MASTER

Dispatching power and ancillary services in autonomous network-based power systems

Agovic, K.

Award date:
2005

Eindhoven University of Technology
Department of Electrical Engineering
Control Systems

technische universiteit eindhoven

Dispatching Power and Ancillary Services

in Autonomous Network-based Power Systems

K.Agovic

Master of Science thesis

Project period: 25.01.2005-28.11.2005
Report Number: 05A/11
Commissioned by: Prof. Dr. Ir. Van den Bosch

Supervisor: A. Jokic

Additional Commission members:
A. Ishchenko (TU/e)

Dispatching Power and Ancillary Services in Autonomous Network-based Power Systems

K.Agović, A.Jokić, P.P.J.van den Bosch

***Abstract*—Competition is being introduced in the electricity markets worldwide. In addition, large penetration of distributed generation introduces new players into the markets and significantly increases the uncertainties in the system. The concept of autonomous power networks is a realistic approach to deal with increased uncertainty and complexity in future power systems. An autonomous power network is the aggregation of producers and consumers presented in the overall power system as one unit. This paper formulates the autonomous network dispatching optimization problem in rather general form and illustrates its efficiency. The number of trade-offs that are included at the forward time energy and ancillary service markets are outlined and discussed.**

***Index Terms*--Power system dispatch, autonomous networks, electricity markets, ancillary services.**

I. Nomenclature

P_i	Power generated from controllable unit i [MW].
$P_{i,min}$	Minimal amount of power generated from controllable unit i [MW].
$P_{i,max}$	Maximal amount of power generated from controllable unit i [MW].
$\tilde{P}_j$	Predicted power from renewable unit j [MW].
$\Delta\tilde{PL}$	Measure of aggregated uncertainty of predicted values for loads and power production from renewable sources inside the Autonomous Network [MW].
P_{ex}	Power that is allocated for sale to the outside grid or that is bought from the grid [MW].
A_i, (B_i)	Capacity of unit i scheduled for the ancillary service A (B) [MW].
$A_{i,max}$, ($B_{i,max}$)	Maximal capacity of unit i available for the Ancillary Service A (B) [MW].
A_{ex}, (B_{ex})	Power of an Autonomous Network traded as the ancillary service A (B) [MW].
A_{req}, (B_{req})	Minimum required capacity of A (B) [MW].
$\tilde{L}$	Predicted load in the autonomous network [MW].
L_A, (L_B)	Capacity of load serving as ancillary service A (B) [MW].
$\tilde{\lambda}_P$	Predicted market price of P_{ex} [€/MWh].
$\tilde{\lambda}_A$	Predicted market price of A_{ex} [€/MWh].
$\tilde{\lambda}_B$	Predicted market price of B_{ex} [€/MWh].
$C_i(P_i)$	Costs function of P_i [€/h].
$C_i(A_i)$	Costs function of A_i [€/h].
$C_i(B_i)$	Costs function of B_i [€/h].
$C(L_A)$, ($C(L_B)$)	Payment to controllable load that can be used as capacity for ancillary service A (B) [€/h].
c, nc	c denotes the set of controllable units, nc the set of non-controllable units.

II. Introduction

POWER SYSTEMS are changing significantly in many aspects. One of the major changes is the large penetration of renewable energy sources, which significantly increases the uncertainties in a network and calls for new solutions and approaches in the power systems operation and control. Due to these changes, the electricity industry is evolving into a distributed and competitive industry in which market forces tend to drive the price of electricity and reduce the costs through increased competition. In electricity markets, two objectives remain central, ensuring a secure operation and facilitating an economical operation. Unbundling of energy from security (ancillary services) through decentralized, competitive market mechanisms should enhance the reliability of the power systems through its economics. Proper competitive markets and strategies based on power system requirements stimulate the competition among the suppliers and among the consumers, which results in optimal energy prices for consumers and producers. All market participants are facing an important task of bidding energy to an Independent System Operator (ISO). Modeling and solving the bid selection process by the ISO has been discussed in [1], [2] and [3]. In [4], bids are selected to minimize total system costs while the Market Clearing Price (MCP) is determined as the price of the highest accepted bid. In [5],[7] and [8] a bid-clearing system is presented. Detailed models are used, including network, reserve, and ramp-rate constraints, and the problem is solved by using linear programming. In [6], the dynamics of pricing is considered in market power assessment.

The purpose of this paper is to formulate and present the concept of Autonomous Network (AN) based power system as a realistic approach of the future power systems where each AN will be facing the optimization problem. By solving this problem in a rather general form, this paper enables and illustrates market based operation and optimization for both dispatch (economic) and ancillary services (reliability). The concept of autonomous power networks is a realistic approach to deal with increased uncertainty and complexity in future power systems. Each AN is an aggregation of physically connected producers and consumers in a relatively small area [9].

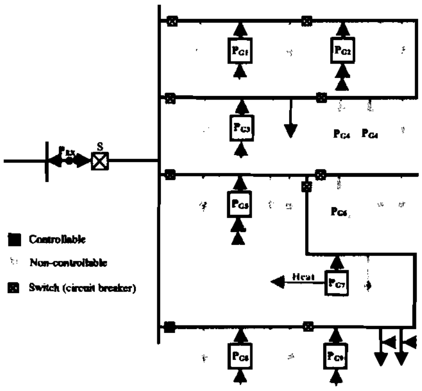

Fig. 1: Illustration of an autonomous power network.

There can be a large variety of units inside an AN as illustrated in Fig. 1, for instance: fuel cells, combined heat and power units, micro turbines, wind turbines, photovoltaic systems etc. Despite this variety, to the overall power system each AN is presented as one producer/consumer for the outside market. Due to aggregation each AN, if efficiently operated, has a rather uniform and predictable behavior. Therefore, it is able to compete more efficiently in the outside market. For example, an AN can make more trusted bids to the outside market than a wind turbine alone. The concept of ANs offers several interesting possibilities that can be expressed through an optimization problem. For instance, a AN market agent can reserve some minimum amount of spare capacity so that successful transition to island operation is possible at any time.

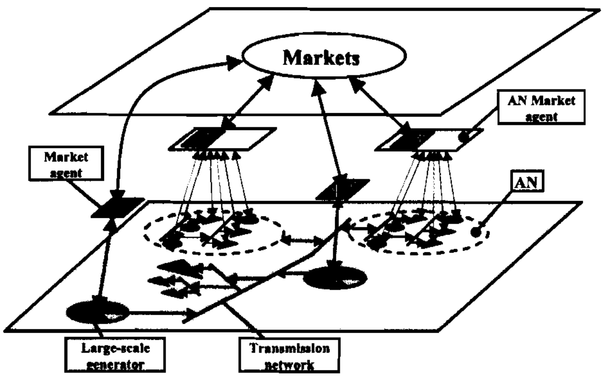

Fig. 2: Autonomous Network market agent in an overall system.

Figure 2 illustrates future power system structure with AN as its major building block. An AN market agent is required to submit bids for energy market and Ancillary Service (AS) markets while optimally deploying its internal resources.

III. INTEGRATION OF THE AUTONOMOUS NETWORKS IN THE (DAY) AHEAD MARKETS

In this section, we formulate AN dispatching optimization problem in rather general form. The emphasis is on the number of trade-offs that AN is facing in its desire to make the optimal decisions with respect to its involvement in the outside markets. Outside markets in this paper are considered as competitive markets for energy and ancillary services among ANs with the objectives to ensure a required reliability level of power system. Since each AN is a small power system of its own, it is clear that in the decision making process it has a relatively large amount of degrees of freedom, i.e. decision variables in optimization problem. Occurrence of trade-offs is natural since it is competing in all of the outside markets, i.e. real power and ancillary service markets, and since the offers in one market influence the offers to the other markets. This multi-market "dilemma" is no novelty, since any producer is facing similar trade-offs. However, making optimal decisions for AN is much more complex than that of, for instance, single power plant. This is caused by the fact that, in scheduling of produced commodities, AN market agent has to decide whether and in what quantity should specific commodity be allocated for internal usage (inside AN), and what amount of the same commodity should be sold/bought from the outside market, i.e. from other ANs. For illustration, AN can decide to allocate a larger amount of its fast available spare capacity for internal usage, allowing it to sell (or buy) reliable, but more expensive real power exchange to (from) the outside market. This required level of reliability is prescribed by the required total accumulated amount of each of the commodities. For instance, hourly spinning reserve requirements are usually defined to be the grater of a fixed percentage of total forecast demand and the largest on-line unit. By assuring this capacity the AN is a reliable individual in the overall market. If the AN market agent decides to buy this capacity from other ANs it can deploy other units e.g. to sell more real power. If the optimal decision is to provide this capacity from own resources, the AN remains with less trading power for power and/or ancillary services markets. This, and several other trade-offs are formulated in form of constrained optimization problem. Here we present one possible problem formulation and discuss some of its features.

Consider the following optimization problem

$$\max_{\substack{P_i,A_i,B_i,\\ L_A,L_B}} \left\{ \tilde{\lambda}_P P_{ex} + \tilde{\lambda}_A A_{ex} + \tilde{\lambda}_B B_{ex} - C(L_A) - C(L_B) - \sum_{i\in c}\left[C_i(P_i) + C_i(A_i) + C_i(B_i)\right] \right\} \tag{1}$$

Subject to:

a) Constraints on unit level

$$P_{i,min} \le P_i \le P_{i,max} \qquad i = 1,\dots,M \tag{2a}$$

$$0 \le A_i \le A_{i,max} \qquad i = 1,\dots,M \tag{2b}$$

$$0 \le B_i \le B_{i,\max} \qquad i = 1,\dots,M \tag{2c}$$

$$g_i(P_i, A_i, B_i) \le 0 \qquad i = 1,...,M \qquad (3a)$$

$$h_i(P_i, A_i, B_i) = 0 \qquad i = 1,...,M \qquad (3b)$$

b) Constraints on AN level

$$\sum_{i \in c} P_i + \sum_{j \in nc} \tilde{P}_j = \tilde{L} + P_{ex} \qquad i = 1,...,M;\ j = 1,...,L \qquad (4)$$

$$\sum_{i \in c} A_i - A_{ex} \ge A_{req}, \qquad i = 1,...,M \qquad (5a)$$

$$\sum_{i \in c} B_i - B_{ex} \ge B_{req} \qquad i = 1,...,M \qquad (5b)$$

$$A_{req} = f(\Delta \tilde{PL}) \qquad (6a)$$

$$B_{req} = f(\Delta \tilde{PL}) \qquad (6b)$$

c) Constraints for an AN-based power system

$$\sum_{n=1}^{N} P_{ex,n} = 0 \qquad n = 1,...,N \qquad (7a)$$

$$\sum_{n=1}^{N} A_{ex,n} = 0, \ \sum_{n=1}^{N} B_{ex,n} = 0 \qquad n = 1,...,N \qquad (7b)$$

For simplicity, the time dependence in the notation is left out, although all the quantities can be considered as time dependent.

A. Remarks

All of the used symbols are listed and shortly described in the nomenclature section; however, it is necessary to explain the meanings of A and B ancillary services. Both can be thought of as a spare capacity of real power that is readily available within some specified time interval upon the request. For instance, A can be load following or automatic generation control capacity and B spinning reserve. Since it is not necessary in this general discussion, we do not restrict ourselves by precisely defining specifications of these ancillary services. In fact, any other number of ancillary services can be added to those two.

We also present the constraints in the optimization problem on a rather general level. However, in Section IV, we present a numerical example where all the constraints are precisely defined, and the results of optimization are presented.

We assume that no ramp constraints are considered, and we present optimal dispatching problem only, without unit commitment. These two assumptions simplify the discussion since we can concentrate on one time period in the forward time markets. This is because the solutions of optimization problem (1)-(7) for any two-time periods are independent of each other. However, the main idea can be readily extended to the problem with ramp constraints and to unit commitment problem.

Although in (1)-(6) the optimization problem is written only for one AN, and not for the overall power system, in our discussions we will address the overall system operation according to constraints (7). Furthermore, second example in the next Section IV presents the operation of overall, AN based power system.

B. Optimization problem

Objective function in (1) is essentially formed of two groups of terms. The first three terms present the revenue of AN from exporting real power (or costs if importing in case if P_{ex} is negative) and ancillary services. The second group is formed from the terms of form $C(X)$, and depending on X, they denote the costs of real power production from renewable sources, from controllable generators, the costs of units for providing A and B ancillary services, and the payment to the loads that provide the same ancillary services.
Note that here we talk of the costs of producing certain commodities, but the problem can also be reformulated so that the costs are replaced by bids, i.e. when we have the market operation inside AN.

Decision variables are defined for each controllable generating unit i. They include real power production P_i and ancillary service capacities A_i and B_i. Further more, the amounts of loads that will be paid for accepting possible interruptions in power supply, i.e. loads that are providing ancillary services, are also decision variables and are denoted with L_A and L_B. For instance assuming that A is a fast acting ancillary service and B is slower, we can think of L_A as an amount of loads that can be disconnected without any warning, while loads for loads L_B are informed in advance for the case of any interruptions.

Aside from knowing the costs for each unit and each service, inputs to the optimization problem for some time period t are:

- prediction of power production from renewable sources ($\tilde{P}_j$),
- prediction of AN internal load ($\tilde{L}$),
- the measure of aggregated uncertainty of predicted values for loads and power production from renewable sources inside the AN ($\Delta\tilde{PL}$),
- prediction of market prices for real power and ancillary services ($\tilde{\lambda}_P, \tilde{\lambda}_A, \tilde{\lambda}_B$).

Values A_{req} and B_{req} are introduced for reliable operation of an AN. We can also think of A_{req} and B_{req} as the values that quantify how uncertain AN is when seen from the outside network, as well as the ability of AN to respond to real-time market conditions. In general, A_{req} and B_{req} are functions of the level of uncertainty $\Delta\tilde{PL}$ in a predicted state of AN. These functions are here presented in the form of constraints (6), but in solving the optimization problem they are directly substituted into the objective function. This makes an AN a reliable and competitive player and trust worth partner.
On the unit level, in addition to simple bounding constraints (2), there is a set of inequality and/or equality constrains (3) making the coupling in between commodities (P, A, B) and describing physical limitations of that particular production unit. Their precise formulations depend on definition of A and B.

Constraint (4) is power balance equation. Note that P_{ex} is not directly the decision variable, but its optimal value is implicitly determined from other decision variables.

The trade-offs that are built into the presented optimization problem are illustrated in the example of next section. Indeed, each AN can have different strategies, and solve differently formulated optimization problems with different set of constraints, but all of them will have to face some of the trade-offs in their desire to make the best possible decisions on the behalf of their owners – producers/consumers inside AN.

The concept of ANs offers numerous interesting possibilities that can be expressed through optimization problems. For instance, if there is a severe contingency in the outside system, AN can decide to disconnect from the system and operate as an island, presenting uninterruptible power supply for a set of its sensitive loads (for instance hospitals). This high level of security for those loads can be included in A_{req} and B_{req} (5). These constraints can state that AN must have required amount of spare capacity so that successful transition to island operation is possible at any time.

Another important possibility is that AN can optimize its operation in such a way that it has a certain required amount of kinetic energy stored in rotating masses inside AN. In other words, it is rather easy to introduce inertia as ancillary service. In that way, for the outside network, an AN can present itself similar to traditional synchronous generators based large scale-power plant.

Since we think of ANs as the major building blocks of the overall power system, it is indeed necessary to present the overall power system forward time market operation. Since ANs are well connected through the transmission network, the overall system is formed from a large amount of parties, which is necessary for the existence of efficient competitive markets. Well-meshed topology of transmission networks and proper designed market structures fit well to serve AN based power systems.

To grant the reliability of the overall network, power, and ancillary service balance among the ANs is introduced as shown in (7), where n is the index of the autonomous network. Note that in the existing system, a power producer does not explicitly buy ancillary services – it can only sell them. The independent system operator has an objective to keep the quantity of ancillary services in the overall system on some required level.

In contrast with this market operation, the ANs trade those services to meet its requirements of spare capacity. As shown in (5), each AN is obliged to have this capacity available. If the AN is not capable to allocate this capacity from own generation units, it can buy them from the other ANs. The market-clearing price (MCP) of trading commodities is reached when the sum of all offered/demanded commodities of ANs is equal to zero (7).

IV. Examples

In this section, the objective function presented in the previous section is worked out into some more details along with the presentation and discussion of results in a case study.

A. Optimization of an Autonomous Network.

During the optimization ancillary service A is chosen to be readily available regulation power capacity that is used for load following and for the compensation of power fluctuations from renewable units inside the AN. The unit providing this ancillary service has to be able to rapidly respond to request for up and down movements in power production. Spare capacity B is taken to be the capacity that is available as a power injection to the network in within several minutes. The constraints that correspond to constraints (3) from the previous section are:

$$0 \le A_i \le \min\left(A_{i,\max}, P_i - P_{i,\min}, P_{i,\max} - P_i\right) \quad i = 1,\ldots,M \quad (8)$$

$$0 \le B_i \le \min\left(B_{i,\max}, P_{i,\max} - P_i\right) \quad i = 1,\ldots,M \quad (9)$$

According to (8), ancillary service A of unit i must fulfill some requirements with respect to the constraints of unit i. A_i has to be smaller or equal to the maximum available capacity of A of the unit i at any time. However, A_i can be varied with respect to the maximum and minimum output levels of the unit i and with respect to the unit operation point P_i. $P_i - P_{i,min}$ limits the regulating-down capacity while $P_{i,max} - P_i$ limits the regulating-up capacity of A_i. Value of A_i is used as up or down regulation capacity symmetrical in relation to P_i ($P_i + A_i$ for up and $P_i - A_i$ for down regulation). This may result that some part of total up or down capacity of A_i remains unused since we use the minimum value of A_i. By further unbundling of this capacity in to two separate trading commodities (e.g. $A_{i,DOWN}$ and $A_{i,UP}$), the optimal utilization of capacity of A_i could be achieved. For the sake of simplicity, the capacity of A_i is used in this example as shown in (8).

The constraint (9) represents ancillary service B. Since B_i does not have the limitations with respect to the minimal unit capacity, it can only provide regulation-up capacity.

In this example, A_{req} is chosen to be equal to the uncertainty $\Delta\tilde{PL}$. Since A is the fast acting capacity, it is able to cover the uncertainty immediately at any time scale. B_{req} is held constant as a fixed percentage of the load, as presented in Fig. 3. It consist of extra power plant generating capacity that is kept running so it can be used on short-notice to respond to increased demand or to supplement an unexpected drop in generation on the grid.

The simulated AN consists of 12 generating units, out of which 8 are controllable, and the remaining 4 units are wind turbines. The values of market clearing prices, internal loads, and production from renewable generators are chosen in such a way that the analysis of results is simplified, rather than taken to have some realistic daily profile. Internal AN loads, as well as the production from wind turbines, are taken to be constant. However, the value of $\Delta\tilde{PL}$ has been varied.

Costs for power production of controllable units are taken to be quadratic functions of produced power. Costs for A and B are taken to be linear functions of the reserved capacities, which should cover the costs of generator maintenance and

wear. Generator wear is caused by fluctuations in power output.
Optimization has been performed for 48 trading blocks and the results are presented in Fig. 3, 4 and 5.
In Fig. 3 the input and output of the optimization is given since it illustrates $\Delta\tilde{PL}$, A_{req} and B_{req}. The trading of commodities, respectively P_{ex}, A_{ex}, and B_{ex}, are presented in the Fig. 5 while their predicted prices are given in Fig. 4. The prices in Fig. 4 are the input of the optimization, while the output is given in Fig. 5.

Here we give some remarks concerning the results:
The constraints that are coupling the commodities are easily observed in the first trading blocks in Fig. 5. While the price of B_{ex} is low the AN imports this commodity to satisfy B_{req}, as the price increases the AN is optimized for sale of B_{ex} which causes the decreases the amount op P_{ex} allocated for sale (9).

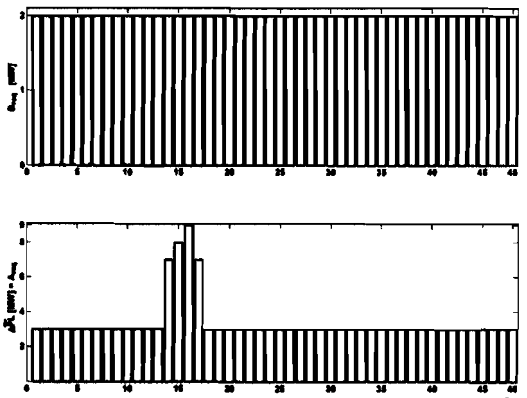

Fig. 3: B_{req} and optimization results of A_{req} caused by uncertainty $\Delta\tilde{PL}$.

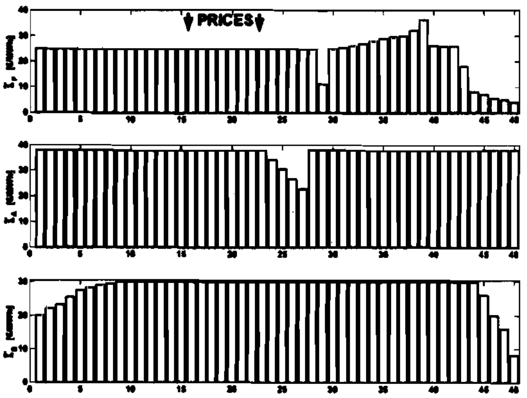

Fig. 4: Predicted spot prices of real power P_{ex} and ancillary services A and B.

As the uncertainties $\Delta\tilde{PL}$ increase in the trading-blocks 14-17 of the Fig. 3, A_{req} increases to grant the reliability. This is also visible in Fig. 5, where the trading of fast capacity A_{ex} decreases in order to compensate for the uncertainties and to preserve the reliability.
Row 1 of Fig. 5 shows the increase of the P_{ex} predicted price after the 30[th] trading-block, which causes the larger allocation of available capacity for P_{ex} and decrease of available capacities for ancillary services.

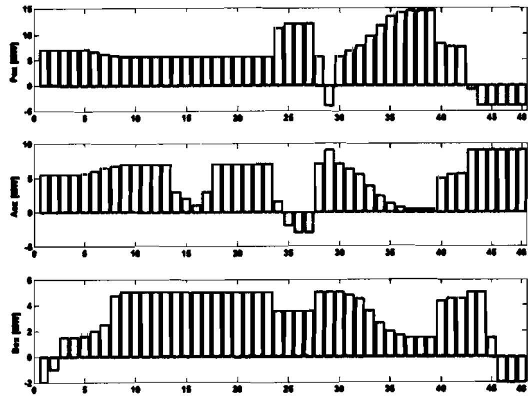

Fig. 5: Optimal results for P_{ex}, A_{ex} and B_{ex}.

B. Autonomous Network based power system

This example outlines the AN-based power system and its behavior. The five simulated interconnected ANs consist of 20 controllable and 10 wind turbines. The costs for power production of controllable units are taken to be quadratic functions of produced power. Costs for AS A, as explained in previous example, are taken to be linear functions of the reserved capacities. It is assumed that each AN will bid his incremental costs which are, for the power trading, the derivative of (10).

$$f(P_i, A_i) = a_i P_i^2 + b_i P_i + c_i + C(A_i) \qquad i = 1,\ldots,M \qquad (10)$$

The costs of generating certain amount of power versus ancillary service presented in Fig. 6, as defined in (10), are the optimization results of one AN for six different amounts of A. As the total amount of A increases, the total amount of power available for trading decreases.

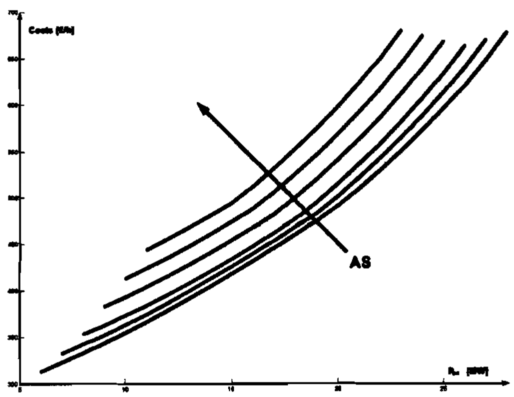

Fig. 6: Influence of ancillary service on real power generation.

As explained in the previous example, each AN is being optimized. From the optimization, the amount of ancillary service A is determined. The optimization, which results the cost curve of the Pex, is preformed with fixed amount of A. The curve, corresponding with the fixed amount of A, represents the cost curve of P_{ex}. According to this curve, each AN submits its incremental cost of the trading commodity P_{ex}.

The incremental costs of five AN are presented in Fig. 7.

AN1 and AN3 (two left lines) are represented as loads while AN2 and AN4 (two right lines) are represent as power generators. AN5 (middle line) can be represented as generator and load. The representation AN5 to the other ANs depends on the market-clearing price. The MCP is equal to the price where the incremental costs of al ANs are the same and where the sum of all trading commodities is equal to zero, according to (7). In this example the MPC is equal to 20.82 €/MWh which results that the AN2, AN4, and AN5 are selected as power producers, while AN1 and AN3 are selected as loads.

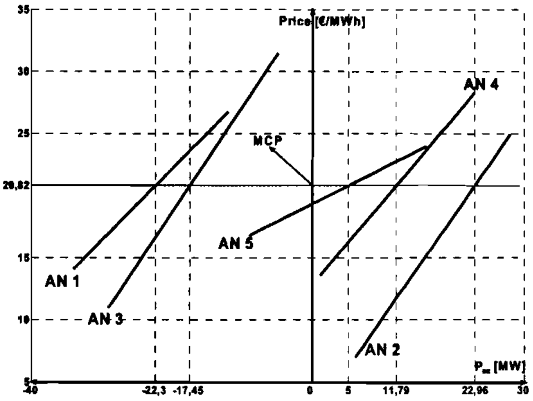

Fig. 7: Incremental costs of five autonomous networks

Although, the incremental cost of the commodity P_{ex} is considered, in the same way as defined in (10) the costs of A can be obtained by performing the optimization for the several amounts of A with fixed amount of P_{ex}.

V. Conclusions

The concept of autonomous power networks is a realistic approach to deal with increased uncertainty and complexity of future power systems. Presented autonomous network dispatching optimization problem is formulated in such a way that it includes number of important trade-offs each AN is facing in its desire to make optimal decisions in the market environment. Proposed approach shows good results when applied to realistic system. Mutual influences of coexisting parallel markets in this way can be optimally handled.

VI. Acknowledgement

This research has been performed within the framework of the research program 'Intelligent Power Systems' that is supported financially by SenterNovem. SenterNovem is an agency of the Dutch Ministry of Economic Affairs.

VII. References

[1] M. Shahidehpour, H. Yamin, Z. Li, *Market operations in Electric Power Systems*, New York: Wiley, 2002, ch. 1 pp 5-20.

[2] S. Soft, *Power System Economic,* New York: Wiley, 2002, ch. 3 pp 232-242.

[3] S. Hao, "A study of basic bidding strategy in clearing price auctions" *IEEE Trans. on Power Systems*, vol. 16, pp. 975-980, Aug. 2000.

[4] S. Hao, G.A Angelidis, H. Singh, A.D Papalexopoulos, "Consumer payment minimization in power pool auctions," *IEEE Trans. on Power Syst.*, vol. 13, no. 3, pp. 986–991, August 1998.

[5] T. Alvey, D. Goodwin, X. Ma, D. Streiffert, and D. Sun, "A security-constrained bid-clearing system for the New Zealand wholesale electricity market," *IEEE Trans. on Power Syst.*, vol. 13, no. 2, pp. 340–346, May 1998.

[6] F. Alvarado, "Market power: A dynamic definition," http://www.pserc.wisc.edu/index_publications.html.

[7] X. Guan, Y.C. Ho, F. Lai, "An ordinal optimization based bidding strategy for electric power suppliers in the daily energy market," *IEEE Trans. on Power Systems,* vol 16, pp 788-797, Nov. 2001.

[8] N.S. Rau, "Optimal dispatch of system based offers and bids-A mixed integer LP formulation," *IEEE Trans. Power Systems*, vol. 14, pp. 274-279, Feb 1999.

[9] F. Provoost, A. Ishchenko, A. Jokic, J.M.A. Myrzik, W.L. Kling, "Self controlling autonomous operating power networks", *CIRED 2005*, Turin, Italy, June 2005.

VIII. Biographies

Kemal Agović was born in 1976 in Gradačac, Bosnia and Herzegovina. He is currently doing his Master's thesis at the Control Systems group of the Department of Electrical Engineering, Eindhoven University of Technology. His research interests are integration of the autonomous networks in the power system dispatch.

Andrej Jokić was born in 1976 in Zagreb, Croatia. He received his Dipl.Ing. degree (cum laude) in Mechanical Engineering from the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb in 2001. He is currently working as a PhD student at the Control Systems group of the Department of Electrical Engineering, Eindhoven University of Technology. His research interests are: large-scale interconnected systems control and optimization.

Paul P.J. van den Bosch was born on 18 March 1948 in Rotterdam, the Netherlands. He obtained his Master's Degree in Electrical Engineering and completed his PhD thesis on "Short term optimization of thermal Power Systems" at Delft University of Technology, where he was appointed full professor in Control Engineering in 1988. In 1993 he was appointed to the Measurement and Control Chair at the Eindhoven University of Technology. His interests include modelling, simulation, motion control, hybrid systems, biocontrol and electrical energy systems.