Decentralized coordination of plug-in hybrid vehicles for imbalance reduction in a Smart Grid

Stijn Vandael
Nelis Boucké, Tom Holvoet
DistriNet, Department of Computer Science
Katholieke Universiteit Leuven, Belgium
{firstname.lastname}@cs.kuleuven.be

Klaas De Craemer
Geert Deconinck
ELECTA, Department of Electrical Engineering
Katholieke Universiteit Leuven, Belgium
{firstname.lastname}@esat.kuleuven.be

ABSTRACT

Intelligent electricity grids, or 'Smart Grids', are being introduced at a rapid pace. Smart grids allow the management of new distributed power generators such as solar panels and wind turbines, and innovative power consumers such as plug-in hybrid vehicles. One challenge in Smart Grids is to fulfill consumer demands while avoiding infrastructure overloads. Another challenge is to reduce imbalance costs: after ahead scheduling of production and consumption (the so-called 'load schedule'), unpredictable changes in production and consumption yield a cost for repairing this balance.

To cope with these risks and costs, we propose a decentralized, multi-agent system solution for coordinated charging of PHEVs in a Smart Grid. Essentially, the MAS utilizes an "intention graph" for expressing the flexibility of a fleet of PHEVs. Based on this flexibility, charging of PHEVs can be rescheduled in real-time to reduce imbalances.

We discuss and evaluate two scheduling strategies for reducing imbalance costs: reactive scheduling and proactive scheduling. Simulations show that reactive scheduling is able to reduce imbalance costs by 14%, while proactive scheduling yields the highest imbalance cost reduction of 44%.

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence - Coherence and coordination, Multiagent systems; J.7 [**Computer Applications**]: Industrial control

General Terms

Algorithms, Economics, Experimentation

Keywords

Multi-agent systems, plug-in hybrid vehicles, Smart Grids.

1. INTRODUCTION

In recent years, there is a global evolution in the way energy is generated and consumed due to climate change, energy independence and the impending decay of fossil fuels. In Europe, these changes are reflected in the 20-20-20 targets: 20% carbon reduction, 20% rise in energy efficiency and 20% production from renewables [1] by 2020. At the present, two major evolutions are already visible.

The first evolution is the explosive growth in the amount of small distributed generators (DG) connected to the local distribution grid (e.g solar panels). By nature, this type of renewable, dispersed electricity generation is unpredictable and uncontrollable.

The second evolution is the increasing amount of PHEVs, hybrid vehicles with a battery that can be charged through a regular power socket. Recent research predicts that in 2030, PHEVs will comprise 5% of the Belgian electricity consumption [2]. Because of this large impact of PHEVs on the electricity infrastructure, controlled charging of PHEVs is an important research topic. Apart from a challenge, PHEVs offer a tremendous opportunity for managing fluctuations caused by distributed generation.

Intelligent electricity grids or Smart Grids enable the management of such advanced production and consumption in the electricity grid. In a Smart Grid, it becomes possible to intelligently coordinate consumers to maintain the net balance and ensure an efficient, reliable and environmentally friendly production, transmission and distribution of electricity.

Multi-agent systems have been identified by the IEEE Power Engineering Society's Multi-Agent Systems (MAS) Working Group as a promising distributed control approach in power engineering [3, 4]. The working group identified the following key benefits of applying MAS in power engineering:

- *Flexibility*: the ability to respond to dynamic situations.
- *Extensibility*: the ability to easily add new functionality and augmenting or upgrading existing functionality.
- *Fault tolerance*: the ability of the system to meet its design objectives in case of failure.

In this paper, a decentralized solution based on MAS is proposed, discussed and evaluated for coordination of the charging of PHEVs to reduce imbalances caused by DG. The paper contributes to this research in three ways:

1. Assessment of the increasing imbalance costs due to renewables and the potential of PHEVs as a means to reduce these costs. (section 2)
2. Description of a multi-agent solution for large-scale coordination of PHEV charging and the explanation of different scheduling strategies to reduce imbalance costs. (section 3)
3. Evaluation through simulation of the multi-agent solution in scenarios with PHEVs and solar panels. (section 4)

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2. BALANCE MANAGEMENT IN THE ELECTRICAL GRID

The unpredictability of renewable DG incurs a risk for traders on the electricity market, called the "imbalance cost". Especially day-ahead markets, where a load schedule has to be predicted 12-36 hours in advance, pose a serious problem. An example are wind farms: even with state of the art forecasting methods, the short-term electricity generation of wind farms cannot be predicted with a high degree of accuracy [5].

At the same time, recent research suggests that PHEVs will comprise 5% of the national electricity consumption [2]. Because cars are parked most of the day, opportunities arise for shifting the charging of PHEVs in time. This way the imbalance caused by unpredictable generation can be offset, while ensuring that PHEVs are charged in time, i.e. before their intended departure.

The management of the balance between production and consumption in electrical grids entails a complex engineering domain. In this section, we aim to identify the key elements and procedures in this domain that are required to clearly define the problem and motivate the solution.

2.1 TSO responsibilities

The electrical grid consists of a transmission grid and a distribution grid. The transmission grid transfers electricity from large power plants to the distribution grid, while the distribution grid distributes electricity to individual households, factories and street lighting. In each country, the transmission grid is maintained by a transmission system operator (TSO) and the distribution grid by one or more distribution system operators (DSO). While the responsibilities of the DSO are mostly infrastructural and administrative, one of the main tasks of the TSO is to constantly monitor and maintain the balance between supply and demand within its control area.

To balance between supply and demand, the TSO needs predictions of the energy that will be injected and withdrawn at each access points to its transmission grid. Each access point has a designated BRP (Balancing Responsible Party). This BRP provides the TSO with a predicted load schedule of the consumers and/or producers behind its respective access point. Based on these load schedules, the TSO manages electricity flows between the access points and the overall balance between production and consumption in its control area.

2.2 BRP responsibilities

The load schedule of a BRP is organized in fixed settlement periods. The length of a settlement period varies per country, but is typically 15 minutes (e.g Belgium and the Netherlands), 30 minutes (e.g England and Wales) or 1 hour (e.g Sweden and Norway). Load schedules submitted to the TSO must be balanced. This means that if a BRP has declared a scheduled supply to another BRP, the reverse transfer of energy must be found in the schedule of this other BRP [6] or in the import/export schedule to another control area.

BRPs need to provide their load schedule before a fixed deadline, called the "gate closure". Most European countries utilize a day-ahead gate closure. For example, in Italy, the gate closure is at 16h00 day-ahead for all settlement periods of the next day (from 00h00 until 24h00). After gate closure, the BRP's load schedule cannot be changed anymore.[1]

2.3 Imbalance cost

During a settlement period, the TSO continually balances supply and demand, taking into account finite network capacity. If there is insufficient supply to meet demand, the TSO dispatches extra supply reserves and vice versa. The costs (demand reserve) or revenues (supply reserve) for dispatching these reserves are settled with the BRPs causing the imbalance. An BRP with negative imbalance (more consumption or less production than planned) pays an imbalance tariff to the TSO, while an BRP with a positive imbalance (less consumption or more production than planned) gets paid an imbalance tariff.[2]

From an BRP's point of view, it is more profitable to sell its production and buy its consumption on the day-ahead market, because the imbalance tariffs for extra consumption are typically high and for extra production low. These lost revenues for an BRP are called the "imbalance price". This imbalance price is the difference between the before price (day-ahead tariff) and the after price (imbalance tariff). In economics, this is called an opportunity cost. The total imbalance cost in each settlement period is calculated as the difference between the metered energy volume with the contracted energy volume, multiplied by the imbalance price:

$$\text{Cost}_{imbalance} = (E_{measured} - E_{contracted}) \cdot \text{Price}_{imbalance}$$

Obviously, it is a challenge for BRPs to accurately predict their load schedules. A BRP responsible for an access point to a local distribution grid consisting of households, typically predicts its load schedule based on synthetic load profiles. For example, in Belgium, the local electricity regulator provides these profiles for every day of the year before the beginning of the year. Examples of a few different load profiles are depicted in figure 1.

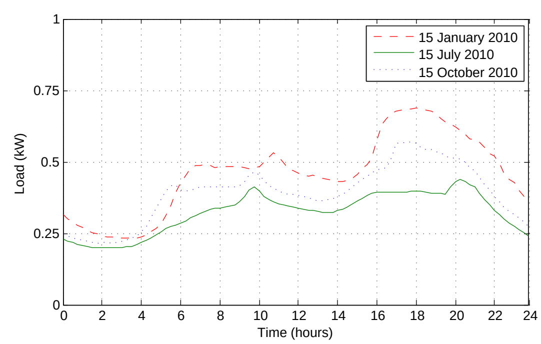

Figure 1: SLPs (synthetic load profiles)

[1]The time interval between the gate closure and the actual start of the corresponding period of operation varies between countries. The gate closure can be within the same day (intraday) or in the previous day (day-ahead) of the period of operation. For example, gate closure in Denmark is half an hour ahead (intraday), in the Netherlands one hour ahead (intraday) and in Italy at 16h00 day-ahead [7]. For intraday, the period of operation is one settlement period and for day-ahead, the period of operation is one day (from 00h00 until 24h00).

[2]In extreme cases, for example, when there is a huge overproduction from renewables, an BRP gets paid for consuming electricity.

3. A MULTI-AGENT SYSTEM SOLUTION FOR IMBALANCE REDUCTION

Supported by the conclusions of the IEEE Power Engineering Society's Multi-Agent Systems (MAS) Working Group [3, 4], as well as by our own experience [8], we target a decentralized, multi-agent system solution for the coordinated charging of PHEVs to reduce imbalances. This solution focuses on the actors and interactions aimed at mitigating the imbalance after gate closure. We assume that before gate closure, the load schedule with predictions of households and distributed generators was assembled by the BRP.

The schematic overview of the multi-agent system is depicted in figure 2. A PHEV agent represents the software managing the charging of a PHEV, a transformer agent controls a low-voltage transformer and the BRP agent manages the access point to the transmission grid. Each type of agents has the following primary goals:

- PHEV agent: *charge the battery of its PHEV in time.*
- Transformer agent: *prevent overloading of its transformer.*
- BRP agent: *minimize imbalance costs.*

These goals are not independent from each other. For example, a PHEV with an empty battery cannot be charged in an hour, because this would cause overloading the low voltage transformer and most likely cause imbalance; or a BRP cannot reduce a negative imbalance when PHEVs are about to leave and still need to be fully charged. The agents need to coordinate with each other to meet the individual goals of all agents.

3.1 Coordination mechanism

The agents are organized in a hierarchical structure (figure 3) and their basic coordination mechanism consist of four steps:

1. The PHEV agents send their charge intentions to the connecting transformer agents. Through aggregation of these charge intentions at each transformer agent, the BRP can assemble an intention graph of all PHEVs in the distribution grid.
2. The BRP agent decides how much energy will be charged in the next time step according to a suitable scheduling strategy (see section 3.2, "scheduling strategies").
3. The BRP agent informs the transformer agents about the energy that will be charged in the next time step. Accordingly, the transformer agents divide this energy between their underlying PHEVs.
4. The PHEV agents start charging the accepted amount of energy.

This coordination mechanism is executed at a frequency dependent on the required adaptiveness of the considered scenario. Initialization of the sequence is done by sending a global synchronization signal from the BRP down to all PHEVs.

The intention graph expresses the intentions of all PHEVs and enables the BRP to estimate the total flexibility of its PHEVs. In figure 4, the working of the intention graph is depicted:

(A) In this figure, an intention graph is depicted for two PHEVs at a given moment in time. The time-scale is divided into time intervals of a quarter hour, while the Y-axis indicates the amount of energy. As indicated in the figure, PHEV A will leave after the second quarter, while PHEV B will leave after the third quarter. Each of the PHEVs still needs 1 kWh of charging energy before they leave.

(B) In order to reduce imbalances (section 3.2), the BRP decides to fully charge PHEV A and half of PHEV B in the first quarter. Accordingly, PHEV A will charge for 1 kWh in the first quarter (= 4 kW), while PHEV B will charge for 0.5 kWh in the first quarter (= 2 kW).

(C) After the first quarter, PHEV A is fully charged and PHEV B still needs to be charged for 0.5 kWh.

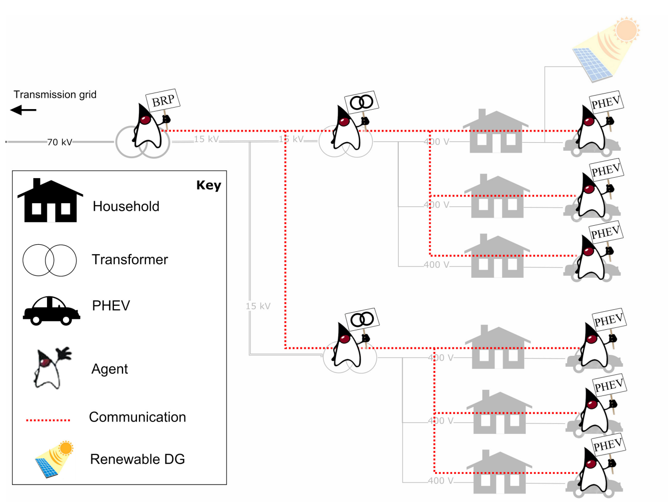

Figure 2: Schematic overview of the MAS.

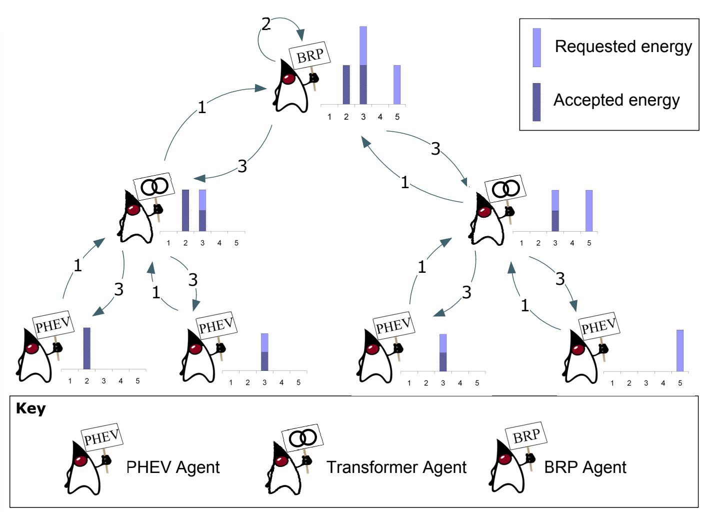

Figure 3: The MAS coordination mechanism.

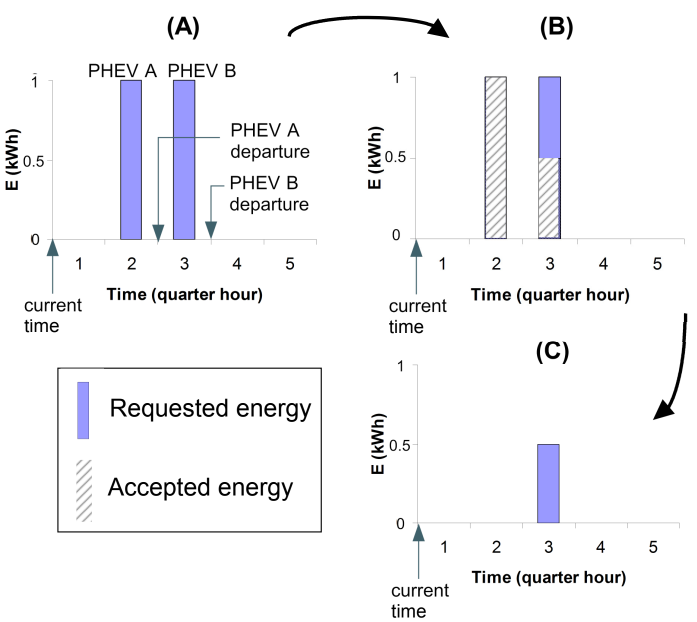

Figure 4: Representation of PHEV intentions.

3.2 Scheduling strategies

The BRP uses a scheduling strategy to achieve its goals. These goals have a strict order, which means that one goal cannot be achieved without achieving the previous goal. In order of importance:

1. Transformer and cable limits
   To avoid infrastructure damage, the transformer and cables have a power limit that cannot be overstepped. For that purpose, the agents send their current and maximum load towards the BRP agent (step 1 in the coordination mechanism). In each strategy, this constraint is integrated. In the rest of the explanation, this constraint is assumed, without repeated mentioning.

2. Charging of PHEVs
   To ensure that PHEVs' owners can fully benefit from their electric car, PHEVs are charged before they depart. The intention graph incorporates this goal.

3. Minimal imbalance costs
   When infrastructure limits are respected and PHEVs can be fully charged, load can be shifted in order to minimize imbalance costs in the BRPs perimeter. This will be the focus of the proposed strategies.

All scheduling strategies presented in this paper are explained with the small example depicted in figure 5. In this example, the BRP agent has to schedule the charging of 10 kWh in five settlement periods of 15 minutes. For this purpose, the BRP agent uses a day-ahead load schedule and a real-time schedule of the five settlement periods.

The **day-ahead schedule** consist of the sum of the predictions of non-PHEV load (households and DG) and PHEV load. This schedule was submitted to the TSO before gate closure (day-ahead) and doesn't change during the operation period.

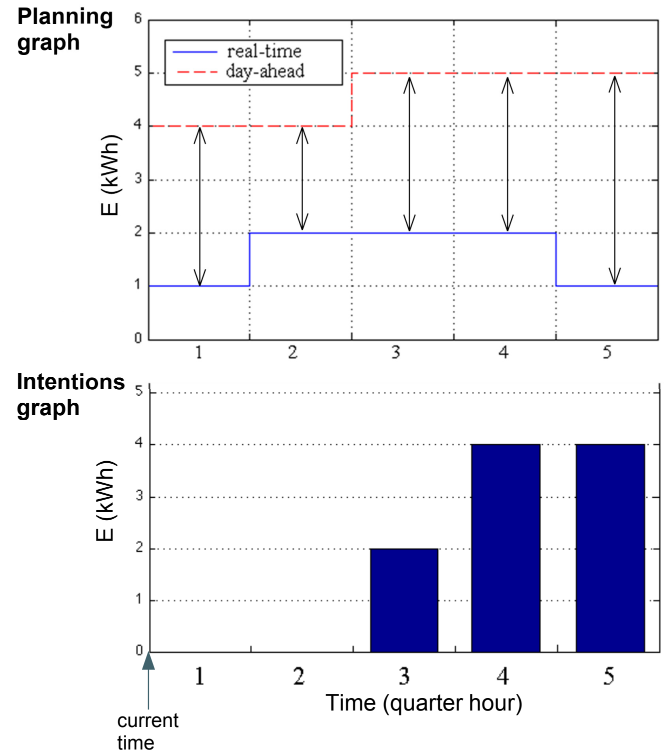

Figure 5: Scheduling example.

The **real-time schedule** only consists of the predictions of the non-PHEV load (households and DG). PHEV load is not included in this schedule, because the real-time schedule is used to online schedule the PHEV load on top.

The BRP schedules the charging of PHEVs onto the real-time schedule to approach the day-ahead schedule as closely as possible to reduce imbalance costs. While we assume that the real-time schedule doesn't change in this small example, this schedule can be updated with new information about non-PHEV loads that become available. For example, new weather information or load measurement data.

3.2.1 Reactive strategy

The reactive scheduling strategy is a strategy where imbalances are postponed as long as possible. Figure 6 shows the result of this strategy on the considered example. The amount of energy (10 kWh) is scheduled in order to meet the balancing requirements in the first three quarters. However, the imbalance is expected to increase from the fourth quarter due to a PHEV charging shortage. In case of a surplus of PHEV charging, reservations are made at the end of the scheduling to postpone any imbalances. Although the portfolio balancing strategy is reactive, PHEVs are ensured to fully charge their battery before departure, given that the transformer load constraints are respected. The PHEV intentions are always reserved in ascending order of departure time to ensure maximum utilization of flexibility.

Advantage: The portfolio is balanced as long as possible.

Disadvantage: The risk of a large future imbalance is great. When high imbalance costs coincide with this large imbalance, total imbalance costs will be high.

Algorithm 1: Reactive scheduling

```
PHEVEnergyLeft = sum(intentions)
for T:  1 to  endTime do
    while prediction(T) < dayahead(T)
         && energyLeft > 0 do
      PHEVEnergyLeft = reserve(T, PHEVEnergyLeft)
    end while
end for
for T in range(endTime, 1) do
      PHEVEnergyLeft = reserve(T, PHEVEnergyLeft)
end for
```

3.2.2 *Proactive strategy*

The proactive strategy is a strategy where imbalances are equally distributed among the schedule. Figure 7 shows the result of this strategy on the considered example. The amount of energy (10 kWh) is scheduled in order to minimize the average distance between the prediction and load schedule. Again, to ensure maximum flexibility in the future, the PHEVs were reserved in the order of their departure time. Note that the imbalance is the same as in the previous strategy, but the imbalance risk is divided over all timesteps. For example, in figure 7, when a large amount of PHEVs connects to the grid after quarter 3, it is possible that consumption becomes too high. In that case, the reactive strategy would be better.

Advantage: The risk for high imbalance costs is divided over the schedule.

Disadvantage: This strategy assumes a good prediction without constant changes.

Algorithm 2: Proactive scheduling

```
PHEVEnergyLeft = sum(intentions)
while PHEVEnergyLeft > 0  do
  if dayahead - prediction > 0 do
    T = timeOfLargestImbalance()
  else
    T = timeOfSmallestImbalance()
  end if
  PHEVEnergyLeft = reserve(T, PHEVEnergyLeft)
end while
```

4. SIMULATION EXPERIMENT: BALANCING SOLAR POWER

4.1 Experiment description

In this experiment, the proposed multi-agent system and its strategies are evaluated and compared for the reduction of imbalances caused by solar panels. The considered scenario is a future situation of a residential area with solar panels and PHEVs.

The scenario contains 200 households with consumption profiles obtained from the Belgian distribution grid provider Infrax [9]. These profiles contain actual measured household consumption on a 15 minute base.

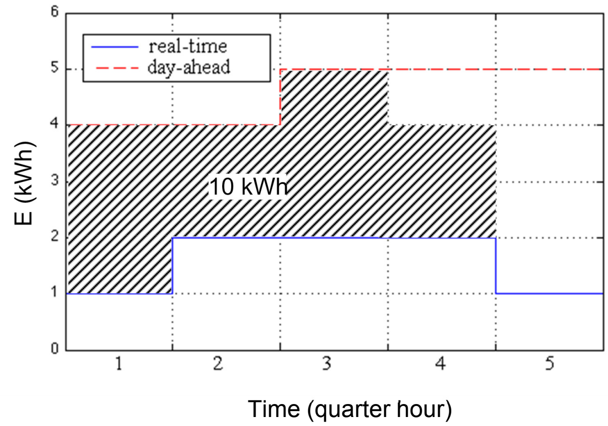

Figure 6: Reactive strategy.

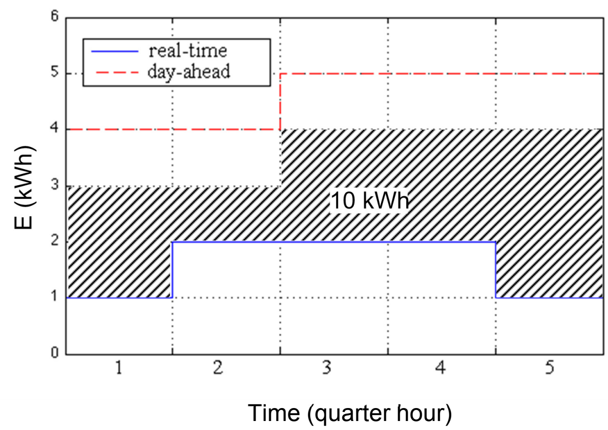

Figure 7: Proactive strategy.

From 200 households, 64 households have solar panels installed. Again, profiles were obtained from the Belgian distribution grid provider Infrax [9] from actual measured data.

For a true representation of the load caused by PHEVs, a realistic model of PHEV usage is utilized [10]. This model represents the state of a car (home, driving ...) on a per minute base. Furthermore, the Chevrolet Volt is chosen, which is expected to go in production at the end of 2010. In our simulations, we suppose that 50% of the vehicles are able to charge at a charging station during the day.

Day-ahead load schedule

The day-ahead load schedule consists of predictions for households, solar panels and PHEVs (figure 8). For household predictions, synthetic load profiles were used from the Flemish Regulation Entity for the Electricity and Gas market (VREG) [11].

For the production from PV (photovoltaic) panels, the solar output trend can be predicted, but not the short-term variations (due to moving clouds, shadow casting etc.). Accordingly, predictions for PV panels were made by applying a moving average filter (of 15 quarter hour samples) on the actual data (figure 9).

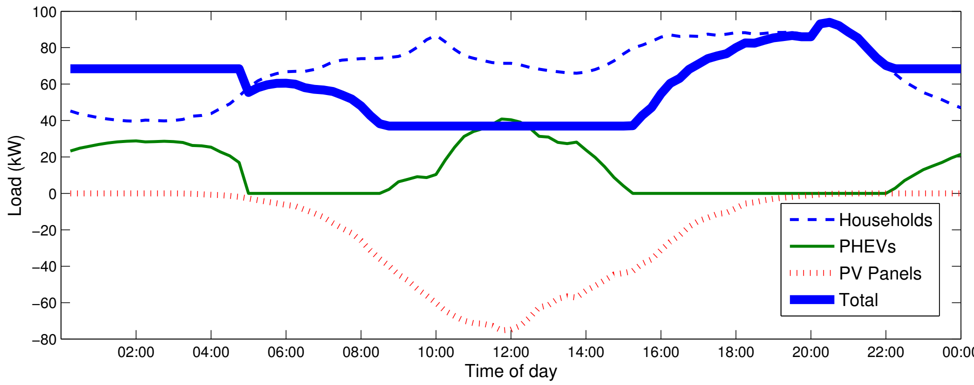

Figure 8: Day-ahead schedule

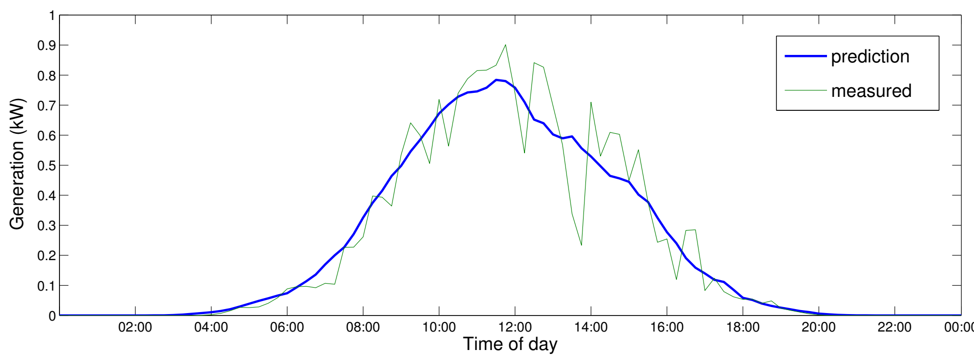

Figure 9: Power prediction of one PV panel

Although PHEVs will be coordinated, their expected load also has to be included in the day-ahead prediction. 50% of the vehicles are only able to charge at home, while 50% of the vehicles also have access to a daytime charging station. Therefore, half of the expected PHEV load (calculated by their battery content) is allocated during the night, while 50% of the PHEV load is allocated during the business hours. During the night, electricity on the Belpex day-ahead market[3] is generally cheaper, which amounts to cheaper electricity for the BRP. During business hours, solar production is highest, which makes charging PHEVs at those moments essential for balancing. Charging PHEVs during evening peak hours, when the household load is high, must be avoided at all costs to prevent overloading the infrastructure and paying high prices on the Belpex day-ahead market.

Imbalance cost

The imbalance cost is an opportunity cost, caused by buying or selling energy at an imbalance price instead of placing correct bids on the day-ahead market. The imbalance cost is calculated by using the day-ahead price (provided per hour by the Belgian day-ahead market Belpex) and the imbalance prices (provided per quarter hour by the Belgian TSO Elia).

4.2 Simulation results

For simulating the described scenario, we built an open-source multi-agent simulator [12]. Simulations show that the reactive strategy is able to lower imbalance costs with 14%, while the proactive strategy is able to lower imbalance costs by 44%. The load imbalances for a typical simulation run using the active and proactive strategy show the reason for this difference (figure 10).

Between 10h00 and 13h30, a positive imbalance is visible for both strategies. This positive imbalance indicates a lower off-take than expected. The reason is that the solar panels are producing more than expected during these periods (figure 9), while the limited amount of PHEVs (figure 8) is unable to charge more to compensate for the overproduction.

The reactive strategy maintains the instantaneous balance, while ignoring possible balancing problems in the future. Accordingly, the active strategy immediately starts fully charging its PHEVs at 10h00 to compensate for the overproduction. The disadvantage is that the cars are fully charged by 12h30 and a high imbalance from 12h30 until 13h30 is unavoidable. During this high imbalance, the TSO was dispatching extra demand reserves, which leads to a high imbalance price for production. In contrary, the proactive strategy was able to avoid these high costs by spreading the risk over the total imbalance period.

[3] http://www.belpex.be

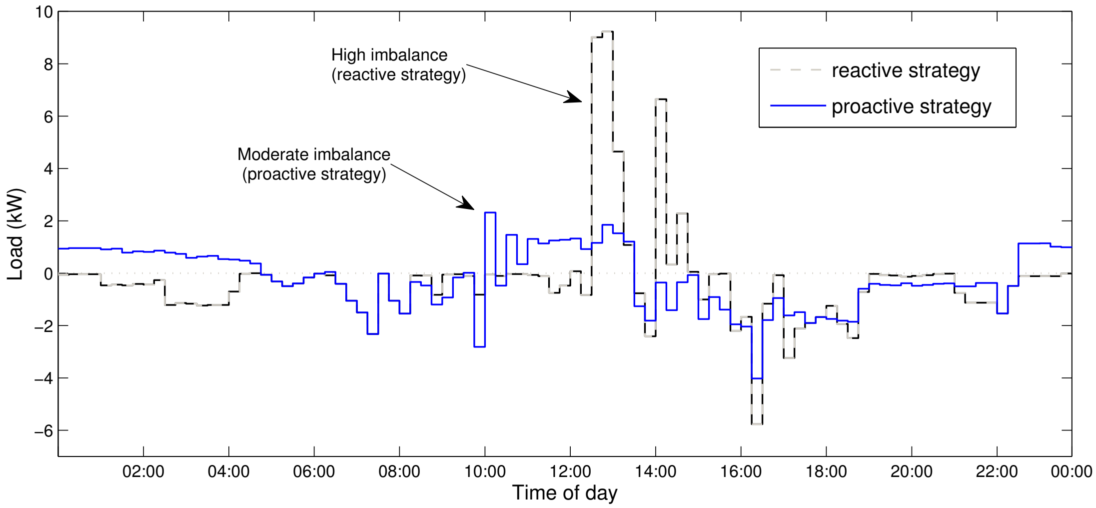

Figure 10: Load imbalance

5. RELATED WORK

In several research studies, multi-agent systems have been identified as the key technology in the future Smart Grid. Examples of MAS applications in Smart Grids range from island-mode control [13], micro-storage management [14] and micro grids [15] to market-based control [16, 17].

In [16], a novel market-based mechanism and trading strategies are proposed for a Smart Grid. In this mechanism, unforeseen demand or increased supply (not traded on the day-ahead market) are coped with by real-time trading between the actors (presented as agents) in the electricity market. The market mechanism proposed in this paper complements with our balancing mechanism in the sense that our balancing mechanism balances within the jurisdiction of one trader, while the mechanism of Vytelingum et. al balances between different traders through a market. Furthermore, because different traders are located on the transmission grid, the market mechanism includes congestion management by pricing the flow of electricity.

In [18], multi-agent coalitions for electrical vehicles are described for participation of these vehicles in the power regulation market. In the regulation market, electrical vehicles are used to provide both regulation-up power and regulation-down power. In this paper, regulation-up power was also provided by V2G (vehicle-to-grid), where vehicles are discharged onto the grid. Kamboj et. al modelled the coalition formation problem and presented various coalition formation strategies. The point of view of this paper is from the TSO's perspective. While vehicles in our paper are used for mitigating balancing cost of an BRP, Kamboj. et al actually deploys vehicles as reserve capacities for the TSO.

The PowerMatcher [19] is a market-based control concept for supply and demand matching in electricity networks. The basic MAS architecture of the PowerMatcher is a tree-structure similar to the one proposed in this paper. In the PowerMatcher, agents buy (consumers) and sell (producers) electricity on an electronic market by using a 'bid function'. This bid function expresses to what degree an agent is willing to pay (consumer) or be paid (producer) for a certain amount of electricity. By matching all these bid functions, the equilibrium price is determined to match demand and supply in a PowerMatcher cluster.

One of the field tests where the PowerMatcher was evaluated, is in the reduction of imbalance caused by trading of wind power on the APX (Amsterdam Power Exchange), by expanding an electricity trader's wind portfolio with flexible sources of demand and supply [20, 21]. For this purpose, a programme agent was included in the multi-agent system to push the market outcome to the programme value (the day-ahead load schedule). While our proposed MAS and the PowerMatcher are both used for reducing imbalance costs, the approaches are fundamentally different. While the PowerMatcher balances according to the degree an agent is willing to pay, our MAS balances according to the charging intentions of PHEVs. The contribution of the PowerMatcher is that a price component is explicitly integrated to incentivize consumers and producers, while our contribution is that PHEVs are assured to be charged before a certain time. Furthermore, while the PowerMatcher only represents short-term flexibility (expressed in Power), our mechanism is able to express long-term flexibility (expressed in Energy).

6. CONCLUSION AND FUTURE WORK

In the future, the coordinated charging of PHEVs will offer opportunities to mitigate imbalance costs. Due to the large scale and dynamic nature of the coordination problem, multi-agent systems are a promising technology in this area. The multi-agent system presented in this article uses an extendable, flexible and scalable technique for expressing PHEV intentions and controlling their charging behavior. Two scheduling strategies were proposed: reactive scheduling and proactive scheduling.

The presented simulation case shows that the MAS is capable of coordinating PHEVs to cope with unpredictable solar generation. Imbalance costs were decreased with 14-44%. Simulations showed that in most cases the reactive strategy was outperformed by the proactive strategy due to the great risks of a concentrated imbalance.

Future work will include the following aspects:

SCENARIOS. To more thoroughly evaluate solutions for balancing with PHEVs, more scenarios need to be tested. An important example is the integration of unpredictable wind power generation. Furthermore, the scenario considered in this paper does not necessarily hold for each region. For example, city regions will have different characteristics compared to rural regions.

SCALABILITY. The local communication and simple aggregation of intention graphs in the proposed MAS suggest a good scalability in terms of communication and execution time. However, this quality should be evaluated explicitly. In previous work [8], the demand-side management of PHEVs was evaluated against a reference solution based on quadratic programming. The same comparison techniques will be used for evaluation of the MAS in this article.

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