ARCHITECTURE AND PRINCIPLES OF SMART GRIDS FOR DISTRIBUTED POWER GENERATION AND DEMAND SIDE MANAGEMENT

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Abstract: The main goals of smart grids are to provide an interface for fair transaction of electricity and to optimize the power flow in electric power networks with less required extra energy storages, particularly in case of integration of renewable energy sources (e.g. photovoltaic and wind) and the plug-in Hybrid Electric Vehicles. Currently, the control principles in smart grids are mainly market-oriented (e.g. agent-based control and event based control), which do not really take into account the constrains of electric power networks. Moreover, the response time of coordination and control via ICT infrastructure might be significant (few seconds to several minutes). Therefore, the architecture and control principles of smart grids have been enhanced and presented. Particularly the concept of virtual agent has been introduced, which interacts the business model of smart grids (e.g. agent based control) to optimize the power flow. Additionally the time shift-able sources/loads of office buildings (e.g. plug-in hybrid electric vehicles) are treated as another means of grid control. The evaluation results verify the architecture and control principles which are presented in this paper.

1 INTRODUCTION

Nowadays the scale of integration of RES (renewable energy sources) as distributed power generation (Carrasco et al., 2006; Roman et al., 2006; Romero-Cadaval et al., 2009; Timbus et al., 2009; Cheng and Lataire, 2005) and plug-in HEVs (hybrid electric vehicles) as mobile loads [6] into the existing electric power networks is gradually increasing to target the goal of 20, 20 and 20. Due to the nature of intermittent power production of RES (e.g. photovoltaic and wind energy) and the un-predictable but maybe high power demand from Plug-in HEVs, there will be notable consequences in the electric power distribution networks (Cheng, 2011; Ueda et al., 2008; Morren and de Haan, 2009; Bletterie and Pfajfar, 2007; Souto Perez et al., 2007). For instance, over voltage, voltage flicker, poor reliability and other power quality problems.

Recent years, the technologies of smart grids are quickly developed to coordinate and control power systems via ICT infrastructures (e.g. power shedding, peak shaving) (Cheng, 2011a; Cheng, 2010; Gungoret al., 2010; Cheng, 2011b). In order to achieve the local power balance, the time shift-able power sources and loads are driven by micro-economics. For example, some refrigerators, washing machines and water boilers will be delayed switching-on, and Micro-CHPs will start to generate electricity, if the price of electricity is high. The main advantages of smart grids (coordination and control power system via ICT infrastructure) are to create a platform for the implementation of financial incentive and for efficiently using the existing resources in electric power networks (e.g. energy storages). However, the power balance based on the ICT infrastructures is in fact to balance the average power within each time interval (e.g. 5 min, 10min, 15 min), and it can have a long response time. Until now, the implementation of business model does not really take into account the constrains in the electric power networks. Moreover, the power variation of renewable energy sources (e.g. PV) can be almost 100% of the peak power within only few seconds in the electric power distribution networks.

In order to limit the impact of the integration of

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renewable energy sources and electric vehicles into the existing electric power networks, power difference must be limited in the different time scales (Cheng, 2011b). The possibly time shift-able sources and loads of office buildings and dwellings can be used as the means of grid control. In addition, supercapacitors can also be applied as the peak power unit (Cheng, 2011b) and (Cheng, 2009), to ensure the stability and reliability during the transient state (around 1min) of the demand side power management (which is based on ICT infrastructure). Further islanding mode of microgrids and seamless switching between islanding mode and grid-connected mode are also expected (Cheng, 2009; Guerrero et al.2011, Balaguer et al., 2011). In this case, the corresponded control principles are very important and have been developed(Cheng, 2009; Guerrero et al.2011, Balaguer et al., 2011; Cheng, 2004; Guerrero et al., 2008; Vasquez, 2009; Iwanski and Koczara, 2008; Guerrero et al., Pai et al., 2010; Zhong et al., 2011; Yuen et al., 2011; Zhou and Francois, 2011)).

In this paper, first the architecture of smart grids is presented. Then the control principles of smart grids in particular, the agent-based control and event-based control are introduced. In addition, the principle of virtual agent for power flow optimisation and control in smart grids is also explained. After that, the characteristics of smart grids in function of electricity price are assessed. Further the system dynamics perspective (due to the long response time of coordination and control via ICT infrastructure) and improvement by using the controllable sources and loads in office buildings (e.g. super capacitor storage and plug-in electric vehicles) are explored. Finally, the architecture and principle of smart grids are evaluated. The evaluation results prove that the architecture and principles can be applied to optimize the power flow in the electric power distribution networks.

2 ARCHITECTURE OF SMART GRIDS

Smart grid is the intelligent electric power network, which can achieve the goals of fair transaction of electricity and at the same time reducing the peak power and maximally supplying local loads from the distributed power generators (e.g. renewable energy sources), to efficiently use the electric power networks. In order to verify the benefits of smart grids, the architecture of smart grid can be presented as in Fig.1, where the market based operation in distribution networks is established. In smart grids, there must be certain percent individual power sources and loads being time shift-able and controllable. These sources and loads can be represented by their agents to their preferable ARP (access responsible party) and act in the auction-based market; or they simply respond in the tariff-based market. DSO (distribution system operator) will play the role of SR (settlement responsible) in the distribution network besides smart metering and providing the measurements to TSO (transmission

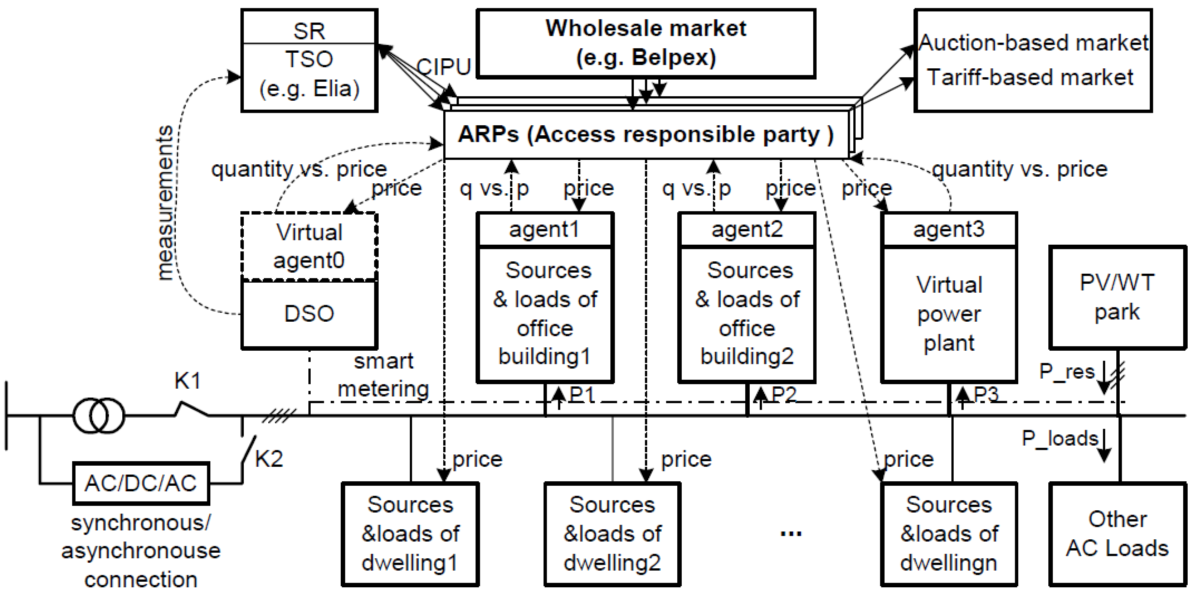

Figure 1: Architecture of a smart grid.

system operator) for the existing market in transmission networks. In Fig. 1, the possible sources and loads of office buildings can be little big renewable energy systems and electric vehicle charging station as in Fig.2. The DC/AC inverter can be thought as the time shift-able AC sources/loads, while there are also time un-shiftable AC sources/loads in the office building.

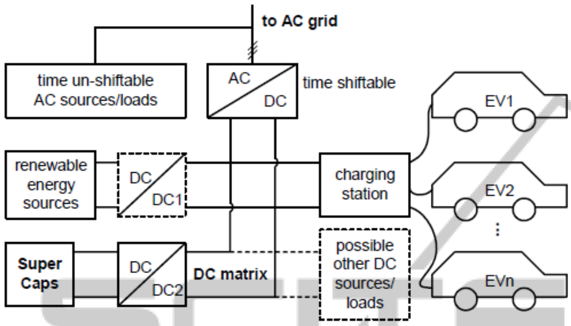

Figure 2: The possible sources and loads of office building.

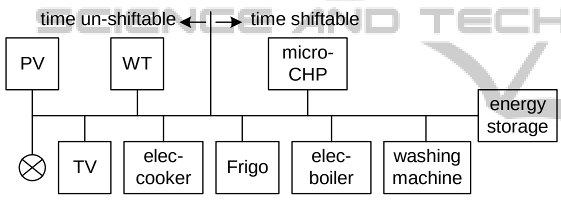

Figure 3: The possible sources and loads of dwelling.

In Fig. 1, the possible sources and loads of dwellings can be photovoltaic (PV), small wind turbine (WT), micro-CHP, lamps, TV, electric-cooker, refrigerator, electric-boiler, washing machine and energy storage as in Fig.3. Some of them are time shift-able (right part), while others are not (left part).

This emulated smart grid (as in Fig. 1) can be in synchronous (K1=on and K2=off) or in asynchronous connection (K1=off and K2=on) with the main grid. The high power rating PV or/and wind turbine (PV/WT park) can also be integrated. The power flow from these renewable energy systems is the disturbance in the grid control. Therefore, the control principles of smart grids are very important in the different time scales for distributed power generation and demand side management.

3 PRINCIPLE OF SMART GRIDS

If there are more generators and loads are time shift-able, then the electric power networks become more controllable. This is being achieved by government incentive now and by market based operation model in near future. The time shift-able sources and loads of office buildings and dwellings can be in agent-based control or in event-based control. In order to simplify the presentation in this paper, the controllable sources &loads of office buildings are assumed to be in agent-based control for auction-based market operation; and the controllable sources &loads of dwellings are assumed to be in event-based control only for tariff-based market operation. For the purpose of settlement responsible and optimisation of power flow in smart grids, a virtual agent is also presented from DSO as explained in sub-section3.3.

3.1 Agent-based Control in Auction Based Market

The goal of agent-based control in auction based market is to achieve the equilibrium between the demanded quantity and the supplied quantity in price-quantity pair in microeconomics way. The principle of agent-based control in smart grids is as in follows. Each agent of the controllable source and load sends a quantity vs. price pair to ARP as in Fig. 1. For example, the quantity vs. price of agent1, the quantity vs. price of agent2 and the quantity vs. price of agent3 are shown in Fig. 4, Fig. 5 and Fig. 6 respectively.

Figure 4: Quantity vs. Price pair of agent1.

Figure 5: Quantity vs. Price pair of agent2.

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Figure 6: Quantity vs. Price pair of agent3.

Figure 7: Quantity vs. Price pair of agent0.

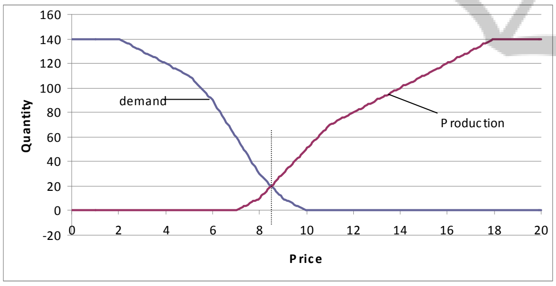

Figure 8: Power demand and power production balance at price=8.5.

The sent quantity vs. price pair of each agent represents its capacity of power production and power consumption at each time. Here, agent1 has a zero quantity around 7 cent; agent2 has a zero quantity around 8 cent; and agent3 has a zero quantity around 9 cent. The maximum capacities of power production and power consumption of these three agents are saturated at 20 kw in this paper (but not necessary to be the same and symmetrical in the real case). The presented virtual agent0 in Fig. 1 sends a quantity vs. price as in Fig. 7 for the optimization of power flow in the distribution power network. (This will be explained in sub-section 3.3) According to the quantity vs. price of each agent, the server in auction based market finds the total demand quantity vs. price of the agents and the total production quantity vs. price of the agents. As a result, the crossing point of the power demand vs. price and the power production vs. the price can be found in Fig. 8. After that the price is sent via ARP to each agent. According to the price of electricity and the quantity vs. price pair of each agent, an agreement of power production or consumption of each agent with ARP is established for next time interval (e.g. 15min). As a result, the average power per time interval (e.g. 15min) between the time shift-able sources and the time shift-able loads can be balanced in auction based market. ARP is also responsible for the integration of renewable energy sources. But the power production of renewable energy sources and the power consumption of other loads are not always predictable. Even they can be highly fluctuated. Indeed, the goal of ARP is to get maximum profit. Therefore, ARP will optimize the power exchange within micro-grid as well as with the main grid. In this case, besides the auction based market, the tariff based market is also required to limit the difference between the predicted power and the measured power.

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3.2 Event-based Control in Tariff Based Market

Not all of the time shift-able sources and loads necessarily send the quantity vs. price pair to ARP. Some of them only need to respond on some events. For instance, the change of electricity price or/and the change of frequency. In this case, the controllable sources and loads are in event-based control. For examples, the water boiler, washing machine refrigerator can be the event-based controllable loads; whilst micro-CHP can be the event-based controllable source. In general, the demanded power will de decreased and the supplied power will be increased if the price of electricity is increased; or vice versa. So event-based control can be used for reconciliation of power imbalance. Consequently a tariff based market is created by ARP. On the participants' side, each moment of switching on/off the time shift-able devices/systems can be based on the change of the electricity price from tariff based market or/and the change of the frequency with consideration of the original functionalities of these systems. In the first instance, according to the electricity price some household devices or systems can be switched on or off at the right time for the financial profits. In the second instance, according to the electricity frequency some distributed power generators and some time shift-table loads can also be controlled to generate or consume a suitable power for the power system stability(in this instance, the time scale will be in ms and it is based on the local measurement). One should be aware that the average power between the time shift-able sources and the time shift-able loads in event based control is not necessarily equal.

3.3 Virtual Agent for Optimization of Power Flow in Electric Power Distribution Networks

The main interest of market operator and participators is their maximum profit. As a consequence, an offset of power flow is generated due to the tariff based market, but optimized power flow in electric power distribution network is still not ensured. Therefore, DSO needs to take the role of settlement responsible and take care of the constrains in electric power distribution networks, to ensure power quality and to minimize the losses.

In this paper, we assume that a virtual agent0 as in Fig. 1 is presented from the distribution system operator (DSO) to the ARPs. As the strategy of the distribution system operator is to efficiently use the distribution networks and to have some financial profit, the optimization of power flow in the electric power distribution network will be done with respect to the power flow in the electric power distribution networks and the real-time price of electricity in transmission networks.

Nowadays the price of electricity in the electric power transmission networks is transparent. For example, Belpex is the Belgian Power Exchange for anonymous, cleared trading in day-ahead electricity, providing the market with a transparent reference price. In this case, DSO will interact with the market based operation model as in Fig. 1. According to the measurements from the smart meter(s), DSO will also send the quantity vs. price pairs via the virtual agent to ARPs. As a result, there will be an additional offset of power flow. Properly changing the quantity vs. price pairs via the virtual agent, DSO will optimize the power flow in smart grids.

However, one should be aware that shifting the quantity vs. price pair in the market based operation model is not free action. Unlikely ARP will still have the maximum profit if DSO shift the power flow. Maybe DSO needs to compensate the financial losses to ARP. So there is a trade-off between the benefit of power optimization and the cost of shifting the quantity vs. price pair in market based operation model. This will be a main concern of DSO if DSO will take the role of settlement responsible in the electric power distribution networks.

During the execution phase of market based operation, the demand side management will limit the difference between the expected power and really produced/consumed power of the distributed power generators or loads, to ensure proper operation in auction based market as well as reconciliation of power imbalance in tariff based market. In this market based operation model of smart grids, both the market operators and participants have the opportunities to gain their profits and face competitions.

4 CHARACTERISTICS OF SMART GRIDS IN FUNCTION OF ELECTRICITY PRICE

Due to the time shift-able sources and loads under agent-based control or event-based control, the characteristics of smart grids will be changed. The difference of average power (in the time scale about several seconds to few minute) between the generated power and the demanded power will gradually be optimised towards to be as the expected.

In this section the characteristics of smart grids as the function of electricity price will be explored. This can be done by the interaction between the virtual agent and the server of smart grids. First the quantity vs. price pair of the virtual agent0 is shifted from left to right, and then it is shifted from right to left. In fact this procedure will also assess the controllability and reachability of the smart grids under certain amount time shift-able loads and with certain amount time shift-able sources. When the quantity vs. price pair of virtual agent0 is maximally shifted to right (increasing price) as in Fig. 9, the maximal power production of the distributed power generators (in agent-based control) is reached. As a result, the power balance reaches the saturation point at price equal to 11 cents as in Fig. 10.

Figure 9: Quantity vs. Price pair of agent0 maximally shifting to right (increasing price).

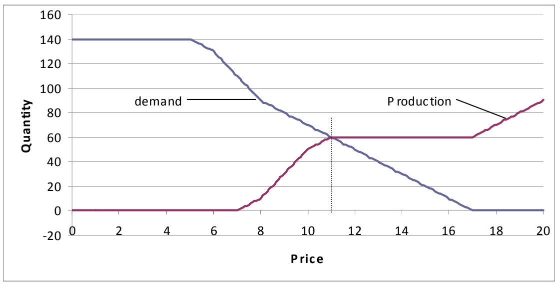

Figure 10: Power demand and production balance saturated at price=11 (reach maximal power production).

Figure 11: Quantity vs. Price pair of agent0 maximally shifting to left (decreasing price).

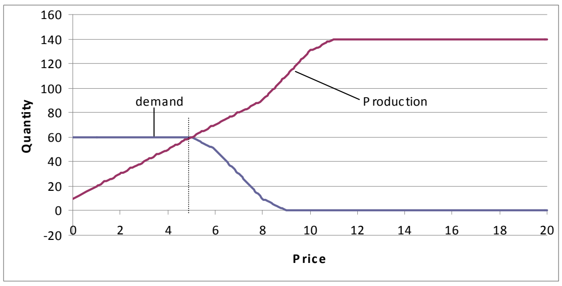

Figure 12: Power demand and power production balance saturated at price=5 (reach maximal power demand).

When the quantity vs. price pair of virtual agent0 is maximally shifted to left (decreasing price) as in Fig. 11, the maximal power demand of the loads (in agent-based control) is reached. As a result, the power balance reaches the saturation point at price equal to 5 cents as in Fig. 12.

In both cases, the maximal power production or power demand in agent-based control is 60 kW, which corresponds to the maximal capacity of power production or consumption of agent1, agent2 and agent3 as shown in their quantity vs. price pairs in Fig. 4, Fig. 5 and Fig. 6. In this way, the controllability and reachability for the optimization of power flow in smart grids are determined.

5 SYSTEM DYNAMICS PERSPECTIVE AND IMPROVEMENT WITH SUPER CAPACITOR STORAGE

Indeed, the curve of demanded power in the function of price and the curve of supplied power in the function of price are always shifted due to the change of the real situation in smart grids. This can logically be classified as the case of demand curve shifting as in Fig. 13 and the case of supply curve shifting as in Fig. 14, though they can be happened in the same time.

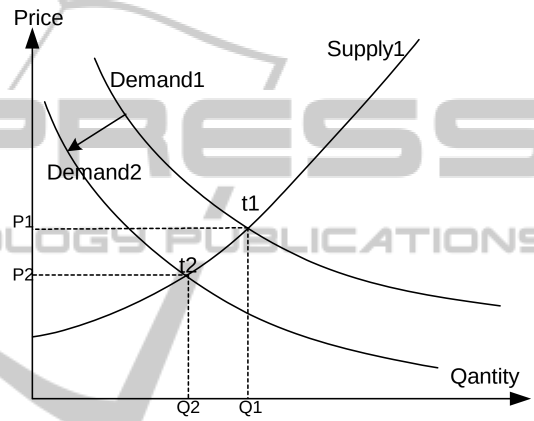

Figure 13: Demand curve shifting.

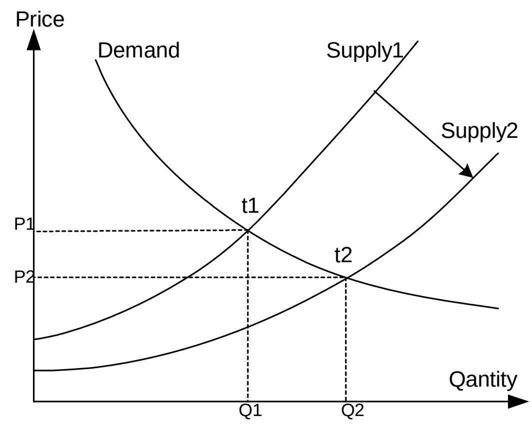

Figure 14: Supply curve shifting.

Assuming the supplied power in the function of price is unchanged, and if the load characteristics are changed, then the demanded power in the function of price will be shifted. For example, the total loads in the smart grids can be decreased from the price and quantity at the time t1 (P1, Q1) to the price and quantity at the time t2 (P2, Q2) as in Fig. 13.

Assuming the demanded power in the function of price is unchanged, and if the total capacity of power generators is changed, then the supplied power in the function of price will be shifted. For example, the total capacity of the distributed power generators in the smart grids can be increased from (P1, Q1) to be (P2, Q2) as in Fig. 14.

As it takes time to achieve a new equilibrium (P2, Q2) from the old equilibrium (P1, Q1), there is a transient state of demand side power management via ICT infrastructure. In this case the demand side management has to be in cooperation with the proper operations of intelligent power converters with energy storage system, to limit the high power difference within short time duration, particularly if there are large scale integration of renewable energy sources and big un-predictable loads. Only if there is sufficient inertia in the electric power networks, stability, reliability and power quality can be ensured. In this case, the possible controllable sources and loads of office building as in Fig.2 can be treated as means of grid control, which generate the required damping in the electric power networks, to allow the demand side management functioning well via the communication network(s).

In the presented architecture of smart grid as shown in Fig. 1, the super capacitor storage is installed with the possibly controllable DC sources and loads of office building as in Fig.2. Accordingly the control principles of the converters have been developed (Cheng, 2011b), (Cheng, 2009). The DC/AC inverter as in Fig.2 is the distributed power generator in smart grid. The distributed power generators will supply the power for the local loads, and they ensure the power quality and grid stability in smart grids. During the transient state of demand side management (via ICT infrastructure), power balance in the smart grid will be achieved by the DC/AC inverter with the possibly controllable sources and loads of office buildings as in Fig.2. According to the real situation in the smart grids, the DC/AC inverter can be operated in power despatching mode or/and in load following mode. In the power despatching mode of the DC/AC inverter, the peak power from renewable energy sources will be filtered by super capacitors, then to charge the batteries of EVs; only the moving average power will be injected into the AC grid (via the DC/AC inverter). In the load following mode of the DC/AC inverter, the high power difference (on the AC side) will immediately be compensated by the super capacitor storage. In addition, reducing the charging power of the on-board batteries of EVs can have some additional power to follow the power demand on the AC side. In this case, power balance can be achieved in long time scale as well as in short time scale in smart grids.

6 EVALUATION RESULTS

In order to verify the architecture and principles of smart grids (which are presented in this paper), the change of power vs. real-time price of electricity is evaluated. The power flows from agent1, agent2 and agent3 are P1, P2 and P3 respectively. In order to simplify the presentation in this paper, only the influence of agent-based sources and loads is shown here. The power injection from renewable energy sources P_res minus the fluctuated loads P_loads is

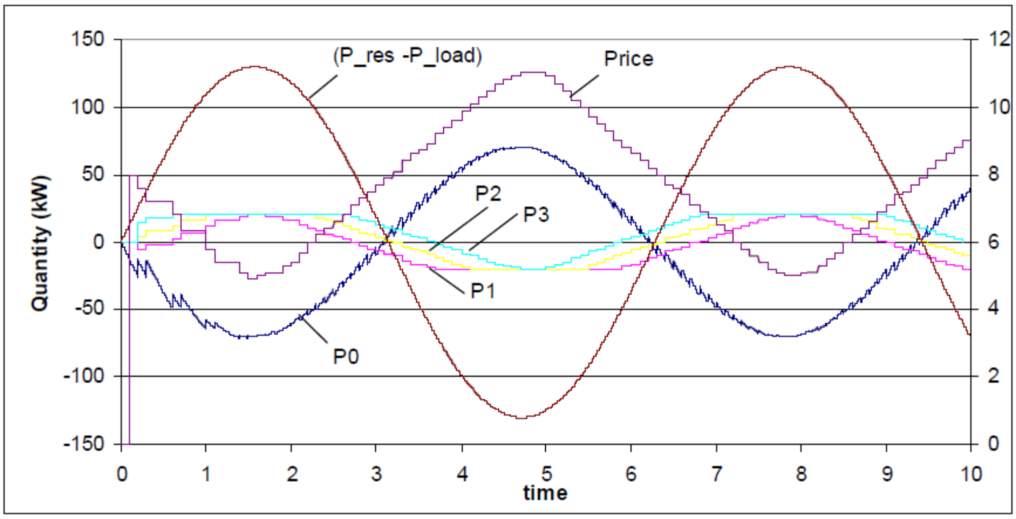

Figure 15: Evaluation results of the principle of power management in smart grids.

used as the disturbance (P_res-P_loads) in the smart grids as in Fig.1.

The evaluation results are presented in Fig. 15. One can see that the maximal power of the renewable energy sources minus other loads is 130kW, but the maximal power of agent0 (through transformer) is only 70kW. This evaluation results prove that the architecture and principles (in particular the virtual agent as presented in this paper) can optimize (flatten) the average power flow in the electric power distribution networks.

7 CONCLUSIONS

Market based operation in smart grids will ensure fair transaction of electricity and enable more time shift-able sources and loads involving in the reconciliation of power imbalance. Particularly, agent-based control and event-based control in smart grids will change the characteristics of electric power networks.

However, the power balance only between the sources and the loads in agent-based control is not sufficient to guarantee an appropriate power flow in the electric power distribution networks. By introducing a virtual agent, the principle of power management in smart grids has been enhanced and presented in this paper. The evaluation results show that the average power flow in case of the integration of renewable energy sources and fluctuated loads can effectively be optimized by applying our method of power management.

As there is a significant response time in demand side management (via the ICT infrastructures), short duration energy storage might be required, to ensure the power quality in the smart grids, if the power fluctuation due to the renewable energy sources (e.g. PVs) or/and other fast varied loads is significant. In this case, the possibly time shift-able and controllable sources and loads of office building (e.g. plug-in electric vehicles with super capacitors) can be treated as another means of grid control. As a result, power balance in smart grids can be achieved in the different time scales with less additional energy storages.

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