PowerMatcher: Multiagent Control in the Electricity Infrastructure

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ABSTRACT
Different driving forces push the electricity production towards decentralization. As a result, the current electricity infrastructure is expected to evolve into a network of networks, in which all system parts communicate with each other and influence each other. Multi-agent systems and electronic markets form an appropriate technology needed for control and coordination tasks in the future electricity network. We present the PowerMatcher, a market-based control concept for supply and demand matching (SDM) in electricity networks. In a presented simulation study is shown that the simultaneousness of electricity production and consumption can be raised substantially using this concept. Further, we present a field test with medium-sized electricity producing and consuming installations controlled via this concept, currently in preparation.

Categories and Subject Descriptors
I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence – *multiagent systems, coherence and coordination*.

I.2.1 [**Artificial Intelligence**]: Applications and Expert Systems – *industrial automation*.

General Terms
Algorithms, Economics, Experimentation.

Keywords
Multi-agent systems, multi-agent control, electronic markets, electricity infrastructure, electrical power systems automation.

1. Background

1.1 Evolution in the electricity net
Several different forces drive a change in the current worldwide energy supply. The portion of electricity in the total energy supply mix is expected to rise substantially [17]. Another ongoing change is the growing penetration of distributed electricity generation. Distributed Generation (DG) can be defined as a source of electric power connected to the distribution network or to a customer site ("behind the meter"). This approach is fundamentally distinct from the traditional central plant model for electricity generation and delivery.

Driving forces behind the growing penetration of DG are [18, 20]:

1. Environmental concerns. Producers of sustainable – or 'green' – electricity are to a large extent distributed generators. Photovoltaic solar cells and wind turbines are examples of these generators. Apart from large-scale wind farms, these generators are connected to the (low-voltage) distribution network or "behind the meter" at customer sites. Governmental aims to increase the portion of sustainable energy in the national energy mix have been translated into incentives and tax policies to promote the uptake of renewable energy sources in European countries as well as in other parts of the world.
2. Deregulation of the electricity market. As a result of the deregulation, the long-term prospects for large-scale investments in power generation are unclear at this moment. As a result of this, a shift of interest of investors from large-scale power generation plants to medium and small-sized generation can be seen. Investments in DG are lower and typically have shorter payback periods than those of the more traditional central power plants. Capital exposure and risk is reduced and unnecessary capital expenditure avoided by matching capacity increase with local demand growth.
3. Diversification of energy sources. Diversification of energy sources is a way to reduce the economic vulnerability to external factors. In particular, a higher portion of sustainable energy in the energy mix reduces the dependency on fossil fuels from politically unstable regions. The European energy need, for instance, is largely imported from outside the EU. As energy demand continues to grow, this external dependence could grow from 50 to 70% in 25 years or less.
4. Energy autonomy. A sufficient amount of producing capacity situated in a local electricity network opens the possibility of *intentional islanding*. Intentional islanding is the transition to stand-alone operation during abnormal conditions on the externally connected network, such as outages or instabilities, e.g. during a technical emergency. In this manner, autonomy can be achieved on different scales, from single buildings to wide-area subsystems.
5. Energy Efficiency (i). In general, distributed generation reduces energy transmission losses. Estimates of power lost in the long-range transmission and distribution systems of western economies are of the order of 7%. By producing electricity in the vicinity of where it is consumed, transport losses are avoided. There is, however, a concern that in cases where the local

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production outgrows the local consumption the transmission losses start rising again. But in the greater part of the European distribution network we are far from reaching that point.

6. Energy Efficiency (ii). Heat production out of natural gas can reach higher efficiency rates by using combined heat-power generation (CHP) instead of traditional furnace burners. CHP is a growing category of distributed generation, especially in regions where natural gas is used for heating. In Northern Europe, for instance, CHP is already commonly used in heating of large buildings, green houses and residential areas. The use of micro-CHP for domestic heating in single dwellings is expected to rise steeply in the next 10 to 20 years.

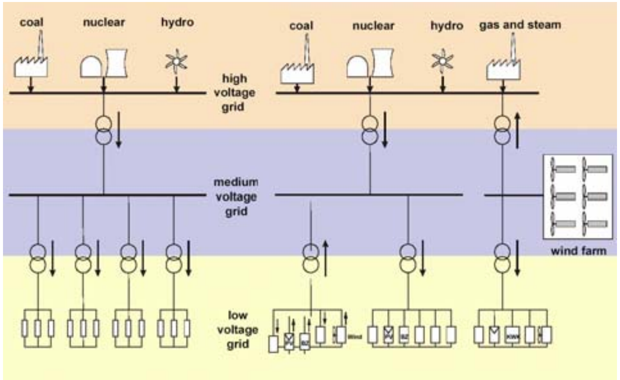

Figure 1: The traditional (left) and the future electricity infrastructure. In the future situation a substantial part of the electricity will be fed into the network at medium and low-voltage sub-networks [19] (original drawing courtesy of ISET).

The growing share of DG in the electricity system may evolve in three distinct stages [20]:

- **Accommodation.** Distributed generation is accommodated in the current market. Distributed units are running free, while centralized control of the networks remains in place.
- **Decentralization.** The share of DG increases. Virtual utilities optimize the services of decentralized providers through the use of common ICT-systems. Central monitoring and control is still needed.
- **Dispersal.** Distributed power takes over the electricity market. Local low-voltage network segments provide their own supply with limited exchange of energy with the rest of the network. The central network operator operates more like a coordinating agent between separate systems rather than controller of the system.

In specific parts of the world there are already signs of the decentralization stage (see for instance [21, 22].)

1.2 Need for new coordination mechanisms

During the second and third stage of DG growth, the structure of the current electricity grid evolves from a hierarchical top-down controlled structure into a network of networks, in which a vast number of system parts communicate with each other and influence each other. In the current electricity infrastructure energy and control information both mainly flow down and money flows up. In a DG-dominated electricity grid, energy, control information, and money will flow in all directions. A combination of distributed generation, electricity storage, demand response, real-time electricity prices and intelligent control opens the possibility of optimization regarding economics, dependability and sustainability.

As distributed generation gradually supplants central generation as the main electricity source, **distributed coordination** will supplant **central coordination**. The standard paradigm of centralized control, which is used in the current electricity infrastructure, will no longer be sufficient. The number of system components actively involved in the coordination task will be huge. Centralized control of such a complex system will reach the limits of scalability, computational complexity and communication overhead.

In addition to the described technical evolution of the electricity infrastructure, there is an ongoing evolution in the market structure. The electricity supply will no longer be in the hands of a small group of big players, but be spread out over a vast number of market players, big ones as well as small ones. This will give rise to new business models in (distributed) electricity production and consumption [5]. In regions with a highly deregulated energy system, like the Scandinavian countries, the United Kingdom, The Netherlands and some USA states, coordination mechanisms based on market-economic principles have been introduced at a central level, i.e. high up in the grid hierarchy. Market mechanisms are used for planning of large-scale production via day-ahead power exchange trading, and for real-time balancing via spinning-reserve auctions held by the Transport System Operators (TSOs). The coordination mechanisms for the low-end of the grid hierarchy, that become necessary during the second and third stage of DG growth, need to comply with the constraints given by the changing market structure. Consequently, these control mechanisms must be based on market-economic principles as well.

2. MAS for power management

2.1 ICT-Requirements

As a result of the electricity evolution as described above, the electricity infrastructure will get more and more inter-linked with ICT-infrastructure. The architecture and algorithmics of this ICT-infrastructure must be adapted to the technical structure of the (future) electricity net and the connected producing and consuming installations, but also to the structure of the liberalized energy market. This ICT-architecture and associated algorithms must be designed using a strong system-wide viewpoint, but must also consider stakes of local actors in the system. In other words, there is a need for a multi-actor coordination system, which optimizes global system objectives (like stability, power quality, and security of supply), in coherence with the interests of local actors in the form of installations for electricity production, consumption, and storage. These local actors vary greatly in characteristics defined by process type, purpose and size, and so do their specific constraints and objectives.

The resulting requirements of the ICT-infrastructure needed for the expected electricity evolution are:

- The ICT-architecture must be flexible, open and extensible.
- The coordination system must exceed boundaries of ownership. The total system includes the electricity network itself, central and distributed generators, electricity storage systems and electricity consuming systems. These system parts are owned by a vast number

of parties, varying from public authorities, via companies, to private individuals.

- In this multi-actor system the stakes on the global level as well as those of individual actors must be taken into account. Control of distributed generators, electricity consuming installations and electricity storage, needs to be based on local information specific for the purpose and characteristics of the device. The power to take decisions on local issues must stay with each individual local actor.
- In a liberalized market setting, control (and local decisions) must be based on economical grounds.
- Communication between system parts must be uniformed and stripped from all local information. This is needed to reach the required flexibility and openness as stated in the first point, but also for reasons of privacy and trade secrecy.

Naturally, the total resulting system (the electricity infrastructure plus the ICT infrastructure) must be dependable, since the power grid is a critical asset in the modern society. Most developed countries currently have a highly dependable electricity supply, and any changes to the system must not weaken it but rather strengthen it. Further, the system must be secure, i.e. hardened against hackers and cheaters[1].

2.2 Meeting the requirements

Multi-agent systems (MAS) and electronic (virtual) markets provide the key technology necessary to meet the ICT requirements as described in the previous paragraph, for the following reasons:

- In multi-agent systems a large number of actors are able to interact, in competition or in cooperation. Local agents focus on the interests of local sub-systems and influence the whole system via negotiations with other software agents. While the complexity of an individual agent can be low, the intelligence level of the global system is high.
- Multi-agent systems implement distributed decision-making systems in an open, flexible and extensible way. Communications between actors can be minimized to a generic and uniform information exchange.
- By combining multi-agent systems with micro-economic principles, coordination using economic parameters becomes possible. This opens the possibility for the distributed coordination process to exceed boundaries of ownership. The local agent can be adjusted by the local stakeholder, and does not fall under the rules and conditions of a central authority.
- Using electronic markets a *Pareto efficient* system emerges, i.e. a system that optimizes on a global level, while at the local level the interests of all individual actors are optimally balanced against each other.

3. Earlier research

The combination of MAS and electronic markets yield distributed rational decision-making. For a good overview of the state of the art in this field, we refer to Sandholm [6]. The work on MAS and electronic markets for energy management as described in this paper builds further on earlier research on market-based control and market-based resource allocation for flow resources. Although these two research topics are closely interrelated, we treat the relevant work in these areas separately.

3.1 Market-based control

In market-based control, a large number of agents are competitively negotiating and trading on an electronic market, with the purpose to optimally achieve their *local* control action goals. In [12] the first agent research applications and simulations carried out under the heading of market-based control were brought together. Most early research was aimed at climate control in office buildings with many office rooms, where local control agents compete in the allocation of cool (or hot) air. (See e.g. [13, 14, 15, 16]).

Recently, a systems-level theory of large-scale intelligent and distributed control was formulated [1, 3]. This theory unifies microeconomics and control theory in a multi-agent theory, and subsumes the agent research applications and simulations as described above. A central result is the derivation of a general market theorem that proves two important properties about agent-based microeconomic control: (1) computational economies with dynamic pricing mechanisms are able to handle scarce resources for control adaptively in ways that are optimal locally as well as globally ('societally'); (2) in the absence of resource constraints the total system acts as collection of local independent controllers that behave in accordance with conventional control engineering theory.

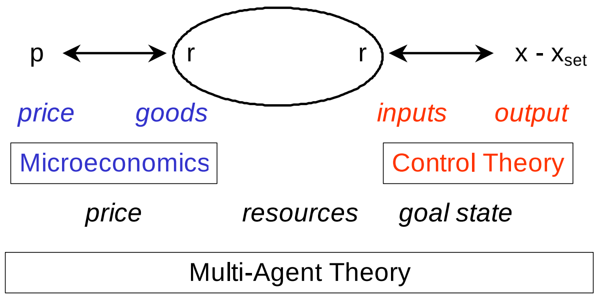

Figure 2: Microeconomics and control engineering unified in multi-agent theory [1].

3.2 Market-based resource allocation

Resource allocation in energy management systems is part of a special type of allocation problems, namely allocation of *flow resources*. An early paper on the use of market algorithms for power load management was published by Ygge and Akkermans [7].

Generally, market algorithms for solving flow-resource problems have two scalability problems: one regarding the number of participants in the market and the other regarding the interdependency in the participant's demand over time. Ygge and Akkermans solved the first problem. In their solution to the problem, the demand functions[2] of the individual agents are aggregated in a binary tree. Because of this, the computational complexity of the market algorithm becomes $O(\lg p)$, where p is the number of participants in the market. Furthermore, this opens the possibility for running the optimization distributed over a series of computers in a network in a way that fits nicely to power systems architectures [8, 9].

The second scalability problem, the one regarding the interdependency in the participant's demand over time is

[1] In this paper, we do not address the important issues of ICT security and dependability directly. We will treat these issues in future publications. For related work on this topic, we refer to [23, 24].

[2] In energy flow systems, supply can be seen as negative demand. Throughout this paper the term *demand* can be replaced by *supply* in case of electricity production.

harder to solve in such a way that the usability in the power field remains intact. One way of dealing with this problem is to ignore it and just suppose there is no interdependency between electricity used in different time periods. Then, a single-commodity market algorithm can be used, where the commodity is the amount of energy to consume in one time period. Then, the trading agents must totally rely on market price predictions in order to utilize flexibility in their demand over time. On the other end of the scale one could consider a multi-commodity market algorithm in which agents can formulate demand functions that are fully interdependent among the commodities. Here the commodities are amounts of energy to consume in a series of consecutive time periods. In this case the search space in which the market equilibrium must be found scales with $O(c^n)$, where n is the number of time periods and c a constant related to the resolution with which prices are expressed. This poses no practical problems as long as the number of time slots (n) is kept low (say, $n<5$). This scalability problem was partly solved by Carlsson and Anderson who propose a market algorithm that can handle demand functions which are tree-structured in the time-domain [10, 11]. Agents are able to express dependencies between bids in different time periods, but in a limited number of ways. This method reduces the search space dramatically and, thus, the scalability with respect to the number of time periods, at the cost of a reduced flexibility in the agent bids

4. PowerMatcher

4.1 Basic concept

The PowerMatcher is a market-based control concept for supply and demand matching (SDM) in electricity networks with a high share of distributed generation. SDM is concerned with optimally using the possibilities of electricity producing and consuming devices to alter their operation in order to increase the over-all match between electricity production and consumption. In the PowerMatcher method each device is represented by a control agent, which tries to operate the process associated with the device in an economical optimal way. The electricity consumed or produced by the device is bought, respectively sold, by the device agent on an electronic exchange market [2].

The electronic market is implemented in a distributed manner via a tree-structure of so-called *SD-Matchers*, as depicted in Figure 3. An SD-Matcher matches demand and supply of a cluster of devices directly below it. The SD-Matcher in the root of the tree performs the price-forming process; those at intermediate levels aggregate the demand functions of the devices below them. An SD-Matcher cannot tell whether the instances below it are device agents or intermediate SD-Matchers, since the communication interface of these are equal. The root SD-Matcher has one or more associated market mechanism definitions, which define the characteristics of the markets, such as the *time slot length*, the *time horizon*, and a definition of the *execution event* (e.g. “every whole quarter of an hour”, “every day at twelve o’ clock”). When an execution event occurs, the root SD-Matcher sends a request to all directly connected agents to deliver their bids. The device bids are aggregated at the intermediate matchers and passed on up-wards. The root SD-Matcher determines the equilibrium price, which is communicated back to the devices. From the market price and their own bid function each device agent can determine the power allocated to the device.

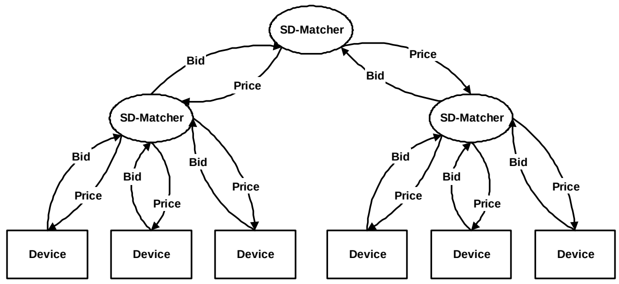

Figure 3: Hierarchy of supply & demand matchers in the PowerMatcher concept. The SD-Matchers implement a distributed electronic market.

4.2 Device agent types and strategies

From the viewpoint of supply and demand matching, devices can be categorized by their type of controllability into the following classes:

- **Stochastic operation devices:** devices like solar and wind energy systems of which the power exchanged with the grid behaves stochastically. In general, the output power of these devices cannot be controlled. For its bidding function the device agent must rely on short-term power predictions. Furthermore, it must accept any market price.
- **Shiftable operation devices:** batch-type devices whose operation is shiftable within certain limits, like (domestic) washing and drying processes. Processes that need to run for a certain amount of time regardless of the exact moment, like swimming pool pumps, assimilation lights in greenhouses and ventilation systems in utility buildings. The total demand or supply is fixed over time.
- **External resource buffering devices:** devices that produce a resource, other than electricity, that is subject to some kind of buffering. Examples of these devices are heating or cooling processes, which operation objective is to keep a certain temperature within two limits. Changing standard on/off-type control into price-driven control allows for shifting operation to economically attractive moments, while operating limits can still be obeyed (Figure 4). Devices in this category can both be electricity consumers (electrical heating, heat pump devices) and producers (combined generation of heat and power). Appliance of additional heat buffering devices can increase the operation flexibility of this type of devices substantially.
- **Electricity storage devices:** conventional batteries or advances technologies like flywheels and super-capacitors coupled to the grid by a bi-directional connection. Grid-coupled electricity storage is widely regarded as an enabling technology for increasing the penetration of distributed generation technologies at reasonable economic and environmental cost [19]. Grid-coupled storage devices can only be economically viable if their operation is reactive to a time-variable electricity tariff, as is present in the PowerMatcher concept. The device agent must try to buy energy at low prices and sell it later at high prices.
- **Freely-controllable devices:** devices that are controllable within certain limits (e.g. a diesel generator). The agent bidding strategy is closely related to the marginal costs of the electricity production.

- **User-action devices:** devices whose operation is a direct result of a user action. Domestic examples are: audio, video, lighting and computers. From the agent point of view these devices are comparable to the stochastic operation devices: their operation is to a great extent unpredictable and the agent must accept any market price to let them operate.

In all described device categories, agent bidding strategies are aimed at carrying out the specific process of the device in an economically optimal way, but within the constraints given by the specific process. Note that this self-interested behavior of local agents causes electricity consumption to shift towards moments of low electricity prices and production towards moments of high prices. As a result of this, the emergence of supply and demand matching can be seen on the global system level.

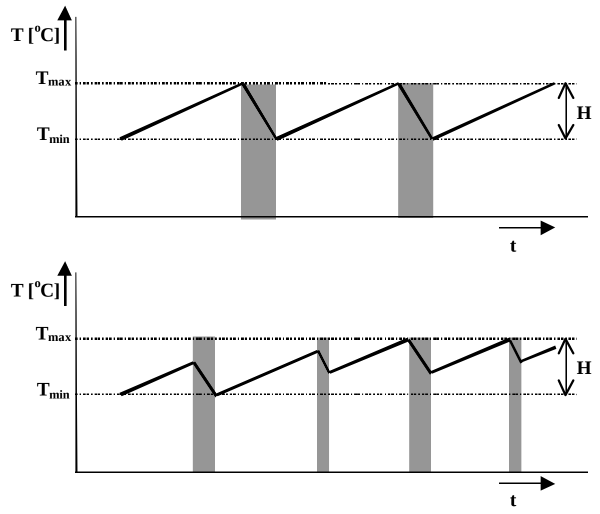

Figure 4: Operation shifting in a cooling process whilst obeying process state limits.

5. Simulation Case

5.1 Case description

In a simulation study the impact of distributed supply and demand matching applied in a residential area was investigated. In the study, a cluster of 40 houses, all connected to the same segment of a low-voltage distribution network (an LV-cell) were simulated. Each house has a *Home Energy Management* (HEM) box, which implements the local energy management strategy of the house (Figure 5). The HEM-box incorporates the intermediate SD-Matcher functionality, together with energy performance feedback to the user, and the possibility for the user to set cost and task preferences. The latter makes it possible to set agent parameters of devices without a user interface.

Within the LV-cell an exchange agent implements the root SD-Matcher. The LV-cell is externally connected to a medium voltage network. Through this connection power can be obtained form and delivered to other parts of the distribution network. The electricity surplus of the cluster is delivered to an external electricity supplier, which delivers electricity to the cluster in case of local shortage. The external supplier can either be a full player on the local electronic market or set tariffs for delivery and retribution. In the latter case, the external tariffs are not influenced by the local price formation, and, typically, the retribution price will be lower than the delivery price. Then, the equilibrium price on the local electronic market will be bounded by the external tariffs.

Half of the 40 simulated dwellings are heated by heat pumps (electricity consumers), the other half by micro-CHP units (small-scale combined heat-power, producers of electricity and heat). The micro-CHPs are also used for production of hot tap water. Washing machines are operated as shiftable operation devices with a predefined operational time window; electricity storage is present in the form of batteries; stochastic operation devices are present in the form of photovoltaic (PV) solar cells and small-scale wind turbines; and user-action devices are represented as lights.

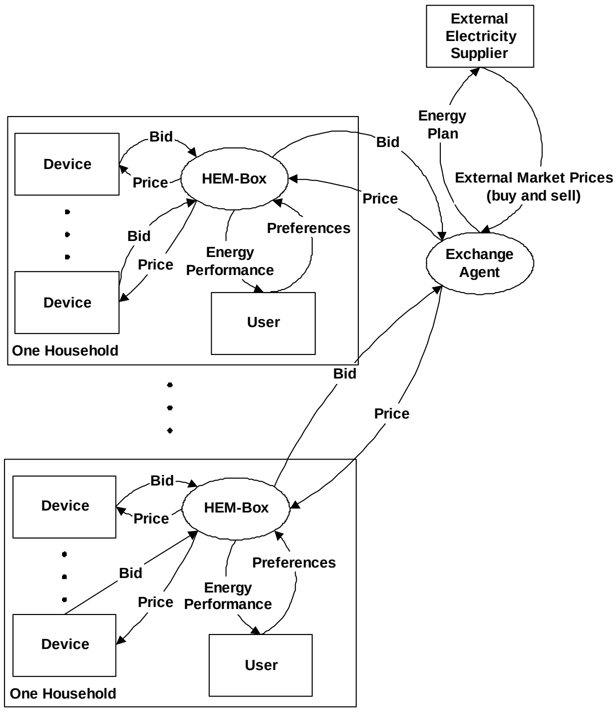

Figure 5: Set-up of the LV-cell simulation (see text).

5.2 Simulation result

Figure 6 and Figure 7 show the result of a typical simulation run for the LV-cell simulation case. In both plots the total consumption and the total production in the cluster have been summed into a single plotline, while production is regarded as negative consumption. The top plot shows the reference case in which all devices are free running. In this case all heating devices are on/off controlled, washing machines start their operation at the start of their operational time window, and batteries are excluded due to the absence of a real-time price signal according which they can be operated. In the bottom plot the SDM-controlled case is shown. Interesting features are:

- Around the 25th 15 minutes period there is a peak in electricity demand caused by the simultaneous starting of a number of heatpumps. Although there is also a small peak in local production at that moment, the greater part of the electricity needed to meet the peak demand is delivered from the external connection to the mid-voltage network. In the SDM-controlled case the peak in external feed-in is 30% lower, due to the reaction of different devices to the price peak on the electronic market at that moment. Consuming device agents shift part of their operation to other moments in time, producing agents shift as much as production as possible to this moment, and battery agents react by switching to discharging mode. In this particular case, consumption reduction accounts for 50% of the peak reduction, battery discharging accounts for 37%, and production increase causes another 13%. From the viewpoint of electricity distribution systems, this is an important result. The highest expected peak demand of a low-voltage net segment determines the capacity the coupling transformer and the network cables or lines. Reducing the peak demand lowers network investments in case of building new sub-networks, and defers network reinforcements in case of demand increase in existing nets.

- Introducing supply and demand matching results in a more flat and smooth profile of the electricity fed in from the mid-voltage network. Fluctuations in local consumption and local production are damped, and the mutual simultaneousness in the remaining fluctuations is high. The standard deviation of the feed-in from the MV-net in Figure 6 is 58% lower in the SDM-controlled case.

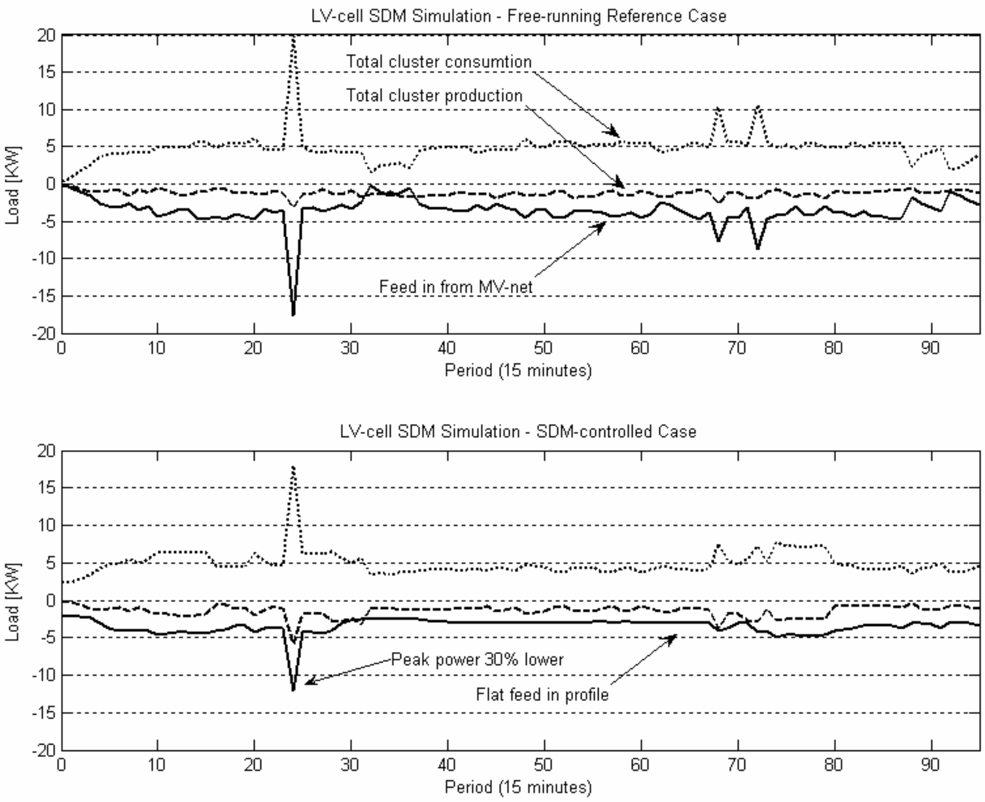

Figure 6: The result of a typical simulation run for the LV-cell simulation (see text).

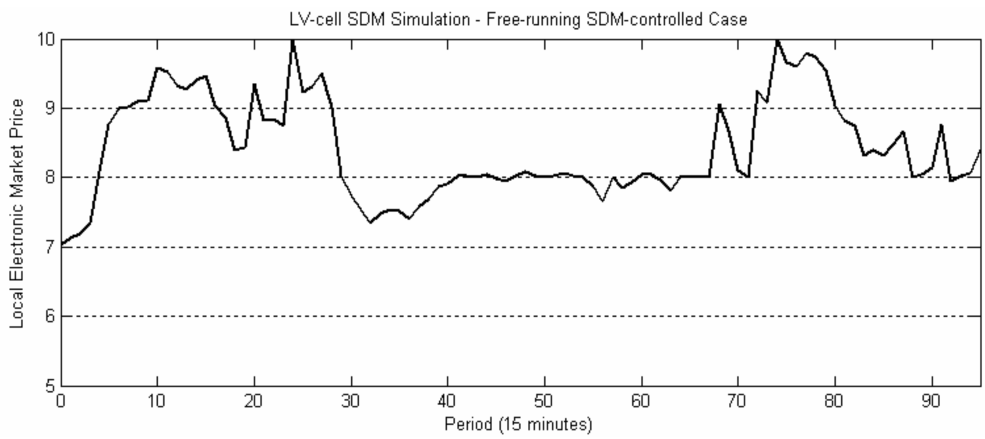

Figure 7: Price development on the electronic market.

6. Field experiment

6.1 Background: balancing responsibility

In countries with a deregulated energy market like the United Kingdom, The Netherlands and the Scandinavian countries, the bigger market parties (those that make use of the transport services of the independent network operators) are obliged to make daily plans for production, transport and consumption of electricity. These plans have to be handed in at the so-called transport system operator (TSO), the operator of the high-voltage electricity network. In The Netherlands these plans have to be handed in before 12:00 hours and plan the 24-hours period starting at the next midnight with a resolution of 15 minutes.

The TSO uses all these plans to ensure the stability of the electricity network. For the sake of this stability, it is important that every balancing responsible party sticks to her own plan. To enforce this, each party that has a deviation from his plan (*imbalance*) is charged for it. These charges are referred to as *imbalance costs*.

6.2 Reducing imbalance costs by SD-Matching

Balancing responsible parties with a high share of wind energy in their production portfolio are faced with extra costs due to the stochastic behavior of wind energy production. Within the EU-funded research project CRISP, a field experiment is currently being prepared in which the aggregated imbalance of a cluster of medium-sized electricity producing and consuming installations is minimized by using the market-based control concept of the PowerMatcher.

The objective of the field experiment is formulated as: “real-time monitoring and control of electricity supply and demand in a commercial setting to avoid short term market imbalance due to intermittent renewable energy sources”. Secondary aim of the experiment is to test the ICT elements needed for implementation of Supply and Demand Matching mechanisms in a real-life environment.

The experiment will run for a full year from April 2005 onwards. The first results of the experiment are expected to be available mid July 2005.

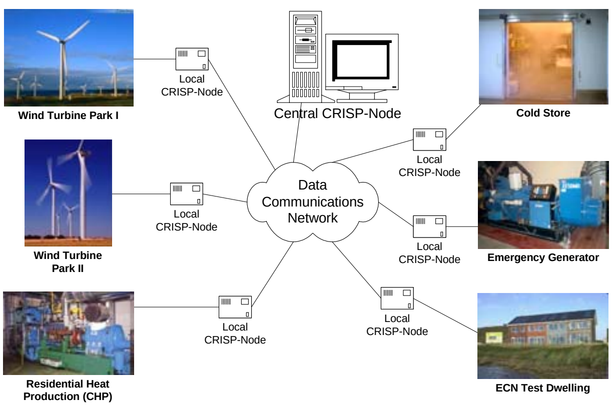

Figure 8: Set-up of the CRISP Supply and Demand Matching field experiment.

7. Conclusion

7.1 Future Research

Future research will include:

- Assessment of different business cases in which the PowerMatcher is beneficial to stakeholders at a local level as well as at a global level. Simulation and implementation studies for selected business cases.
- Investigation of different market configurations:
    - Time-ahead planning by using multi-commodity market algorithms.
    - Stacking of market mechanisms with different characteristics, e.g. a day-ahead market mechanism with 24 one-hour timeslots combined with an hour-ahead market of four slots of 15 minutes.
- Investigation of the use of MAS and electronic markets for *virtual power plants* (VPPs). VPPs are aggregations of small and medium-sized electricity producing and consuming devices acting as a normal conventional power plant.

7.2 Conclusions

Various drivers push the production of electrical power in the current electricity infrastructure towards decentralization. Multi-agent technology and electronic markets form an appropriate technology to solve the resulting coordination problem. The PowerMatcher concept proposed in this article is a market-based control concept for supply and demand matching (SDM) in electricity networks with a high share of distributed generation.

The presented simulation case shows that this concept is capable of utilizing flexibility in device operation via agent bids on an electronic power market. Via agent reactions on price fluctuations, the simultaneousness between production and consumption of electricity by devices in a sub-network is increased. As a result, the net import profile of the sub-network is smoothed and peak demand is reduced, which is desired from a distribution network operational viewpoint. Further, a field experimental setup in which the PowerMatcher concept will be tested in a real-life environment is presented.

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