing from the battery of the EV. This method allows the simulations to incorporate the non-ideal charging characteristics (i.e., situations where the realized charging currents deviate from the current limit set by the EVSE) and different phase usages (i.e., single-phase and three-phase EVs). For further explanation of the charging profile modelling method, see [10,14]. However, conversely to [10,14], this paper includes a new EV model (Renault Zoe) in addition to the four EV models considered in [14]. In this paper, it is assumed that the EVs that support phase-specific control are able to adjust each phase current individually according to the formed two-dimensional lookup tables so that one phase current does not influence on the others. However, since this kind of control was not possible to be tested with the charging station and the EVs during the preliminary measurements, it remains unknown how well different EV models can execute phase-specific control. The influence of this assumption on the results is discussed further in Section 5.1. In case of perfectly balanced three-phase network, the same simulation model is used. However, instead of considering the separate limits of each phase in the control algorithm, the algorithm considers only the total current limit and the sum of phase currents.

The considered EV models and their key parameters are presented in Table 5. It is worth noting that the BMW has three different charging modes: *low mode*, *reduced mode*, and *maximum mode*. In each mode, the charging profile is different, but the key parameters remain the same. The simulation model utilizes the charging session data mentioned in Section 3.1. To couple the charging profile modelling method (i.e., the charging current behavior) with the charging session data (i.e., arrival time, charged energy, etc.), different charging power groups are considered (see Table 5). Depending on the charging peak power seen in the data, certain charging profile is selected for the charging session. For example, if a charging session in the data has charging peak power of 4.0 kW, charging profile of Nissan Leaf 2012 is applied for it. In case the charging power is 10–15 kW, a random BMW i3 2016 mode (*low mode*, *reduced mode*, or *maximum mode*) is chosen. And, if the charging power is 15–25 kW, the model is randomly chosen to be either Smart or Renault.

The simulation model is implemented using Python programming language. The lookup tables of the charging profiles are read from an Excel file.

4. Results

This section presents and analyses the simulation results from three viewpoints: load balancing potential in terms of revenue increments in different scenarios and cases, the influence of EVSE occupancy on the results, and the influence of capacity usage rate on the results. Each viewpoint forms its own subsection. The analysis focuses on the charging operator's percentual revenue increment that is achieved using the load balancing functionalities. A fixed volumetric charging price (€/kWh) is assumed to calculate the percentual revenue increment. Therefore, the percentual revenue increment ($R_{+\%}$) equals to the percentual increment of the charged energy according to Eq. (2). In the equation, E_a is the charged energy in case of Scenario 2–4 (i.e., a load balancing functionality is in use), E_b is the charged energy in case of Scenario 1 (i.e., load balancing functionality is not in use), c_p is the fixed volumetric charging price.

$$R_{+\%} = \frac{E_a - E_b}{E_b} \times 100\% = \frac{(E_a - E_b)\times c_p}{E_b \times c_p} \times 100\% \tag{2}$$

Analysis of phase unbalance metrics is excluded from the paper. This is because there is no incentive for the charging site operator to execute load balancing actions in case of a low capacity usage rate (it would not affect the charging energy) and the proposed algorithm does not try to balance loading in such cases. The numerical results are summarized in Tables 6–8.

4.1. Load balancing potential

The simulation results show that the revenues of the charging sites can be increased with load balancing actions in the examined cases. It is also seen that the load balancing benefits correlate with the congestion. Depending on the case, the phase reconfiguration achieves 0.8–4.1 % revenue increment. In most cases, the phase-specific control achieves higher benefits (0.7–5.9 %) compared with the phase reconfiguration when assuming that all three-phase EVs support the phase-specific control. The benefits of the phase-specific control seem to be highly

Table 5
The parameters of the considered EV models.

Model	Max charging current	Max charging power	Charging power group
Nissan Leaf 2012	1 × 16 A	3.7 kW	0–4.5 kW
Nissan Leaf 2019	1 × 32 A	7.4 kW	4.5–10 kW
BMW i3 2016	3 × 16 A	11.0 kW	10–15 kW
Smart EQ ForFour 2020	3 × 32 A	22.1 kW	15–25 kW
Renault Zoe 2020	3 × 32 A	22.1 kW	15–25 kW

Table 6
The results of each scenario for REDI.

Subcase	Scenario	N_{total}	$N_{total,p}$	$N_{total,n}$	$N_{max,p}$	$E_{un,total}$ (kWh)	$E_{un,total,p}$ (kWh)	$E_{un,total,n}$ (kWh)	E_{total} (kWh)	$R_{+\%}$ (%)
"99"	Baseline	10,508	10,376	132	19	8422.1	7406.9	1015.2	80282.2	0.0
	Phase reconfiguration	10,508	10,376	132	19	6853.3	5838.2	1015.2	81851.0	2.0
	Phase-specific control (25 %)	10,508	10,376	132	19	7897.8	6882.6	1015.2	80806.5	0.7
	Phase-specific control (50 %)	10,508	10,376	132	19	7470.3	6455.2	1015.2	81234.0	1.2
	Phase-specific control (75 %)	10,508	10,376	132	19	7082.8	6067.6	1015.2	81621.5	1.7
	Phase-specific control (100 %)	10,508	10,376	132	19	6790.8	5775.6	1015.2	81913.6	2.0
	Balanced three-phase system	10,508	10,376	132	19	6048.3	5033.1	1015.2	82656.0	3.0
"95"	Baseline	10,508	9824	684	15	16589.8	11277.3	5312.6	72114.5	0.0
	Phase reconfiguration	10,508	9824	684	15	14341.2	9028.6	5312.6	74363.2	3.1
	Phase-specific control (25 %)	10,508	9824	684	15	15703.8	10391.3	5312.6	73000.5	1.2
	Phase-specific control (50 %)	10,508	9824	684	15	14990.5	9677.9	5312.6	73713.8	2.2
	Phase-specific control (75 %)	10,508	9824	684	15	14441.4	9128.9	5312.6	74262.9	3.0
	Phase-specific control (100 %)	10,508	9824	684	15	13969.0	8656.5	5312.6	74735.3	3.6
	Balanced three-phase system	10,508	9824	684	15	12812.8	7500.3	5312.6	75891.5	5.2
"90"	Baseline	10,508	9251	1257	13	22920.5	13158.3	9762.1	65783.8	0.0
	Phase reconfiguration	10,508	9251	1257	13	20475.3	10713.2	9762.1	68229.0	3.7
	Phase-specific control (25 %)	10,508	9251	1257	13	21927.6	12165.5	9762.1	66776.7	1.5
	Phase-specific control (50 %)	10,508	9251	1257	13	21041.3	11279.2	9762.1	67663.0	2.9
	Phase-specific control (75 %)	10,508	9251	1257	13	20383.1	10621.0	9762.1	68321.2	3.9
	Phase-specific control (100 %)	10,508	9251	1257	13	19844.5	10082.4	9762.1	68859.8	4.7
	Balanced three-phase system	10,508	9251	1257	13	18485.2	8723.1	9762.1	70219.1	6.7
"80"	Baseline	10,508	7976	2532	10	35042.2	14238.9	20803.3	53662.1	0.0
	Phase reconfiguration	10,508	7976	2532	10	32862.7	12059.3	20803.3	55841.7	4.1
	Phase-specific control (25 %)	10,508	7976	2532	10	34011.1	13207.8	20803.3	54693.2	1.9
	Phase-specific control (50 %)	10,508	7976	2532	10	33145.1	12341.8	20803.3	55559.2	3.5
	Phase-specific control (75 %)	10,508	7976	2532	10	32474.2	11670.9	20803.3	56230.1	4.8
	Phase-specific control (100 %)	10,508	7976	2532	10	31880.5	11077.2	20803.3	56823.8	5.9
	Balanced three-phase system	10,508	7976	2532	10	30314.2	9510.9	20803.3	58390.1	8.8

N_{total} is the total number of EVs in the case.
$N_{max,p}$ is the maximum number of EVs simultaneously plugged in.
Subscript p denotes EVs that were plugged in whereas subscript n denotes EVs that could not find available EVSE.
$E_{un,total}$ is the total amount of energy that was left uncharged.
E_{total} is the total amount of energy that was charged.
$R_{+\%}$ is the percentual revenue increment when compared with the baseline scenario.

Table 7
The results of each scenario for Tripla.

Subcase	Scenario	N_{total}	$N_{total,p}$	$N_{total,n}$	$N_{max,p}$	$E_{un,total}$ (kWh)	$E_{un,total,p}$ (kWh)	$E_{un,total,n}$ (kWh)	E_{total} (kWh)	$R_{+\%}$ (%)
"99"	Baseline	10,702	10,524	178	18	4355.8	3209.3	1146.5	60186.6	0.0
	Phase reconfiguration	10,702	10,524	178	18	3847.7	2701.2	1146.5	60694.6	0.8
	Phase-specific control (25 %)	10,702	10,524	178	18	4230.1	3083.6	1146.5	60312.3	0.2
	Phase-specific control (50 %)	10,702	10,524	178	18	4105.6	2959.0	1146.5	60436.8	0.4
	Phase-specific control (75 %)	10,702	10,524	178	18	4009.3	2862.7	1146.5	60533.1	0.6
	Phase-specific control (100 %)	10,702	10,524	178	18	3909.7	2763.2	1146.5	60632.7	0.7
	Balanced three-phase system	10,702	10,524	178	18	3619.8	2473.2	1146.5	60922.6	1.2
"95"	Baseline	10,702	9873	829	13	10377.0	5132.8	5244.1	54165.4	0.0
	Phase reconfiguration	10,702	9873	829	13	9158.3	3914.2	5244.1	55384.0	2.2
	Phase-specific control (25 %)	10,702	9873	829	13	10052.7	4808.5	5244.1	54489.7	0.6
	Phase-specific control (50 %)	10,702	9873	829	13	9680.7	4436.5	5244.1	54861.7	1.3
	Phase-specific control (75 %)	10,702	9873	829	13	9396.6	4152.5	5244.1	55145.8	1.8
	Phase-specific control (100 %)	10,702	9873	829	13	9142.6	3898.4	5244.1	55399.8	2.3
	Balanced three-phase system	10,702	9873	829	13	8366.7	3122.6	5244.1	56175.6	3.7
"90"	Baseline	10,702	9303	1399	11	14653.6	5925.3	8728.3	49888.8	0.0
	Phase reconfiguration	10,702	9303	1399	11	13297.3	4568.9	8728.3	51245.1	2.7
	Phase-specific control (25 %)	10,702	9303	1399	11	14201.0	5472.7	8728.3	50341.4	0.9
	Phase-specific control (50 %)	10,702	9303	1399	11	13817.8	5089.5	8728.3	50724.5	1.7
	Phase-specific control (75 %)	10,702	9303	1399	11	13476.7	4748.4	8728.3	51065.7	2.4
	Phase-specific control (100 %)	10,702	9303	1399	11	13162.6	4434.2	8728.3	51379.8	3.0
	Balanced three-phase system	10,702	9303	1399	11	12302.4	3574.1	8728.3	52239.9	4.7
"80"	Baseline	10,702	7870	2832	8	24752.5	7056.3	17696.2	39789.9	0.0
	Phase reconfiguration	10,702	7870	2832	8	23383.6	5687.4	17696.2	41158.8	3.4
	Phase-specific control (25 %)	10,702	7870	2832	8	24215.7	6519.5	17696.2	40326.6	1.3
	Phase-specific control (50 %)	10,702	7870	2832	8	23740.5	6044.3	17696.2	40801.8	2.5
	Phase-specific control (75 %)	10,702	7870	2832	8	23372.4	5676.2	17696.2	41170.0	3.5
	Phase-specific control (100 %)	10,702	7870	2832	8	22933.6	5237.4	17696.2	41608.8	4.6
	Balanced three-phase system	10,702	7870	2832	8	21820.4	4124.2	17696.2	42722.0	7.4

dependent on the share of EVs that supports the control method. The average revenue increments for each case and scenario are presented in Fig. 6.

The results also demonstrate that balanced three-phase system is able to charge 1.2–8.8 % higher amount of energy compared with the baseline scenario. However, this assumption is not realistic and the

Table 8
The results of each scenario for RT.

Subcase	Scenario	N_{total}	$N_{total,p}$	$N_{total,n}$	$N_{max,p}$	$E_{un,total}$ (kWh)	$E_{un,total,p}$ (kWh)	$E_{un,total,n}$ (kWh)	E_{total} (kWh)	$R_{+\%}$ (%)
"99"	Baseline	21,210	20,938	272	33	10064.4	8351.6	1712.8	143182.3	0.0
	Phase reconfiguration	21,210	20,938	272	33	8598.0	6885.2	1712.8	144648.7	1.0
	Phase-specific control (25 %)	21,210	20,938	272	33	9685.9	7973.1	1712.8	143560.8	0.3
	Phase-specific control (50 %)	21,210	20,938	272	33	9302.3	7589.5	1712.8	143944.4	0.5
	Phase-specific control (75 %)	21,210	20,938	272	33	9072.5	7359.8	1712.8	144174.2	0.7
	Phase-specific control (100 %)	21,210	20,938	272	33	8836.2	7123.4	1712.8	144410.5	0.9
	Balanced three-phase system	21,210	20,938	272	33	8187.0	6474.2	1712.8	145059.7	1.3
"95"	Baseline	21,210	20,200	1010	27	19013.0	12326.3	6686.6	134233.7	0.0
	Phase reconfiguration	21,210	20,200	1010	27	16533.6	9846.9	6686.6	136713.1	1.8
	Phase-specific control (25 %)	21,210	20,200	1010	27	18252.8	11566.1	6686.6	134993.9	0.6
	Phase-specific control (50 %)	21,210	20,200	1010	27	17642.5	10955.8	6686.6	135604.2	1.0
	Phase-specific control (75 %)	21,210	20,200	1010	27	17149.4	10462.8	6686.6	136097.3	1.4
	Phase-specific control (100 %)	21,210	20,200	1010	27	16701.1	10014.5	6686.6	136545.6	1.7
	Balanced three-phase system	21,210	20,200	1010	27	15652.8	8966.2	6686.6	137593.9	2.5
"90"	Baseline	21,210	19,111	2099	23	29584.8	15151.2	14433.6	123661.9	0.0
	Phase reconfiguration	21,210	19,111	2099	23	26520.7	12087.1	14433.6	126726.0	2.5
	Phase-specific control (25 %)	21,210	19,111	2099	23	28545.1	14111.5	14433.6	124701.6	0.8
	Phase-specific control (50 %)	21,210	19,111	2099	23	27725.7	13292.1	14433.6	125521.0	1.5
	Phase-specific control (75 %)	21,210	19,111	2099	23	27039.5	12605.9	14433.6	126207.2	2.1
	Phase-specific control (100 %)	21,210	19,111	2099	23	26475.1	12041.5	14433.6	126771.6	2.5
	Balanced three-phase system	21,210	19,111	2099	23	25065.7	10632.1	14433.6	128181.0	3.7
"80"	Baseline	21,210	17,354	3856	19	44241.5	17005.7	27235.8	109005.2	0.0
	Phase reconfiguration	21,210	17,354	3856	19	40953.0	13717.1	27235.8	112293.7	3.0
	Phase-specific control (25 %)	21,210	17,354	3856	19	43093.9	15858.1	27235.8	110152.8	1.1
	Phase-specific control (50 %)	21,210	17,354	3856	19	42193.6	14957.8	27235.8	111053.1	1.9
	Phase-specific control (75 %)	21,210	17,354	3856	19	41375.1	14139.3	27235.8	111871.6	2.6
	Phase-specific control (100 %)	21,210	17,354	3856	19	40709.4	13473.6	27235.8	112537.2	3.2
	Balanced three-phase system	21,210	17,354	3856	19	39055.9	11820.1	27235.8	114190.8	4.8

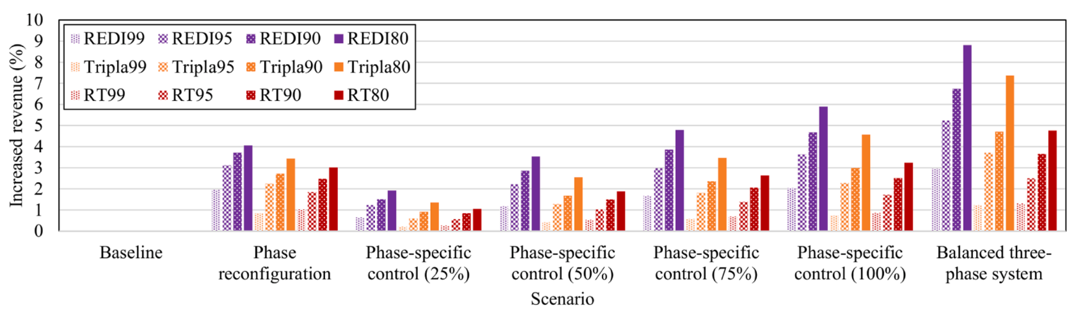

Fig. 6. Average revenue increment for each case and scenario.

considered load balancing functionalities are unable to achieve the same charging energy. This means that in case of highly congested charging systems, the assumption of balanced three-phase system is likely to lead to modelling inaccuracies where the charging energy is optimistically high.

When analysing the individual days of the simulated period, it is seen that up to 13.7 % revenue increments was achieved with the proposed phase-specific control. Conversely, there are several days where the load balancing does not provide any value for the charging site especially in case of a lower congestion. This result is assumed to be due to the daily variance of the usage of the charging infrastructure. The daily revenue increments achieved using the phase-specific control are presented in Fig. 7.

For RT, the percentual load balancing potential is lower compared to REDI and Tripla in most cases. This result is in line with [14] where it is shown that the average relative load unbalance tends to decrease as the size of the charging site increases. On one hand, the lower relative load balancing potential in larger charging sites decreases the economic benefits. On the other hand, since the charging energy of a larger charging site is higher, a lower relative increment leads to a more notable absolute increment. For example, assuming charging pricing of 0.15 €/kWh, the average revenue increment of the phase-specific control is up to 474 €, 272 €, and 530 € over the five-month period in REDI, Tripla, and RT, respectively. This equals a monthly revenue increment of 95 €, 55 €, and 106 €, respectively. Therefore, the load balancing is seen profitable in case of highly congested charging sites with around 10–30 EVSEs.

When comparing REDI with Tripla, the load balancing potential is assumed to be lower in Tripla due to two reasons. Firstly, the share of three-phase EVs is lower in Tripla than in REDI (see Table 3). This means that there are fewer EVs that can execute the proposed phase-specific control, and thus, there is reduced load balancing potential. Secondly, as seen in persistence curve in Fig. 1, the EVSE occupancy in Tripla is slightly more peak oriented than in REDI. This means that the EVSE occupancy is lower on average in Tripla than in REDI. More detailed analysis of the EVSE occupancy and its influence are given in the next subsection.

4.2. EVSE occupancy

When analyzing the EVSE occupancy (i.e., the share of time in which EVSEs are occupied) the results show a trend: the phase-specific control increases the revenue more when the EVSE occupancy is higher. The daily revenue increments and the corresponding EVSE occupancy rates are presented in Fig. 8. It is also seen that the phase-specific control does not seem to bring value if the EVSE occupancy rate is around 20 % or

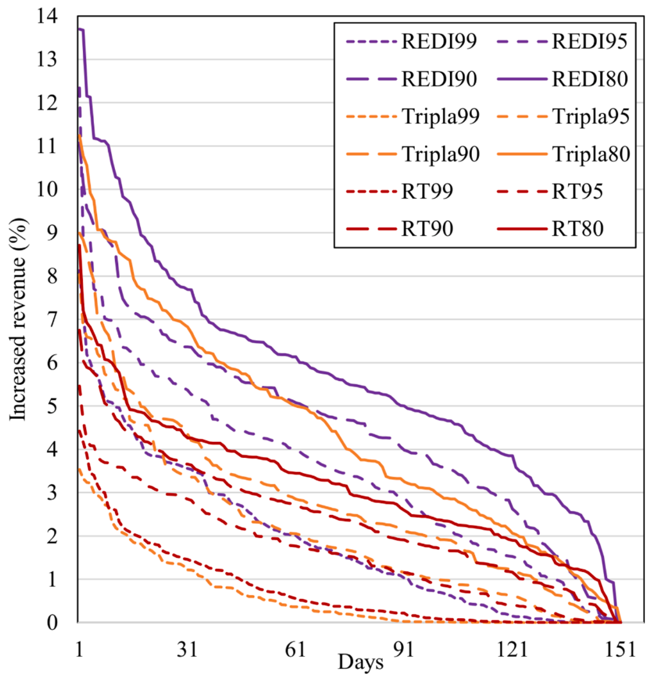

Fig. 7. Persistence curve of the daily revenue increments for each case and scenario.

lower. This can be seen more clearly in Fig. 9, where the average revenue increments with the corresponding EVSE occupancy rates over the whole simulation period are shown. In Figs. 8 and 9, it is assumed that all three-phase EVs supports the phase-specific control.

It is worth noting that the considered cases assumed a total charging capacity of (3 × 6 A) × N_{EVSE}, and this assumption plays an important role. To analyse the correlation with the capacity usage rate, a similar analysis is carried out in the next subsection from capacity usage rate point of view.

4.3. Capacity usage rate

The capacity usage rate describes the share of the used capacity compared with the available total charging capacity. In this analysis, the capacity usage rate of the baseline scenario is evaluated, and the corresponding revenue increment achieved by the phase-specific control is calculated. These values can then be used to assess the point at which the phase-specific control will become beneficial. In Fig. 10, the daily revenue increments with the corresponding capacity usage rates are presented. The figure shows the tendency that the higher the capacity usage rate is, the more beneficial the phase-specific control will be. The general trend can be seen more clearly in Fig. 11, where the average revenues over the whole simulation period are shown. According to Fig. 11, phase-specific control becomes profitable when the capacity usage rate is around 20–30 %, and the revenue increments are 3–6 % at around 30–40 % capacity usage rate.

5. Discussion

This section discusses the used methods and the received results from three viewpoints: the used assumptions in the simulations, the potential applications of the proposed phase-specific control, and future viewpoints of the considered load balancing solutions. Each topic is discussed separately in the following subsections.

5.1. Assumptions

This paper assumes that the control system knows whether an EV supports a phase-specific control in the subscenarios of Scenario 3. For a control system to get this information, two practical options are seen. First, the EV could transfer this information through the digital communication defined in IEC 61851. Second, a control algorithm that is responsible for the *Capacity usage rate correction* (such as CCE feature [24] which is considered in this paper) could be improved so that it is able to learn whether an EV supports the said phase-specific control or not. Regardless of which one of the options would be used, it is not expected to have notable influence on the results.

In the paper, it is also assumed that the EVs that support the phase-specific control are able to adjust each phase current independently. This means that an EV could, for example, start charging with full power from phases A and B while not drawing any power from phase C if the control system so decides. Since the EVs ability to execute phase-specific control has not been previously studied, it remains uncertain how many EVs and how well the EVs could support the phase-specific control.

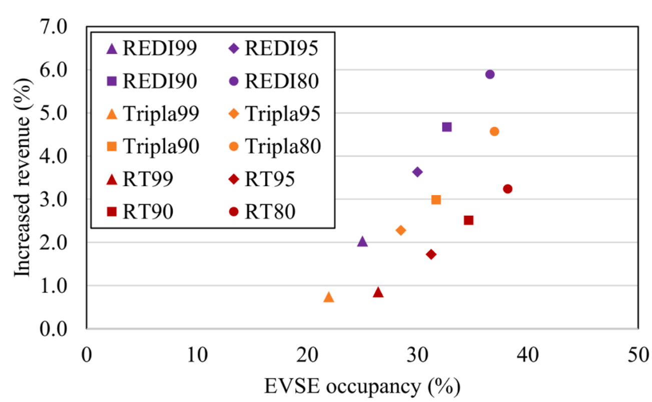

Fig. 9. Average EVSE occupancy and the related revenue increment gained with the phase-specific control.

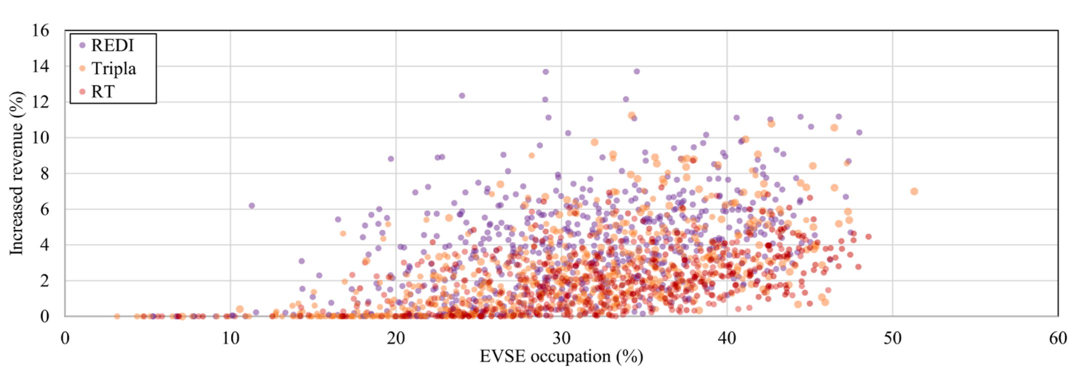

Fig. 8. Daily EVSE occupancy and the related revenue increment gained with the phase-specific control method.

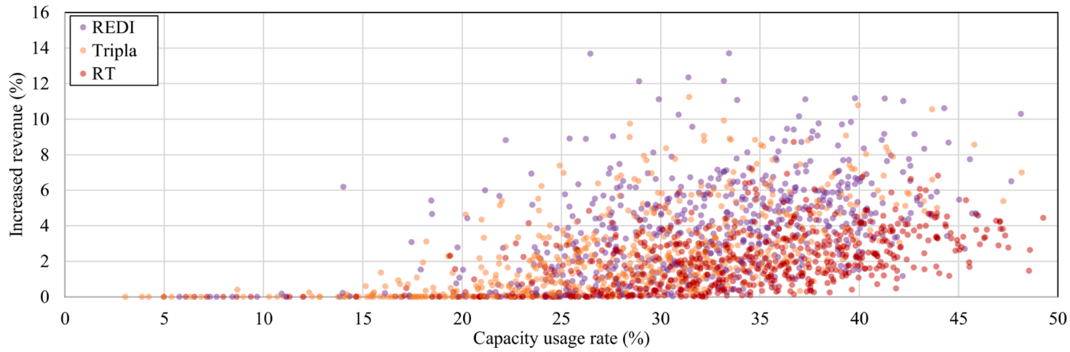

Fig. 10. Daily capacity usage rate and the related revenue increment gained with the phase-specific control.

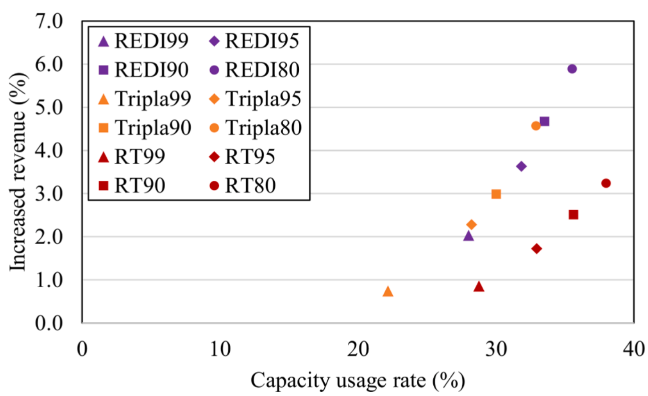

Fig. 11. Average capacity usage rate and the related revenue increment gained with the phase-specific control.

5.2. *Potential applications*

It is worth noting that this paper considers only the direct charging energy related benefits seen by the charging site operator. While these benefits can be meaningful alone, it is not the only possible benefit for the charging site operator. As the charging energy increases, so increases the quality of charging service and attractiveness from a customer perspective. This can increase the charging site usage and thus also the income for the charging site operator in the long run.

This paper investigates commercial charging at shopping centre premises. The load balancing could also be economically beneficial in other cases, such as workplace charging or home charging in apartment building premises if the EV penetration is high enough. It is also worth noting that a charging site can be considered as a highly congested if the same feeder or fuse is used to feed other non-EV loads as well. In this this kind of cases, the load balancing may in fact be even more beneficial since the non-EV loads are also likely to be unbalanced, and thus, available charging capacity may be unevenly distributed for the three-phases. The proposed phase-specific control could also be used by an aggregator to alleviate the unbalance issue related to increasing amount of PV systems in residential areas mentioned in [11,26]. This could be beneficial from the grid operator point of view as the load balancing affects positively on the performance and life expectancy of the electricity grid assets [16].

5.3. *Future viewpoints*

According to [14], the share of three-phase EVs is predicted to increase over the years 2020 – 2040. In case all EVs would charge using three-phase, there would be a limited amount of need for load balancing functionality. However, according to [14], the share of single-phase EVs is assumed to remain significant at least for the next few decades due to relatively slow renewal speed of the car fleet. This could mean that the need for the load balancing slightly decreases in the future. More notably, it is assumed that the load balancing potential of the phase reconfiguration would decrease. Conversely, the increasing number of three-phase EVs would presumably increase the amount of EVs that can support the phase-specific control. Thus, the load balancing potential of the phase-specific control is estimated to increase in the future.

6. Conclusions

This paper analyses the load balancing potential from revenue point of view in commercial charging sites. It is commonly known that EV charging loads can be unevenly distributed on the three phases. In case of a highly congested charging site, the load unbalance can also lead to a suboptimal charging energy which reduces the profits and the quality of the charging service of the charging site. Therefore, it is in the charging site operators' interest to improve load balancing when possible.

To balance loading in a charging site, two separate control methods are considered: phase reconfiguration and a novel phase-specific control. The phase reconfiguration utilizes an additional module that is capable of connecting the charging load of a single-phase EV into the phase that is the least congested. The proposed phase-specific control exploits the on-board charger of an EV to separately adjust the current drawn from each phase. This approach does not require modification to the hardware of the charging infrastructure and thus can be more attractive from the charging site operator perspective. The conducted analysis is made based on the results of extensive simulations. These simulations are carried out using the models, algorithms, and parameters of the relevant state of the art studies.

The contributions of this paper consist of answering the three research questions formed based on the recognized gaps in the scientific literature. The research questions and the findings are as follows:

1. *How much the charging energy of a commercial charging site can be improved with a load balancing functionality?* The results show that the proposed control method (phase-specific control) increases the charging energy of the charging site up to 5.9 % whereas the phase reconfiguration yields up to 4.1 % increment. The benefits of the load balancing control methods seem to be highly dependent on the congestion of the charging site. It is seen that the load balancing becomes economically beneficial when the capacity usage rate exceeds ~ 20 % and notable benefits can be achieved at ~ 30–40 % capacity usage rate.
2. *What are the applications and future aspects of the load balancing solutions?* It is expected that the proposed phase-specific control increases the charging energy of the charging site in all cases where the charging capacity is highly congested. Therefore, it can be useful at other locations such as workplaces or apartment building premises as long as the available charging capacity is relatively low compared to the charging demand. Based on the previous findings in the scientific

literature, these kinds of cases are expected to be common in the future. The results also indicate that the load balancing potential of the phase-specific control increases in the future as the share of three-phase EVs increases. Conversely, the usefulness of the phase reconfiguration is expected to diminish.

3. What is the influence of assuming a perfectly balanced three-phase network on the charging energy of a charging site? The results show that up to 8.8 % higher charging energy is seen when assuming perfectly balanced charging loads. This assumption means that the charging energy of the charging site will be modelled as unrealistically high in case the charging site is highly congested. Therefore, in these kinds of cases, it is discouraged to use the said assumption to ensure accurate modelling results.

This paper considers charging sites with 8–33 EVSEs. The results show that the relative benefits of the proposed phase-specific control are lower in larger charging sites, yet the absolute benefits are higher. However, this finding may not be applicable in case of very large scale charging sites. Therefore, future work should investigate the load unbalances and load balancing needs in larger charging sites more thoroughly. It is also currently uncertain how many EVs and how well the EVs can execute phase-specific control. This should be studied in future works to increase the understanding of what extent different control methods can be used in real-life implementations.

CRediT authorship contribution statement

Toni Simolin: Conceptualization, Software, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing, Validation. **Kalle Rauma:** Conceptualization, Data curation, Investigation, Validation, Resources, Writing – original draft, Writing – review & editing. **Antti Rautiainen:** Writing – review & editing. **Pertti Järventausta:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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