MASTER

Dynamic market behavior of autonomous network based power systems

Wittebol, E.H.M.

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Eindhoven University of Technology
Department of Electrical Engineering
Control Systems

technische
universiteit
eindhoven

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by E.H.M.Wittebol

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Commissioned by: Prof.Dr.Ir. P.P.J.Van Den Bosch

Supervisor: A.Jokic

Additional Commission members: A.Jokic, A.Ishchenkco
Prof. name (TU/e): P.P.J.Van Den Bosch
Name (Company): Eindhoven University of Technology

SUMMARY

Nowadays, competition in the electricity market is applied by electricity production companies. Power systems are more and more relying on a large number of smaller, distributed producers, in contrast to the traditionally structured power systems which were based on large-scale power plants. All these producers have an extensive spectrum of possible behaviors in both physical and economical layers of the power system. Furthermore, the increased penetration of distributed generation and the large scale introduction of renewable energy sources results in a large amount of market players and increased uncertainties. The market is changing from a monopolistic structure to a competitive market. Since economical forces are one of the major drives behind these changes, the idea of controlling the system by price is appealing. However, the complete reliance on market mechanisms for controlling and operating power systems will need some guarantees to ensure that such a system will indeed perform efficiently and in addition, as a minimal requirement, that it will be stable.

The paper called 'Dynamic Market Behavior of Autonomous Network based Power Systems' presents the concept of autonomous networks as an efficient way to make such a complex system manageable. The approach of applying control system theory for analysis of market feedback mechanisms can lead to novel insights of complex market dynamics and even more, it offers some guidelines for efficient and robust market designs. Modeling and analysis of autonomous network based power system market behavior is presented. Decentralized control of power imbalance is introduced and its stabilizing effect on the entire power system is shown. The concept of introducing autonomous power networks as major building blocks of the system is a realistic approach towards a solution. In particular, the paper analyses the market behavior of those building blocks, and proposes some solutions to increase real-time market robustness.

Dynamic Market Behavior of Autonomous Network based Power Systems

E.H.M.Wittebol, A.Jokic, P.P.J.van den Bosch

Abstract: **Nowadays, competition in the electricity market is applied by electricity production companies. Increased penetration of distributed generators and renewable energy sources results in a large amount of market players and increased uncertainties. This paper presents the concept of autonomous networks as an efficient way to make such a complex system manageable. Modeling and analysis of autonomous network based power system market behavior is presented. Decentralized control of power imbalance is introduced and its stabilizing effect on the entire power system is shown.**

***Index terms*:** **Electricity market dynamics, distributed generation, autonomous power networks, power system control**

I. NOMENCLATURE

$P_{g,i}$	Power generation of producer i [MW]
$P_{d,j}$	Power demand of consumer j [MW]
$P_{EX,i}$	Power exchange [MW]
$P^0_{EX,i}$	Set point for power exchange [MW]
A_i	Capacity for ancillary services [MW]
a_i, b_i, c_i	Cost function parameters.
$MC(P_{g,i})$	Marginal cost function [€/h]
$MB(P_{d,j})$	Marginal benefit function [€/h]
$\tau_{g,i}$	Time constant of producer i [h]
$\tau_{d,j}$	Time constant of consumer j [h]
τ_λ	Time constant of real-time market price update [h]
τ_A	Time constant of ancillary market price update [h]
λ_P	Real-time market price [€/MWh]
λ_A	Ancillary service market price [€/MWh]
E	Overall network energy imbalance [MWh]
k_{AS}	Ancillary Service feedback gain
k_E	Energy imbalance feedback gain
k_P	Power exchange error feedback gain

II. INTRODUCTION

FOR SOME YEARS NOW, the electricity market structure, as well as the power system structure itself, has been going through significant changes. Nowadays, power systems are more and more relying on a large number of smaller, distributed producers, in contrast to the traditionally structured power systems which were based on large-scale power plants. The market is changing from a monopolistic structure to a competitive market.

Since economical forces are one of the major drives behind these changes, the idea of controlling the system by price is appealing. However, the complete reliance on market mechanisms for controlling and operating power systems will need some guarantees to ensure that such a system will indeed perform efficiently and in addition, as a minimal requirement, that it will be stable.

The approach of applying control system theory for analysis of market feedback mechanisms can lead to novel insights of complex market dynamics and even more, it offers some guidelines for efficient and robust market designs. This paper is taking that direction, and its starting point is the model of market dynamics which was first introduced by Alvarado in [1]. Although there is already a list of references following from [1], like for instance [2],[3],[6], none of those references is considering the novel power system characteristics introduced by having a large amount of dispersed generators. All these generators have an extensive spectrum of possible behaviors in both physical and economical layers of the power system. These novel approaches and control structures are necessary to correctly manage the operation of such a large amount of required market players.

The concept of introducing autonomous power networks as major building blocks of the system is a realistic approach towards a solution. In particular, this paper analyses the market behavior of those building blocks, and proposes some solutions to increase real-time market robustness.

III. DYNAMIC MARKET MODELING

In electricity power markets, supply and demand are determined by the behavior of producers and consumers, which all have the objective of making the optimal profit and keeping their costs at a minimum. Most of the currently existing real time markets rely on frequently updated auctions. The importance of this fast response of real-time markets will be even more emphasized in future power systems which are expected to rely on a large amount of renewable energy sources. Those intermittent and uncontrollable producers, like for instance wind turbines and photovoltaic systems, will increase the uncertainty in any forward time prediction of the system state and with that, the efficiency of the real time market becomes crucial.

In order to formulate some problems related to real time market behavior in future power systems, and eventually to be able to analyze market dynamics in control system context, we will take the liberty of idealizing the periodically updated market auctions as a continuous process.

Here we adopt the market model that was first introduced by Alvarado [1]. After shortly presenting this model with some discussions, we make an addition to it by introducing power and energy imbalance ancillary services, and analyze their impact on market stability.

A. *Existing market dynamics model*

Commonly, the quadratic cost function (1) and the resulting affine marginal cost function for producers $MC(P_{g,i})$ (2) and marginal benefit function for consumers $MB(P_{d,i})$ (3) are used for characterizing some unit i, j:

$$C_i(P_i) = a_i + b_i P_i + \tfrac{1}{2} c_i P_i^2 \quad (1)$$

$$MC_i(P_{g,i}) = b_i + c_i P_{g,i} \quad (2)$$

$$MB_j(P_{d,j}) = b_j + c_j P_{d,j} \quad (3)$$

Energy imbalance E in the overall system is given with

$$\dot{E} = \sum_{i=1}^{n} P_{g,i} - \sum_{j=1}^{m} P_{d,j} \quad (4)$$

It is defined as the time integral of the difference between total generation and total demand in the system. We will refer to this difference as power imbalance.

In interpreting (4) it is important to distinguish between consumption and demand. With demand we refer to the amount of power that is consumed if the system frequency and voltage are equal to their target values for all consumers. Consumption however, is the actual usage of power at the actual system frequency and voltage, and is always equal to generation (if losses in the network are neglected). Curtail assumption in the market model of Alvarado [2] is that the market price setting mechanism is given with:

$$\tau_\lambda \dot{\lambda}_P = -E \quad (5)$$

In this relation, the time constant τ_λ determines the dynamics of the price update. In [3] however, a different price update model is used:

$$\tau_\lambda \dot{\lambda}_P = -k_E E - \lambda_P \quad (6)$$

We will return to price update dynamics later in this section. The behavior of producers and consumers as economically rational decision makers is modeled with the following set of first order differential equations:

$$\tau_{g,i} \dot{P}_{g,i} = -b_{g,i} - c_{g,i} P_{g,i} + \lambda_P, \qquad i = 1,\dots,n \quad (7)$$

$$\tau_{d,j} \dot{P}_{d,j} = b_{d,j} + c_{d,j} P_{d,j} - \lambda_P, \qquad j = 1,\dots,m \quad (8)$$

In (7) and (8) both producers and consumers are assumed to take the market price as an exogenous quantity, which means that they are price takers and no market power is exercised. Producers increase their generation when market prices exceed their marginal costs, and consumers increase their consumption when market prices become lower than their marginal benefit, thus achieving equilibrium where market prices equal marginal costs. For the model including market power behavior we refer to [7].

It is important to emphasize some assumptions made in this model and its resulting limitations. First, it is assumed, and we hold to that assumption in this paper, that there is a "sufficient" separation in time scales of market dynamics and the dynamics of underlying physical system. This time scale separation is common for hierarchical control structures. Here presented market dynamics is describing higher and slower acting hierarchical level in power imbalance control, and the underlying physical system, together with all of its fast acting local controllers, presents the faster, lower level. This sufficient separation actually implies that the lower level acts more or less as an all pass process for the frequency band of the upper layer. In particular, the produced real power quantity $P_{g,i}$ in (7) presents only the low frequency components of the produced power. This low frequent behavior is captured in the time constant $\tau_{g,i}$ that is reflecting the ramp limits of that particular generator i. Equations (4)-(8) give a rather low frequent coupling of market dynamics and the dynamics of the physical system (network). Clearly, as the time scale of market updates begins to approach the time scale of physical (electromechanical) dynamics, the potential of undesirable dynamic performance, and even instability, becomes a real issue [3].

It can be seen that the system described with (4), (5), (7) and (8) is an unstable system, i.e. only the price signal that is determined by (5) is not enough to ensure system stability. The price update (6), with appropriately chosen τ_λ and imbalance gain k_E, results in a stable system. In this case however, there remains a steady state error in energy imbalance.

The failure of (5) to stabilize the system, has been complemented by Alvarado in [2] by adding the supplementary stabilizing signal to either the suppliers or consumers. In the case that the signal is sent only to the suppliers, equation (7) becomes:

$$\tau_{g,i} \dot{P}_{g,i} = -b_{g,i} - c_{g,i} P_{g,i} + \lambda_P - k_{E,i} E, \qquad i = 1,\dots,n \quad (9)$$

where $k_{E,i}E$ is added as a (feedback) signal. For stability however, gain $k_{E,i}$ has to be carefully chosen, which indeed depends on other system parameters, and in particular on τ_λ.

B. *Additions to existing model*

In addition to the study of market behavior of autonomous network based power systems, in this paper we add more supplementary feedback signals to Alvarado's model, analyze the resulting system and discuss some of its features. In particular we make (some) producers responding to power imbalance in the system. This results into the following equation:

$$\tau_{g,i}\dot{P}_{g,i} = -b_{g,i} - c_{g,i}P_{g,i} + \lambda_P - k_{E,i}E - k_{P,i}\dot{E} \qquad (10)$$

So, with (10) we have that producers i, in addition to the market price, respond to system energy imbalance and system power imbalance with corresponding gains $k_{E,i}$ and $k_{P,i}$. These gains are in general different for different types of producers, for some producers they can even be zero (all combinations are possible). For the producer with $k_{E,i} \neq 0$ we will say that it performs Energy Ancillary Service (EAS), while in the case of $k_{P,i} \neq 0$ it performs Power Ancillary Service (PAS). It is also possible that the producer is price insensitive, but is serving one or both of the ancillary services. In that case we have the following equation for describing the producer's behavior

$$\tau_{g,i}\dot{P}_{g,i} = k_{AS,i}(P^0_{g,i} - P_{g,i}) - k_{E,i}E - k_{P,i}\dot{E} \qquad (11)$$

Where $P^0_{g,i}$ is the desired steady state production of generator i, and $k_{AS,i}$ is the corresponding gain on the difference from that steady state. It is also possible to extend the EAS and PAS to demand side.

With respect to $k_{AS,i}$ and $k_{P,i}$ it is mentioned that values for $k_{AS,i}$ depend on the minimum and maximum generation limits of the respective unit i. Values for $k_{P,i}$ depend on the amount required penalization for the power imbalance.

It is easy to see that the system described with (4), (5), (10), and (11) has zero imbalance in the steady state and that the price sensitive producers and consumes in the steady state are all in their economically optimal working points. Later we will address the influence of ancillary services on the overall system behavior in some more detail.

Adding the power imbalance feedback signal to some of the producers raises several questions. System wide power imbalance is hard to measure. It is causing changes in the system frequency, so it can be detected in that way; however, those changes do not only carry the information of power imbalance in the sense we defined it earlier in this section, but are also the result of different oscillations of the power in the physical system. Direct use of this signal for the feedback adds faster dynamics to our new model, and we have to even more emphasize the possible undesired dynamic performance, or even instability, caused by this interaction with the physical system.

On the other hand, a nice property of using power imbalance feedback is its stabilizing effect on the power market, which results in the possibility of using the desired faster market updates. This is the main reason why in this section we discuss the possibility of using the power imbalance signal. In the next sections however, together with the introduction of autonomous networks, we present a more realistic market stabilizing system structure.

Our statement that PAS and EAS are having a stabilizing effect is based on the analysis of groups of producers and consumers where some producers are performing those services. The analysis shows that the addition and increase of accumulated power imbalance gain in the system results in an increased stability region in the (k_E, t_λ) parameter space (see Fig. 4). We do not give a more detailed presentation of these results at this point since qualitatively they are the same as the results presented in Section VI (In particular we refer again to Fig. 4).

With the remarks of possible undesired behavior in coupling with the physical network dynamics, it is obvious that there is great caution needed to properly design EAS and PAS services, so that a good trade-off is reached in between economically efficient, fast market operation and the overall system robustness.

IV. Autonomous Power Networks

An Autonomous power Network (AN) is the aggregation of physically connected producers and consumers whose operation is coordinated/controlled with one central unit acting as an interface between internal producers/consumers and the rest of the power system.

The goal of such a unit is the efficient deployment of internal resources and active involvement in overall system competitive markets where it reflects the preferences of its owners, i.e. of its internal producers/consumers. In the physical as well as in the economical layer (power and ancillary service markets) each AN is presented as one single producer/consumer.

An illustration of a typical distribution network with a large amount of dispersed generation that acts as an autonomous network is presented in Fig. 1.

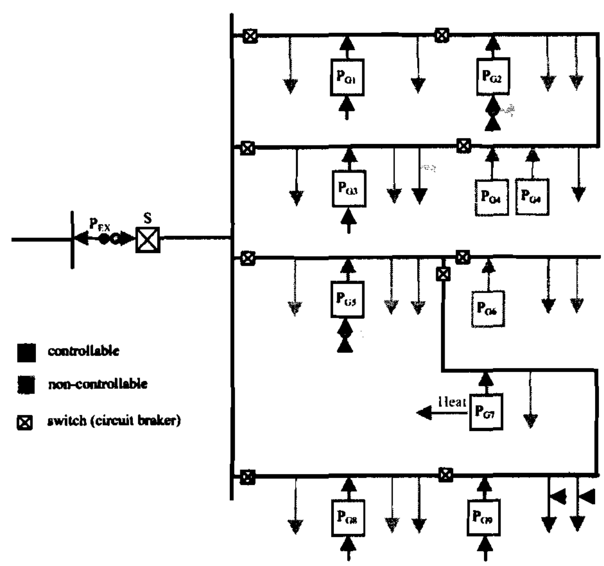

Fig. 1: Illustration of autonomous power network

Each AN is the mixture of a large variety of generators and producers, with each having different characteristics: in dynamics, in efficiencies and costs, in controllability etc. Proper design and operation of the AN makes it to become a well behaved unit, capable of being a major building block of the future power system.

V. AUTONOMOUS NETWORK AS A MARKET PLAYER

The goal of this section is the presentation of an AN based power system with the addition of the novel power imbalance control structure based on energy ancillary services (EAS), power ancillary services (PAS) and real-time power market.

The main idea is the decentralization of PAS so that each AN responds only to the locally measured power changes. In particular, we replace the overall system power imbalance in (10) and (11) with the variations in power exchange ($P_{EX,i}$) in between each AN and the rest of the system (see Fig. 2 and 3).

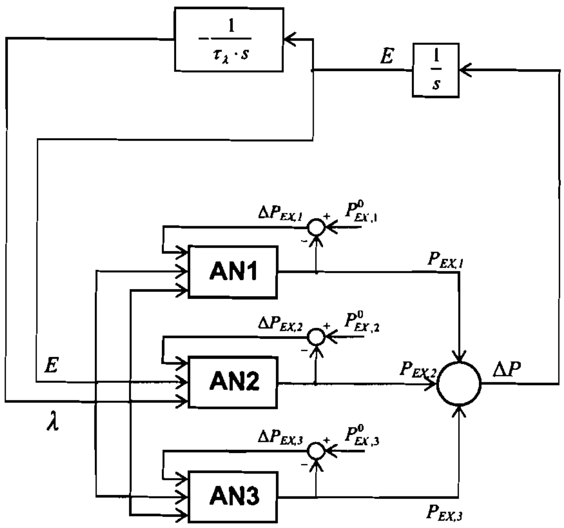

Fig. 2: AN Power system with decentralized control signals

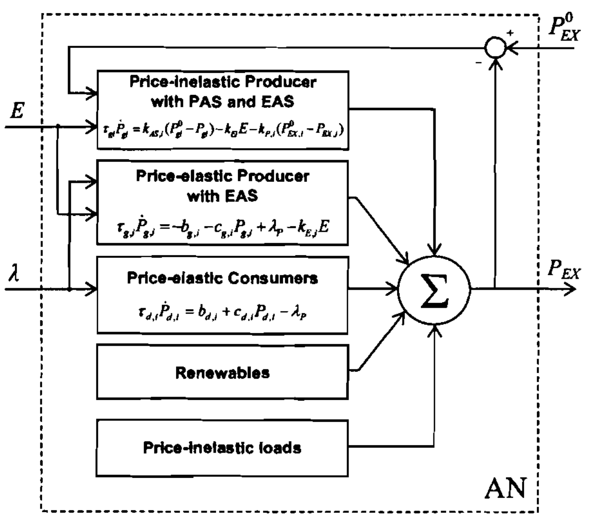

Fig.3: Internal structure of autonomous network

Actual feedback signal used in PES is the deviation $P_{EX,i}$ with respect to its reference value $P^0_{EX,i}$ .The equations for price elastic producer performing EAS and PAS, and price inelastic producer performing EAS and PAS are now given with (12) and (13), respectively.

$$\tau_{g,i}\dot{P}_{g,i} = -b_{g,i} - c_{g,i}P_{g,i} + \lambda_P - k_{E,i}E - k_{P,i}(P^0_{EX,i} - P_{EX,i}) \quad (12)$$

$$\tau_{g,i}\dot{P}_{g,i} = k_{AS}(P^0_{g,i} - P_{g,i}) - k_{E,i}E - k_{P,i}(P^0_{EX,i} - P_{EX,i}) \quad (13)$$

Note that the control system structure presented in Fig. 2 and Fig. 3 is similar to the traditional Automatic Generation Control (AGC). One of the goals of AGC is to control the power flow in the tie-lines between neighboring control areas, so that in the steady state this power flow matches its scheduled value. For that purpose, AGC control contains an integral control action.

In contrast to this, power exchanges $P_{EX,i}$ within AN's are controlled only with proportional control action, allowing the steady state to deviate from the reference values. Applying integral action in this loop would result in having in steady state all $P_{EX,i}$ values corresponding to their reference values $P^0_{EX,i}$. This disables real-time trading between AN's.

By using only proportional feedback control (by means of $k_{P,i}$) an additional stabilizing signal is added to the system, however a steady state deviation remains. These deviations in power exchange, allow for the real-time trading between AN's.

Obviously, there is a trade-off between positive and negative effects in applying PAS. As will be presented in the next section, the negative influences of PAS are somewhat diminished by the possibility of using faster market price updates (τ_λ) while preserving system stability.

The reference values used for the power exchange $P^0_{EX,i}$ can be scheduled values, which for instance are determined in the day-ahead markets. In some market structures there exists also an hour-ahead market, which can provide the AN with even faster updates for the reference exchange value $P^0_{EX,i}$. In general, each AN is allowed to update is own reference, however in the case of fast updates, this should included in the model, and additional analysis will be necessary.

On the overall network level, the energy imbalance signal is still used and it is resulting in the overall system steady state having zero energy imbalance.

Now we refer to other trade-offs introduced by PAS and EAS services. Notice that the producer whose behavior is described with (12) and (13), in the system steady state will not operate in its optimal working range. This is caused by the fact that although the energy imbalance E will be zero, there still remains a steady state deviation in $P_{EX,i}$. To compensate this producer for not working in its optimal point with respect to the real power market price, and to award its contribution to overall system stability, the producer is paid for offering those ancillary services to the network. The price it is paid for these services would then however be determined by the ancillary service markets. A description of dynamic behavior and the coupling in between the real-time power market and the ancillary service market is subject for future research.

Furthermore, we have to emphasize once again that using power imbalance signals in the context of market behavior requires thorough analysis to avoid negative interaction with for instance, controllers in the physical layer that are responsible for power oscillation damping.

VI. EXAMPLE

In this example we analyze the behavior of an AN based power system which consists of three interconnected AN's according to the network structure in Fig. 2 as presented in section V. In each autonomous network, two generators are assigned to provide only ancillary services (both are price insensitive) and three generators are price sensitive. There are also two price-sensitive loads and several price inelastic and randomly changing loads. Furthermore, two wind generators with random power production have been included. Table 1 list the system parameters for producer and consumer in each AN used in the analysis.

AN 1							
i	$c_{g,i}$	$c_{d,i}$	$b_{g,i}$	$b_{d,i}$	$\tau_{g,i}$	$\tau_{d,i}$	$k_{as,i}$
1	0.3	-0.2	2	10	0.1	0.1	0.5
2	0.3	-0.2	4	7	0.2	0.2	0.5
3	0.2		3		0.2		
AN 2							
i	$c_{g,i}$	$c_{d,i}$	$b_{g,i}$	$b_{d,i}$	$\tau_{g,i}$	$\tau_{d,i}$	$k_{as,i}$
1	0.5	-0.4	2	8	0.2	0.1	0.6
2	0.2	-0.2	1	10	0.3	0.1	0.4
3	0.3		2		0.2		
AN 3							
i	$c_{g,i}$	$c_{d,i}$	$b_{g,i}$	$b_{d,i}$	$\tau_{g,i}$	$\tau_{d,i}$	$k_{as,i}$
1	0.2	-0.3	3	10	0.2	0.2	0.3
2	0.4	-0.5	2	8	0.4	0.2	0.7
3	0.3		3		0.3		

Table 1: Various system parameters used in the simulation

We can think of the values for $\tau_{g,i}$ and $\tau_{d,j}$ being expressed in minutes, as well values of τ_λ on the vertical axis in Figure 4. Stability analysis has been done for four different system configurations. In the initial system, no PAS loops were used. In each following iteration of the analysis, a PAS loop was added to one AN at the time with $k_{p,i} = 0.3$ (ending with the complete system where all AN's have PAS loops).

Stability regions in the (k_E, τ_λ) parameter space for this four different cases are presented in Fig. 4. The areas above the curves present a stable region. The increase of stability regions corresponds to addition of PAS loops.

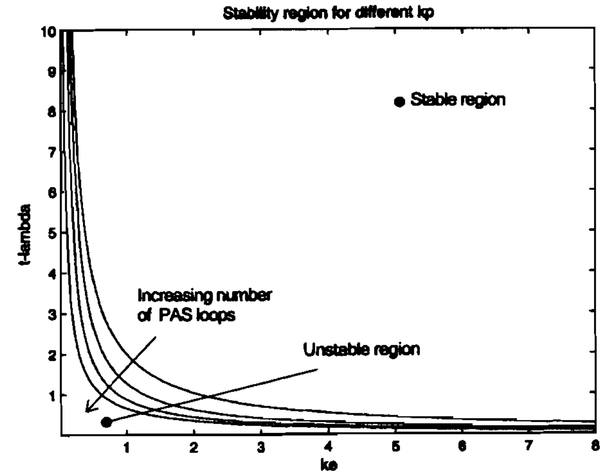

Fig. 4: Stability regions for an increasing number of PAS feedback loops

VII. CONCLUSION

This paper illustrates how the application of small autonomous networks influences the network stability of real-time electricity market operation. Increased penetration of distributed generators and renewable energy sources results in a large amount of market players and increased uncertainties. All this leads to significant increase of systems complexity and requires development of new approaches to successfully operate such a complex system.

Introducing autonomous networks including ancillary services and decentralization of mechanisms to reduce power imbalance will result in a greater overall market stability region. Furthermore, it leads to the possibility of increasing the frequency of real time market updates without jeopardizing system stability.

VIII. ACKNOWLEDGEMENT

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IX. REFERENCES

[1] F.Alvarado, "The stability of Power System Markets", IEEE Transactions on Power Systems, Vol. 14, No 2, pp. 505-511, May 1999

[2] F.Alvarado, "The Dynamics of Power System Markets, Technical Report PSERC-97-01", Power Systems Engineering Research Consortium, University of Wisconsin, March 1997

[3] F.Alvarado, "Stability Analysis of Interconnected Power Systems Coupled With Market Dynamics", IEEE Transactions on Power Systems, Vol. 16, No 4, pp. 695-701, November 2001

[4] Y.Lui, "Control theory application in power market stability analysis", 2004 IEEE International Conference on Electricity Utility Deregulation and Power Technologies (DRPT2004), pp. 562-569, April 2004

[5] James D. Weber, "An individual Welfare Maximization Algorithm for Electricity Markets", 2002 IEEE Transactions on Power Systems, Vol. 17, No. 3, pp. 590-596, August 2002

[6] F.Alvarado, "The role of Energy Imbalance Management on Power Market Stability", 1998 Proceedings of the 31st Annual Hawaii International Conference on Power Systems, pp. 4-8

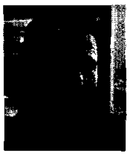
[7] D.Watts, F.Alvarado, "The Influence of Futures Markets on Real time Price Stabilization in Electricity Markets", 2003 IEEE Hawaii International Conference On Systems Sciences, pp. 1-7, January 2003

[8] F.Alvarado, "Is System Control Entirely by Price Feasible ?", 2002, Proceedings of the 36th Hawaii International Conference on System Sciences

[9] F.C.Schweppe, M.C.Caramanis, R.D. Tabors and R.E.Bohn, "Spot Pricing of Electricity", Nordwell, MA: Kluwer, 1988

X. BIOGRAPHIES

Erik H.M. Wittebol was born on 25 September 1980 in Sittard, the Netherlands. At this moment he is working on his Master thesis assignment with the Control Systems Group at the Department of Electrical Engineering, Eindhoven University of Technology. His current research interest is on the dynamical market behavior of interconnected power systems



Andrej Jokic 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 process control.

Initial research into ancillary market behavior

INTRODUCTION

In this section we present a dynamic model for the Ancillary Service (AS) market and describe its coupling with the real power market. Introduction of several types of ancillary services (such as spinning reserve, regulation, load-following, automatic generation control (AGC) etc.) are required because of security and stability issues in the network. In the proposed model for the AN-based market structure, the defined ancillary services for PAS and EAS have been included through feedback loops in a similar manner to the structure of AGC.

Each of these services will have to meet a certain minimum, depending on the kind of service; for instance in the case of spinning reserve, the reserved amount is a percentage of the load determined in forward markets or at least the size of the largest generator, whichever one is the largest.

DEFINITIONS FOR ANCILLARY CAPACITY

In this section, we investigate only one generalized type of ancillary service. We define this to be a fast acting ancillary service (for instance AGC, regulation, PAS or EAS) and denote the corresponding ancillary capacity for providing this type of service with A_i. If necessary, other services B_i, C_i etc. can be included. For offering ancillary capacity to the AS-market, the considered generator is paid the AS-market price λ_A, while for the actual production of real power $P_{g,i}$, the generator is paid the real time market price λ_P.

The costs of providing ancillary capacity depend on the kind of service. In the case of AGC, PAS or EAS, these costs are for instance caused by increased wear, required additional maintenance, operating in a non-optimal range and loss of production opportunity. For more information on possible causes and on determining the actual costs for a certain service, we refer to [1], [2]. For ancillary service A_i that is considered here, we assume that those costs are linear. This gives the following combined functions (1), (2) and (3) for respectively cost C_i, revenue R_i and resulting profit π_i for both real-time power and ancillary capacity.

$$C_i(P_{g,i},A_i) = a_i + b_i P_{g,i} + \tfrac{1}{2} c_i P_{g,i}^2 + dA_i \qquad (1)$$

$$R_i(P_{g,i},A_i) = \lambda_P P_{g,i} + \lambda_A A_i \qquad (2)$$

$$\pi_i(P_{g,i},A_i) = R_i(P_{g,i},A_i) - C_i(P_{g,i},A_i) \qquad (3)$$

Because π_i is convex, for maximization of profit the optimal production $P_{g,i}$ and AS offering quantities A_i can be determined by setting the derivative terms in (4) and (5) to zero and solving the resulting equations:

$$\frac{\partial \pi_i}{\partial P_{g,i}} = \lambda_P - b_i - c_i P_{g,i} = 0 \qquad (4)$$

$$\frac{\partial \pi_i}{\partial A_i} = \lambda_A - d = 0 \qquad (5)$$

ANCILLARY SERVICE MARKET MODEL

In determining the AS-market price, we assume that price mechanisms (11),(12) based on imbalance in ancillary capacity (10) and power imbalance (9) are equivalent to those applied in the real-time market. Now we present the market model and dynamic behavior of the ancillary service market in a similar form as has been performed for the real-time market:

$$\tau_{g,i}\dot{P}_{g,i} = -b_i - c_i P_{g,i} + \lambda_P - k_{P,i}\dot{E} - k_{E,i}E \qquad (6)$$

$$\tau_{A,i}\dot{A}_i = \lambda_A - d \qquad (7)$$

$$\tau_{d,j}\dot{P}_{d,j} = b_{d,j} + c_{d,j}P_{d,j} - \lambda_P \qquad (8)$$

$$\dot{E} = \sum_{i=1}^{n} P_{g,i} - \sum_{j=1}^{m} P_{d,j} \qquad (9)$$

$$\dot{F} = \sum_{i=1}^{n} A_i - A^{req} \qquad (10)$$

$$\tau_A \dot{\lambda}_{AS} = -F \qquad (11)$$

$$\tau_\lambda \dot{\lambda}_P = -E \qquad (12)$$

In general the quantity of ancillary capacity A_i that a generator can provide is constrained. These constraints result in the coupling with the real power market, because $k_{P,i}$ and $k_{E,i}$ now become a function of A_i. The actual constraints for providing capacity depend on physical parameters for the generator concerned. For instance, ancillary services can in some situations only be offered in a certain limited operating range P_1 to P_2 of the considered generator. Furthermore, the maximum amount A_{max} for A_i will depend on the ramp limits of the generator, which not necessarily, have to be constant over the complete generation range P_{min} to P_{max}. For simplicity, we express the constraint for A_i as a function of $P_{g,i}$, and the figure below shows the resulting feasible region.

$$0 \le A_i \le \min(P_{g,i} - P_{\min,i}, P_{\max,i} - P_{g,i}, A_{\max}) \qquad (13)$$

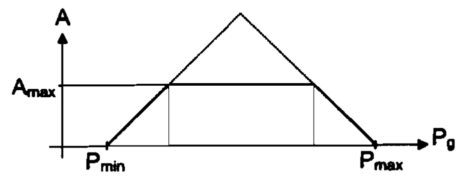


Fig 1: Feasible region for A_i and $P_{g,i}$

Directions for Future Investigation

As stated in the previous section, the resulting P_g and A_i are subject to generation limits. Expressing these limits can be approached in different ways and will be a point for further research. One possible approach is the application of a penalizing function in coupling $P_{g,i}$ and A_i. Modeling of this function can be implemented by using a non-linear continuous function that penalizes if limits are approached. In this case the system will stay continuous. Another approach is changing the system structure into a hybrid system description. In this approach, the states of the system will have to be changed according to the actual operating mode the system is in. Furthermore, the resulting coupling via $k_{P,i}$ en $k_{E,i}$, as function of A_i has to be investigated and required amount of AS in the network A_{req} is still to be determined.

References

[1] M.E.Flynn, M.P.Walsh, M.J.O'Malley, "Efficient Use of Generator Resources in Emerging Electricity Markets", IEEE Transactions on Power Systems, Vol. 15, No. 1, February 2000.

[2] V.Siriariyaporn, D.J.Gotham, F.T.Sparrow, "Determining the Cost of Uncertainty to Electric Utilities in Serving Highly Varying Loads", IEEE International Conference on Electricity Utility Deregulation, Restructuring and Power Technologies (DRPT2004), Hong Kong, April 2004