Dynamic power redistribution among electric vehicle charging stations in distribution networks

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Abstract. The rapid growth of electric vehicle charging in urban areas imposes increasing stress on low- and medium-voltage distribution networks, leading to voltage deviations, higher current loading, and harmonic distortion. This paper investigates dynamic power redistribution among multiple EV charging stations as a means of mitigating these effects. A detailed simulation model of a residential-commercial distribution feeder, including EV chargers and power electronic interfaces, was developed in MATLAB/Simulink. Single-phase and three-phase charging scenarios, with and without LCL filters, were analysed. The proposed dynamic control strategy adapts charging currents according to available feeder capacity and real-time network conditions. Simulation results show that dynamic power redistribution improves voltage profiles, reduces peak loading of lines and transformers, and decreases total harmonic distortion compared to conventional fixed-power charging. The paper confirms that coordinated and adaptive charging can significantly increase the hosting capacity of distribution networks for EV without immediate grid reinforcement.

1 Introduction

The electrification of road transport is progressing rapidly and is becoming one of the key pillars of decarbonisation strategies worldwide. As the number of electric vehicles (EV) increases, so does the demand for charging infrastructure, especially in urban distribution networks where residential, commercial, and public charging points are often concentrated. While EV charging enables cleaner mobility, it also introduces new operational challenges for distribution system operators, including increased peak loading, voltage deviations, phase unbalance, and higher levels of harmonic distortion caused by power electronic converters [6].

Most existing distribution networks were not originally designed to accommodate large numbers of high-power and simultaneously operating EV chargers. Conventional charging strategies, which rely on fixed charging power or locally limited current, do not consider the instantaneous state of the network and may therefore lead to inefficient utilisation of available capacity or even to violation of technical limits. As a result, there is a growing interest in coordinated and adaptive charging methods that can improve grid hosting capacity without requiring immediate reinforcement of infrastructure.

To address these challenges, increasing attention has been devoted to coordinated and adaptive charging strategies that can dynamically adjust charging power according to network operating conditions. One promising approach is dynamic power redistribution among charging stations, where the available feeder capacity is continuously allocated among active chargers in order to avoid local overloads while maintaining acceptable voltage profiles and power quality.

This paper investigates the impact of EV charging on both low-voltage (0.4 kV) and medium-voltage (22 kV) distribution networks with particular focus on dynamic power redistribution among multiple charging stations and harmonic mitigation using LCL filters. A comprehensive simulation model of a residential-commercial distribution feeder was developed in the MATLAB/Simulink environment, including residential loads, commercial loads, photovoltaic generation sources, and EV charging stations.

The proposed approach dynamically adjusts charging currents according to the available feeder capacity while ensuring that network operating limits are not exceeded. The performance of the proposed strategy is evaluated using time-domain and frequency-domain analyses, comparing conventional fixed-power charging with adaptive redistribution of charging power.

The main contribution of this paper is a quantitative evaluation of how coordinated EV charging affects phase loading, voltage stability, and harmonic distortion in distribution networks. The results provide practical

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insight into how adaptive charging strategies combined with appropriate converter design can increase EV hosting capacity without immediate reinforcement of existing grid infrastructure.

2 Test system and simulation framework

A MATLAB/Simulink (Simscape Electrical) model was developed to analyse EV charging impacts in two operating contexts: a residential area with aggregated household demand and a supermarket area with a dedicated charging station.

2.1 Distribution network model

The main supply level is 22 kV, representing the distribution grid. A transformer reduces this voltage to the household level 400 V for low-voltage consumers. The model includes two 22 kV / 400 V transformers, reflecting separate supply paths for the residential and supermarket subsystems.

To represent balancing power exchange with the external grid, a Three-Phase Source block (Power Grid) is used as the upstream supply, ensuring energy balance during PV deficits.

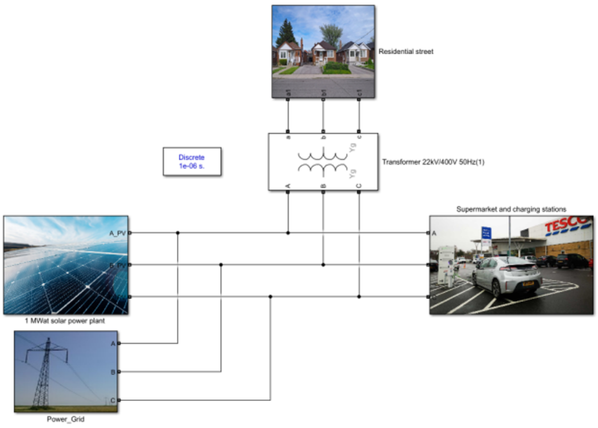

Fig. 1. The overall network structure (sources, transformers, residential area, supermarket + charging station, EV)

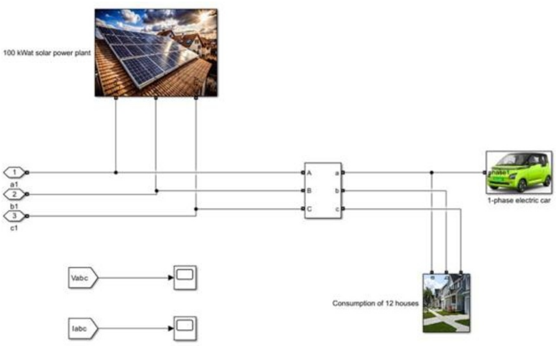

Fig. 2. Residential street subsystem (12 residential houses + single-phase EV charging case)

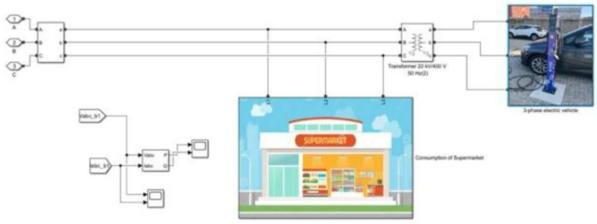

Fig. 3. Supermarket subsystem with a three-phase EV charging station connected through a distribution transformer

2.2 Loads and EV charging

Two typical dynamic demands were modelled:

- Aggregated load of 12 residential houses,
- A large commercial load (supermarket).

EV charging is studied in two modes:

- Single-phase charging in the residential subsystem (LV 400 V context).
- Three-phase charging in the supermarket subsystem (through the transformer station, including impacts on both 22 kV and 0.4 kV levels).

2.3 Photovoltaic generation included in the grid model

The model includes two photovoltaic sources: a 1 MW three-phase PV plant connected to the 22 kV network and a 100 kW rooftop PV plant distributed across residential houses.

2.4 EV Charging station and electric vehicle model structure

The electric vehicle and its charging interface were modelled as a cascaded power conversion system enabling controlled energy transfer between the distribution grid and the battery. The model structure is identical for both single-phase and three-phase charging configurations, differing only in the AC-side converter topology.

Each EV charging station consists of an AC/DC grid-side converter, DC-link capacitor, bidirectional DC/DC converter, battery model, and charging current controller.

A block diagram of the EV charging station structure is shown in Figure 4.

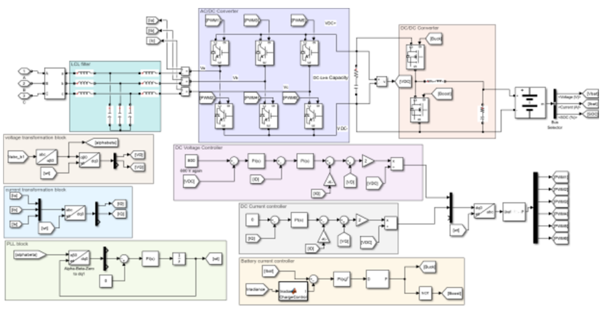

Fig. 4. Structure of three-phase EV charging station with V2G/G2V support

2.5 Converter control and filtering

The inverter control uses standard grid-synchronised control blocks including PLL synchronisation, dq transformations, voltage and current controllers, and PWM generation for a three-phase IGBT inverter.

An LCL filter was designed to mitigate converter harmonics. The PWM switching frequency was 10 kHz and the resonance frequency was selected as 1 kHz (f_sw/10). For the analysed system (S = 630 kVA, U = 22 kV, f = 50 Hz) the resulting parameters were $C \approx$ 69 nF and $L \approx$ 366 mH.

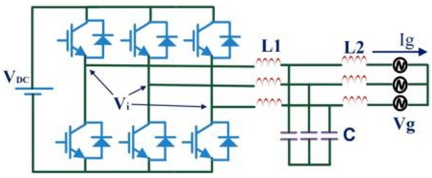

Fig. 5. Three-phase inverter + LCL filter grid connection structure

2.6 Simulation time mapping

To represent a daily cycle efficiently, the model uses:

- time step: 1×10^{-6} s,
- 1 simulated day mapped to 24 seconds (24 h ÷ 24 s), preserving daily profiles while reducing computation time.

2.7 Dynamic power redistribution strategy

To investigate the increasing penetration of electric vehicle charging in distribution networks, a dynamic power redistribution strategy among multiple charging stations was implemented in the simulation model. The objective of this strategy is to ensure that the total charging demand does not exceed the technical limits of the distribution feeder while maintaining acceptable voltage profiles and power quality.

The redistribution mechanism dynamically adjusts the charging current of each EV charging station according to the available feeder capacity.

The feeder current constraint can be expressed as:

$$I_{\text{base}} + \sum_{i=1}^{N} I_{\text{EV},i} \leq I_{\max} \quad (1)$$

The available current capacity for EV charging is therefore

$$I_{\text{available}} = I_{\max} - I_{\text{base}} \quad (2)$$

The redistribution controller allocates charging currents among active stations according to the available capacity. For the case of equal priority charging stations, the allocated current becomes

$$I_{\text{EV},i} = \frac{I_{\text{available}}}{N} \quad (3)$$

If charging stations have different priority levels or requested charging powers

$$I_{\text{EV},i} = \frac{P_i}{\sum_{k=1}^{N} P_k} \cdot I_{\text{available}} \quad (4)$$

This approach allows the system to dynamically adapt charging currents to the instantaneous loading conditions of the distribution feeder while preventing overload of lines and transformers.

In the implemented MATLAB/Simulink model, the redistribution controller continuously monitors feeder current and updates the charging current references of individual EV charging stations.

3 Simulation results

This section presents the main results obtained from time-domain and frequency-domain simulations. The objective was to evaluate the impact of EV charging configuration (single-phase versus three-phase) and the influence of LCL filtering on current loading and harmonic distortion in low-voltage (0.4 kV) and medium-voltage (22 kV) distribution networks.

3.1 Phase current loading (1-ph charging)

When the EV is connected to a single phase of the low-voltage network, a significant increase of current is observed only in the supplying phase, while the remaining two phases remain almost unchanged. This leads to pronounced phase unbalance.

A zoomed fragment of the phase current waveform shows that the amplitude of current in the loaded phase is approximately 16 A higher than in the other two phases.

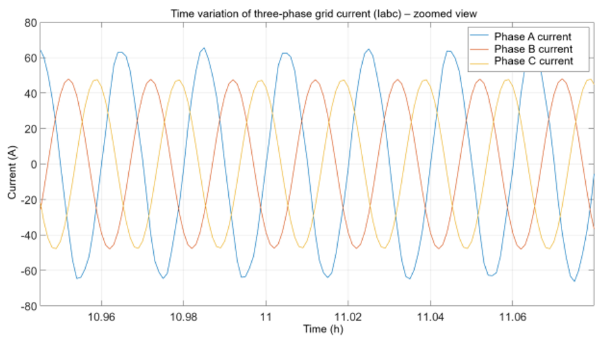

Fig. 6. Phase current during single-phase EV charging (zoomed fragment).

3.2 Phase current loading (3-ph charging)

In the three-phase charging configuration, the EV is connected symmetrically to all three phases of the distribution network. Simulation results show balanced currents with approximately equal amplitudes in each phase. This indicates uniform loading of the transformer and feeder and the absence of phase unbalance. A zoomed fragment of the current waveform demonstrates that the amplitudes of currents in all three phases reach approximately 20 A, confirming symmetrical operation.

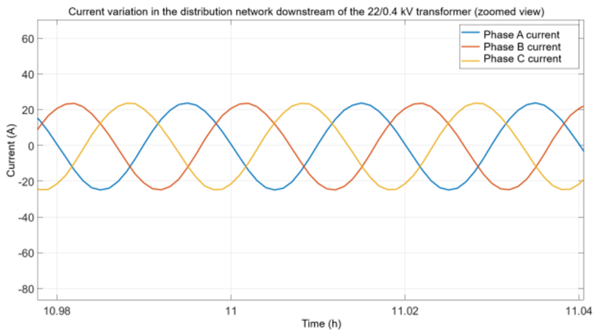

Fig. 7. Phase currents during three-phase EV charging.

3.3 Harmonic distortion during single-phase charging (without LCL filter)

Without LCL filtering, voltage and current waveforms exhibit noticeable distortion caused by PWM switching of the converter. FFT analysis of the phase current shows significant harmonic components. The total harmonic distortion of the phase A current reaches THD = 5.53 %, as shown in Figure 8. The dominant harmonic components appear at integer multiples of the fundamental frequency due to switching effects of the power electronic converter.

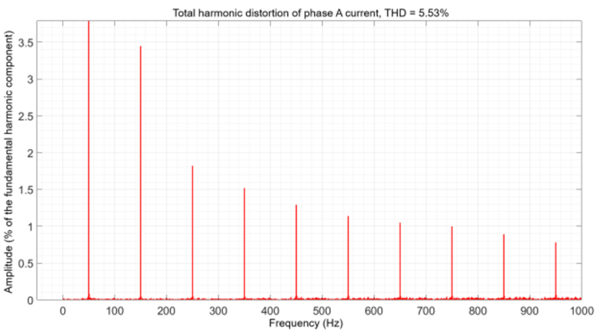

Fig. 8. FFT spectrum of phase current during single-phase EV charging without LCL filter.

3.4 Harmonic distortion during single-phase charging (with LCL filter)

After applying the LCL filter, the harmonic content of the phase current is significantly reduced. The FFT spectrum presented in Fig. X shows that the total harmonic distortion decreases to THD = 3.16 %. This confirms the effectiveness of the LCL filter in suppressing converter-generated harmonics and improving the power quality of the charging system.

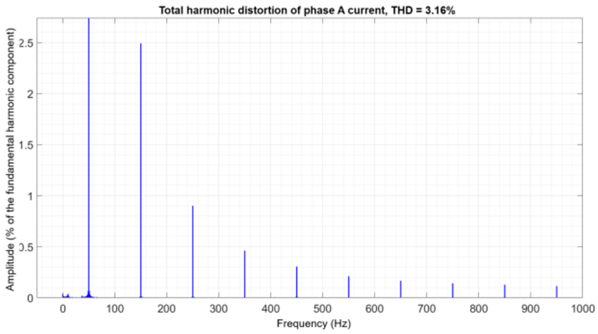

Fig. 9. FFT spectrum of phase current during single-phase EV charging with LCL filter.

3.5 Harmonic distortion in 22 kV network during three-phase charging (without LCL filter)

In the medium-voltage part of the network (22 kV), the impact of EV charging on harmonic distortion was also analysed. Without LCL filtering, the total harmonic distortion of the phase current reaches THD = 5.31 %. After applying the LCL filter, the THD decreases significantly to THD = 0.18%, demonstrating effective suppression of higher-order harmonics in the medium-voltage feeder.

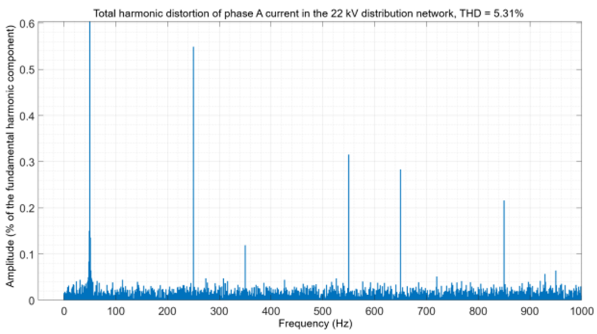

Fig. 10. FFT spectrum of phase current in 22 kV network during three-phase EV charging without LCL filter.

3.6 Harmonic distortion in 22 kV network during three-phase charging (with LCL filter)

When the LCL filter is applied at the converter output, harmonic distortion in the medium-voltage network is significantly reduced. FFT analysis of the phase current shows a clear attenuation of dominant harmonic components compared to the unfiltered case.

3.7 Harmonic distortion in 0.4 kV network during three-phase charging (without LCL filter)

In the low-voltage residential network (0.4 kV), the influence of converter harmonics is more pronounced due to the lower short-circuit power of the feeder.

Without LCL filtering, the total harmonic distortion of the phase current reaches THD = 78.67%. After introducing the LCL filter, the harmonic distortion decreases significantly to THD = 2.51%, which represents a substantial improvement in power quality in the residential distribution system.

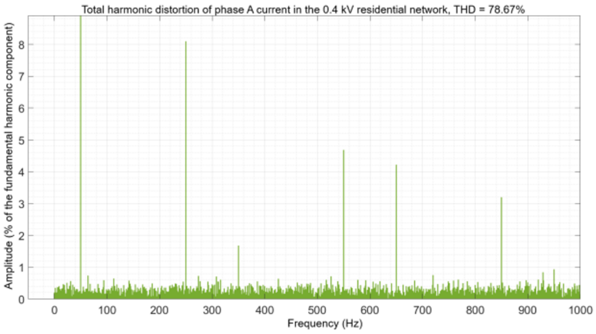

Fig. 12. FFT spectrum of phase current in 0.4 kV network during three-phase EV charging without LCL filter.

3.8 Harmonic distortion in 0.4 kV network during three-phase charging (with LCL filter)

With LCL filtering implemented, harmonic spectra in the low-voltage network become significantly cleaner. FFT analysis of the phase current confirms a substantial reduction of dominant harmonic components.

3.9 Dynamic power redistribution scenario

To illustrate the principle of dynamic power redistribution, an additional scenario with multiple simultaneously operating EV charging stations was considered. In this scenario, the feeder current limit was set to 120 A while the base feeder load was approximately 52 A.

Without coordinated charging control, simultaneous operation of three charging stations would increase the feeder current to approximately 142 A, exceeding the feeder capacity.

With dynamic redistribution applied, the available feeder capacity was allocated among active charging stations. The charging current of each station was automatically limited to approximately 22-24 A, ensuring that the feeder current remained below the allowed limit.

This demonstrates that adaptive charging current allocation can prevent feeder overload while maintaining simultaneous operation of multiple charging stations.

4 Discussion

The simulation results provide important insights into how EV charging affects distribution networks and how these effects can be mitigated by appropriate charging configuration, filtering, and coordinated control. The discussion focuses on interpreting the observed phenomena from the perspective of dynamic power redistribution among EV charging stations and current best practices reported in the literature.

4.1 Impact of charging configuration on network loading

Single-phase EV charging leads to a clear concentration of current in one phase of the low-voltage feeder, resulting in phase unbalance and increased thermal stress of conductors and transformer windings. Such behaviour is well known as a limiting factor for EV hosting capacity in residential networks, where voltage drop and unbalanced loading often become critical before thermal limits are reached [1].

In contrast, three-phase charging distributes the charging power symmetrically among all phases. The balanced current waveforms observed in the simulations confirm that three-phase charging provides a significantly more grid-friendly solution. From the viewpoint of dynamic power redistribution, this result implies that whenever infrastructure allows, three-phase charging should be preferred, as it simplifies the redistribution task and increases the usable feeder capacity.

4.2 Harmonic distortion and the role of local filtering

The FFT analyses show that without LCL filtering, EV chargers inject noticeable harmonic components into the grid. These harmonics are present not only at the point of connection but also propagate through the distribution transformer to the 22 kV network. This confirms that EV charging can influence power quality beyond the local low-voltage level.

With the implementation of LCL filters, a substantial reduction of dominant harmonic components is achieved in both low-voltage and medium-voltage networks [2].

For dynamic power redistribution, this finding is important. If redistribution strategies dynamically modify charging currents among multiple stations, the chargers must remain power-quality neutral across a wide operating range. Local filtering therefore represents an enabling technology that allows redistribution to be applied without causing unacceptable harmonic distortion.

4.3 Multi-station dynamic power redistribution scenario

Dynamic power redistribution aims to allocate available feeder capacity among multiple charging stations in real time while respecting network constraints. The presented results provide the physical background for this concept:

- Balanced three-phase charging reduces phase-specific bottlenecks.
- LCL filtering limits harmonic emission, making current setpoint changes less problematic from a power-quality perspective.

Together, these aspects create favourable conditions for dynamic redistribution. Instead of assigning fixed charging powers, the charging current of each station can be adapted according to transformer loading, feeder current limits, and voltage conditions. Similar approaches reported in the literature demonstrate that network-aware current setpoint control can significantly increase EV hosting capacity without requiring immediate reinforcement of infrastructure [3].

The results therefore support a hierarchical mitigation concept:

- ensure low harmonic emission at the device level,
- apply feeder-level dynamic power redistribution to avoid overloads and voltage violations.

This effect was also confirmed in the additional redistribution scenario, where uncontrolled simultaneous charging would increase the feeder current to approximately 142 A, while adaptive redistribution limited the current per station to 22-24 A and kept the total feeder current below the 120 A limit.

4.4 Practical Implications

The findings indicate that:

- Distribution system operators benefit from promoting three-phase charging where possible.
- Charger manufacturers should integrate effective output filtering and stable current control.
- Smart charging systems should combine local converter control with feeder-level redistribution algorithms.

Such coordinated solutions are increasingly recognised as a key element of large-scale EV integration strategies [4].

4.5 Limitations

The presented study is based on a simulation model of a representative urban distribution feeder. Although the model captures the main electrical phenomena associated with EV charging, the analysed scenarios include only a limited number of charging stations.

Future work will focus on large-scale charging scenarios with a higher number of simultaneously operating EV charging stations and implementation of advanced dynamic power redistribution algorithms. Experimental validation using hardware testing and laboratory test benches is also planned.

5 Conclusion

This paper investigated the impact of electric vehicle charging on low- and medium-voltage distribution networks with emphasis on dynamic power redistribution among charging stations and converter-side harmonic mitigation. A MATLAB/Simulink model including residential and commercial loads, single-phase and three-phase EV charging stations, photovoltaic generation, and power electronic interfaces was used for time-domain and frequency-domain analyses.

Simulation results demonstrate that single-phase EV charging causes pronounced phase unbalance in the low-voltage network. The supplying phase exhibits an increase of current of approximately 16 A compared to the remaining phases, which leads to higher thermal stress and increased risk of voltage deviation. In contrast, three-phase charging results in balanced phase currents with amplitudes of approximately 20 A in each phase, confirming symmetrical loading of the feeder and transformer.

FFT analyses show that without LCL filtering, EV chargers inject noticeable harmonic components into the grid. These harmonics are observable not only at the 0.4 kV level but also propagate through the transformer to the 22 kV network. After implementation of an LCL filter at the converter output, dominant harmonic components are significantly attenuated in both voltage and current spectra, indicating a substantial improvement of power quality. From the perspective of dynamic power redistribution, the results confirm that:

- Three-phase charging reduces phase-specific bottlenecks and increases usable feeder capacity.
- Effective LCL filtering ensures that dynamic modification of charging currents does not lead to excessive harmonic distortion.

These two conditions form a practical foundation for feeder-level redistribution of charging power among multiple EV charging stations based on available network capacity.

In the additional multi-station scenario, uncontrolled charging would have increased the feeder current to approximately 142 A, whereas dynamic redistribution reduced the charging current per station to 22-24 A and maintained the feeder current below the 120 A limit.

The results also confirm the strong influence of converter filtering on harmonic distortion. In the analysed scenarios, the THD in the 22 kV network was reduced from 5.31 % to 0.18 %, while in the 0.4 kV residential network the THD decreased from 78.67 % to 2.51 % after applying the LCL filter.

The paper confirms that coordinated and adaptive charging strategies, supported by appropriate power-electronic design, can increase EV hosting capacity of distribution networks without immediate grid reinforcement.

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