

COORDINATED CHARGING OF ELECTRIC VEHICLES: IMPACT ON THE LOW-VOLTAGE DISTRIBUTION GRID.

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ABSTRACT: Electric vehicles are expected to become more and more popular in the near future. A major concern exists however that charging the batteries of these electric vehicles will present a considerable extra load for the distribution grid, mainly in residential areas where the grid infrastructure was not designed to accommodate these extra loads. Power quality problems, unbalance and congestion are expected to occur, especially in case the electric vehicles are charged in an uncoordinated way. In this paper, the impact of different amounts of electric vehicles on the distribution grid is studied. Furthermore, we investigate the effect of intelligent charging of the electric vehicles, using a market-based coordination mechanism. Load flow analysis shows that a considerable improvement of the power quality is achieved by applying coordination to the charging of electric vehicles.

INTRODUCTION

It is expected that the electrical distribution grid will have to accommodate several new types of loads in the near future. Electric Vehicles (EV) and Plug-in Hybrid Electric Vehicles (PHEV) for example, are expected to become more and more popular [IEA, 2009]. The charging of the batteries of these cars requires a large amount of electrical energy which the distribution grid will have to provide. A major concern exists that the increasing use of electric vehicles will result in a considerable extra load on the distribution grid, especially in residential areas where the grid infrastructure was not designed to accommodate these additional loads. Problems that are likely to occur are an increased voltage drop over the distribution feeders, undesirable peaks in the power consumption and an excessive voltage unbalance, when all vehicles are plugged in at the same time. However, as the EV owners only require their car to be charged in the morning, a certain amount of flexibility is available during the night to charge the cars. This flexibility can be used to spread the charging of different vehicles over time [Clement et al., 2009, Lopes et al., 2009]. In this paper a market based coordination mechanism is used for the charging of electrical vehicles. We show that by applying coordination, the power quality of the distribution grid is significantly increased.

SCENARIO

In order to determine the influence of the market-based coordinated charging strategies on a low-voltage distribution network, simulations were done on a typical distribution grid topology found in Belgium. This section describes the used grid topology and the load profiles in each grid-connection.

The reference distribution network is supplied by a 250kVA transformer and consists of 3 branch feeders. The feeders are 4*150 mm² EAXVB cables with a total length of 400 m. Each feeder supplies 21 houses. The spur feeder cables, which connect the houses to the branch feeder cable, have a length of 5 m. All houses are equally distributed over the three feeders, and over the three phases of the feeders. A schematic of the used network topology is shown in Fig 1. A total of 63 houses is connected to the reference distribution grid. The load profiles representing the power drawn by the households are based on measurements done on three different households during a number of different winter days. Each measured profile spans 24 hours starting and ending at 12 p.m. and has a resolution of 5 minutes. These profiles are slightly shifted in time before they are randomly assigned to a grid connection. These shifts in time are necessary to avoid peaks in a single profile to occur in the aggregated profile of the neighbourhood.

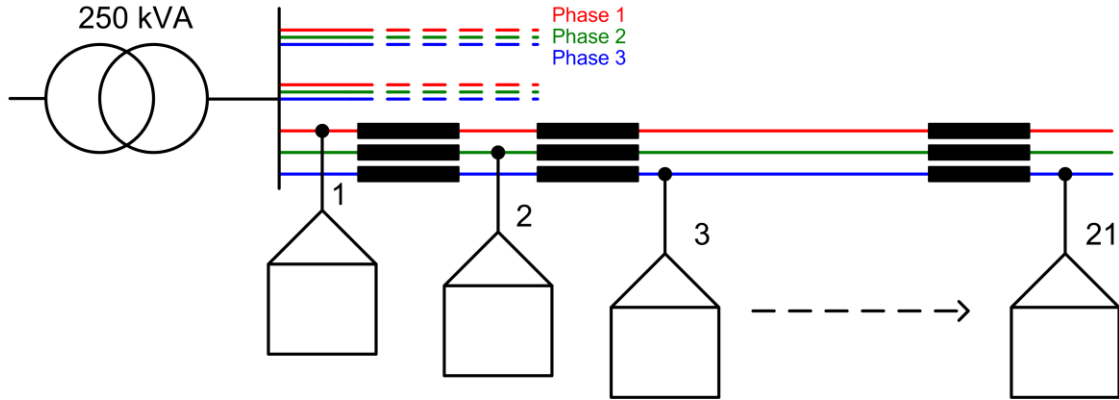


Figure 1: Distribution grid topology

In order to calculate the node currents, line currents and node voltages in the network, a load-flow analysis was performed on the network. Because of the radial nature of the distribution grid, a backward-forward sweep method was used in the load-flow algorithm [Ciric et al., 2003].

Three simulation scenarios were defined, each having a different penetration degree of electric vehicles. It is assumed that 1.5 cars per household are present. In the 'light'-scenario 10% of these cars are electric vehicles, in the 'medium'-scenario 30% of the cars are electric and in the 'heavy-scenario' 50% of the cars are assumed to be electric. In each of these scenarios, 70 % of the electric vehicles are Plug-In Hybrid Vehicles (PHEV), and 30% are full Electric Vehicles (EV). We assume a PHEV to have a battery capacity of 15kWh and an EV a capacity of 25kWh. A single-phase connection is provided in each house to charge the cars, and two types of chargers are assumed: a standard socket of 3.6 kW, and a heavy-charging socket of 7.4 kW. Half of the electric vehicles has a heavy charger, and the other half has a standard charger. Table 1 shows the amount of electric vehicles present in each scenario. All electric vehicles are randomly spread out over all household connections.

The plug-in times of the electric vehicles are varied around 5.30 p.m. using a normal distribution with a standard deviation of 45 minutes. The vehicles are supposed to be fully charged around 6.30 a.m., again varied randomly using the same normal distribution as the plug-in time of the vehicles. The initial state of charge (SOC) of the vehicles is randomly varied between 20% and 60% with a uniform distribution.

The batteries of the electric vehicles are initially charged with a constant current, until the SOC of the battery pack reaches 80%. The remainder of the charging process happens under constant voltage, while the current decreases exponentially. The battery charger asks full power during constant current charging, and the charging power decreases exponentially during constant voltage charging. In the simulations it is assumed that constant voltage charging time equals the time to charge the battery from 20%-80% under constant current. In this scenario we assume no smart charging, i.e. a battery will always take the maximum wanted power from the grid.

Table 1: Amount of PHEV and EV in the three different scenarios.

Amount of vehicles	PHEV	PHEV	EV	EV
	1-phase 3.6kW	1-phase 7.4kW	1-phase 3.6kW	1-phase 7.4kW
Light scenario	4	3	2	1
Medium scenario	10	10	5	4
Heavy scenario	17	16	7	7

MARKET BASED COORDINATION

The distribution grid is organized as a commodity market where agents act on behalf of the transformer and the households. An agent is a software or hardware computer system that is able to make autonomous decisions, is able

to interact with other agents and is able to react, reactively and pro-actively, to changes in its environment [Bradshaw, 1997]. The commodity that is bought and sold in the market is electrical energy. In a single-shot multi-unit auction, buyers and sellers submit their bids and offers for a commodity, after which a clearing price is established [Wilson, 1997]. This clearing price balances demand and supply. Each buyer is allocated to consume the amount of electrical energy that he is willing to buy for the clearing price. The sellers are allocated to produce the amount of goods they are willing to sell for the clearing price. All players on the market do not know each other's strategies nor bids. Such a market mechanism can be used to match demand and supply on the electricity grid [Kok et al., 2005, Hommelberg et al., 2007].

Each household is represented by an agent that bids for electricity on the market. The transformer is also represented by an agent which acts as the sole supplier of electricity. Within a household, each device is also represented by an agent. These device agents send their bids to the household agent who aggregates these bids before sending the aggregated bid to the market. The bidding strategy of the EV agent is to bid a price that increases linearly as the charging deadline approaches. This charging deadline is the time at which the electric vehicle has to start charging in order to be fully charged in time.

The main advantage of a market based approach to coordination is that it requires no centralized planning algorithm, it scales well to a large numbers of devices as well as a large diversity of devices. Furthermore, since the only interaction between the market players is by means of bidding functions, a market based approach has less privacy issues than a centralized coordination approach.

SIMULATION RESULTS

Influence of coordinated charging on peak load of the transformer

Figure 2 shows the total apparent power through the distribution transformer for the three different scenario's, with and without the use of the market-based coordination mechanism. When no coordination is applied to control the charging of the electric vehicles, a peak load occurs in the distribution transformer exceeding the transformer's rating in the 'heavy' scenario. The use of coordination causes the charging of the electric vehicles to be spread out over time. The traded volumes in the market never exceed the transformer's rating. In the 'heavy-scenario' a reduction in peak load of 52% is achieved when using the market-based charge coordination mechanism.

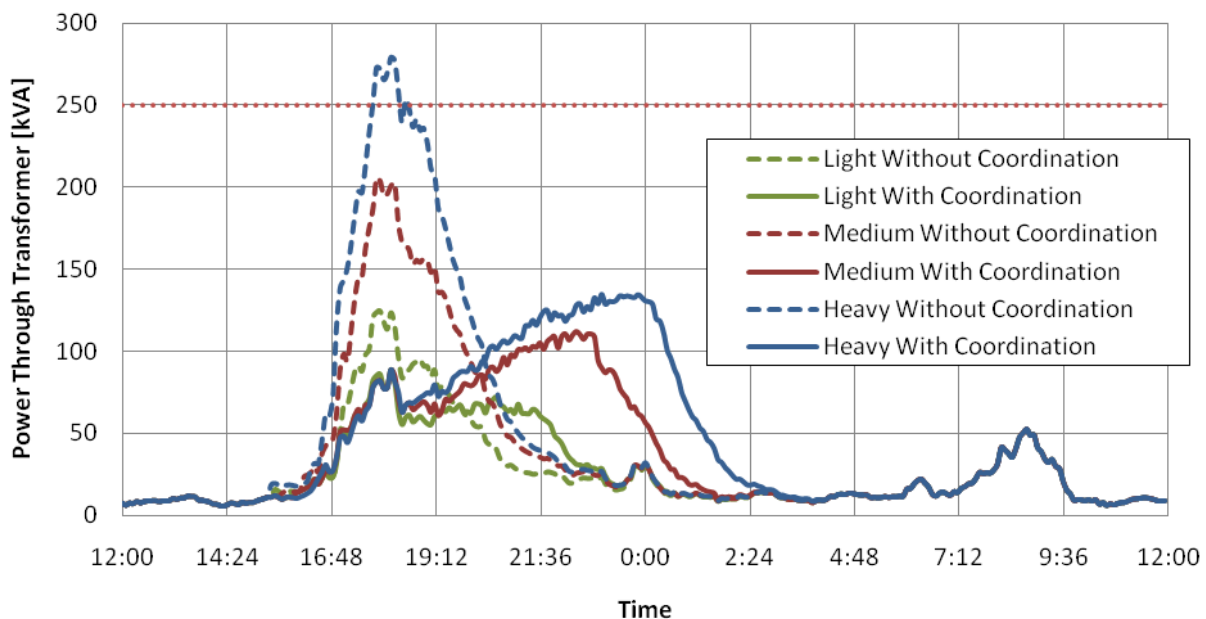


Figure 2: Apparent power through the distribution transformer in each scenario with and without coordinated charging.

Influence of coordinated charging on voltage drop over feeder

When all EVs are charged at the same time, the voltage drop over the distribution feeder increases. Standard EN50160 [Std.EN50160] stipulates that the voltage on the distribution feeder should be between 230/400 V \pm 10%. The possibility exists that the grid voltage drops below the limit set by the standard at the peak load moments. Table 2 gives the lowest grid voltage reached during the day at the end of one feeder of the distribution network. In the 'medium' and 'heavy' scenario, the grid voltage falls below 10% in some of the phases. When using the charge coordination strategy, the lowest grid voltage never falls below the limits set by standard EN50160.

Table 2: Lowest voltage [p.u.] reached during the day at the end of a feeder for the three scenario's, when no coordination is applied to the charging of the electric vehicles, and with the market-based coordination strategy.

	Without coordination			With coordination		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Light Scenario	0,93	0,97	0,97	0,94	0,95	0,97
Medium Scenario	0,96	0,83	0,95	0,96	0,90	0,97
Heavy Scenario	0,89	0,95	0,87	0,94	0,96	0,93

Influence of coordinated charging on unbalance

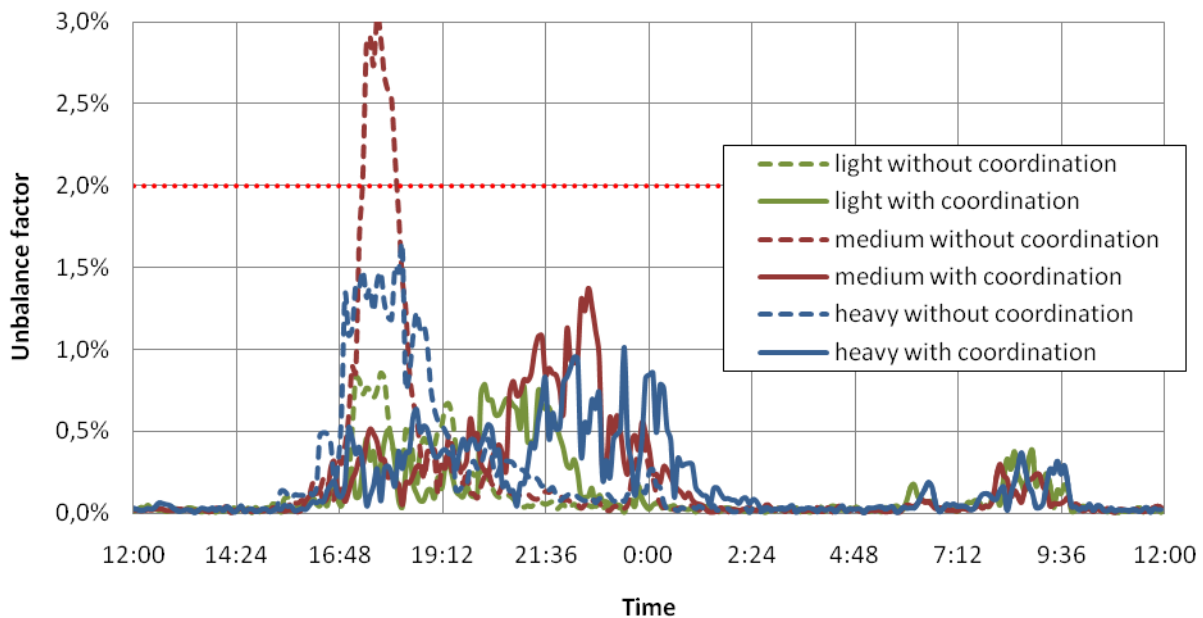


Figure 3: Variation of the unbalance factor of a distribution feeder during the day, for the three scenario's when no coordination is applied to the charging of the electric vehicles, and with the market-based coordination strategy.

In standard EN50160 is also stipulated that the unbalance between the phases has to be limited. The unbalance factor, defined as the negative-sequence to positive sequence voltage ratio, has to be limited to 2%. Figure 3 shows the unbalance factor for one distribution feeder during the day, for the three scenarios. Since all connections in the distribution network are single-phase, the unbalance is considerable, especially in the 'medium' scenario; where the unbalance factor exceeds the limit, and rises up to 3%. However, when coordination is applied to the charging of the

electric vehicles, the charging of the vehicles is spread out over time, and consequently the supply voltage unbalance drops below the limit.

CONCLUSIONS

In the future, the electrical distribution grid will have to accommodate new loads, such as electric vehicles. The concern exists that with the increased use of these new loads, problems will occur in the distribution grid. In this paper the use of a market-based coordination mechanism for the charging of electrical vehicles is introduced. Three scenarios were defined with a different penetration degree of electric vehicles. A series of experiments demonstrates the effect of these electric vehicles on the distribution grid. Already at 30% electric vehicles, the voltage drop at the end of the distribution feeder runs outside the norm. At 50% electric vehicles, problems with peak load and voltage unbalance occur. When we apply the market based coordination mechanism in the different scenarios, results show that even with 50% electric vehicles, no problems occur with peak load, undervoltage or voltage unbalance. This indicates that no grid reinforcement investments are immediately needed to accommodate the charging of the electric vehicles, when the market-base charging coordination is used.

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