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Influence of inter area Transfer Capacity on the Regional Power System Planning

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***Abstract*-- Differences in energy prices between liberalized market regions are one of the elements to be considered during power system planning. The regional prices of electricity depend on the regional portfolio of generation units. In the paper one focus of the power system planning, namely the planning of interconnections, i.e. transmission network capacities for energy exchanges between market regions has been analyzed taking into account regional market prices of electricity. First the linear mathematical model of the energy exchanges between regions and the necessary input data are presented. The objective of energy exchanges is to minimize the supply costs in a selected area consisting of several neighbouring market regions. The simplex method was selected to solve the optimization problem. In the optimization process the Power Transfer Distribution Factors (PTDF) are used for the estimation of cross-border load flows. As an example, the results of investigation of an area with eight market regions are discussed in the paper. Moreover the sensitivity of market prices regarding changes of emission constraints for generation units is analyzed, using a method based on the marginal costs of energy production. Finally the recommendation for planning of interconnection is provided.**

***Index Terms*-- Power System Planning, Power Flow, Linear Programming, Simplex, Power Transfer Distribution Factor.**

I. Introduction

The liberalization of the energy market has initiated a new trend into energy trading. It has changed from looking for the cheapest energy in the neighborhood into looking for the cheapest energy wherever is accessible [1]. This new trend has caused an intensive increase of interregional energy exchanges and corresponding load flows. In the past the interconnections between the regions were primarily used for mutual support and security reasons. The energy flows on these interconnections have to be restricted because of thermal limits and security margins. In the present situation the transmission network is becoming more and more a market place for the commodity electricity. The new market players, represented by energy traders or Independent Power Producers are selling the energy where it is most beneficial and possible.

Because the energy sector is one of the largest producers of pollutants, the energy policy is tending to make the energy sector friendlier for the environment by promoting the renewable energies and decreasing the limits for emission of pollutions. Even if new technologies and materials improve the overall efficiency of the new power plants, there are still many old power plants which operate with low efficiency. However, if the interconnection capacities would remain unchanged and the power generation companies would shut down these old power plants without building enough new generation capacity a huge energy deficit and a loss of the secure energy supply could occur in some regions. In principle, this energy gap could be filled also by renewable energy to a certain extent. However, such an option is not available in every region. Knowing these opportunities for future development, it has to be investigated how much interconnection capacities will be necessary for energy exchanges between regions to avoid such an energy deficit and moreover to reach an integrated electricity market in the considered area.

This paper is a contribution to the answer to this question. It describes three stages of problem modeling and solving. At first, in Chapter 2, the preparation of input data is shown. Chapter 3 and Chapter 4 include the modeling of energy markets and the energy exchanges and corresponding load flows between the regions. In Chapter 5 the implementation of the proposed methodology is illustrated by an exemplary area.

II. Preparing Input Data

A. Demand

The economic demand of power that would be consumed if the system were operating normally is defined as load (L) [2]. In the model the load of each market region has a typical characteristic. The shape of load curve depends on the season, the weekday and the daytime. In the winter time the daily peak load appears in the evening at about 6 p.m. whereas in the summer the daily peak load appears at midday time, Figure 1.

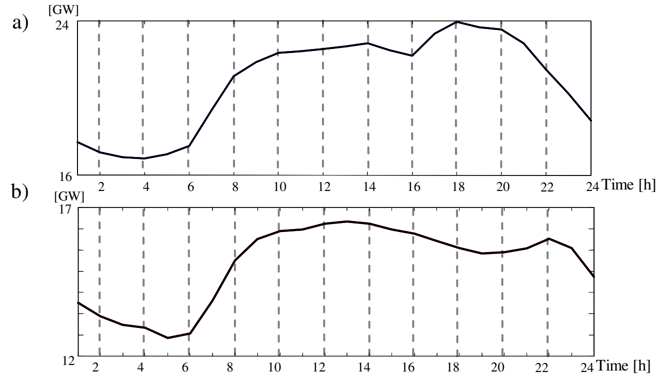

Fig. 1. Typical daily load curves in: a) winter season; b) summer season

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To model a monthly load curve where the work days and weekends are not treated separately, the hourly load curve of a typical day is repeated as often as the month has days. In the model the yearly load curve is split into three seasons as follows:

- Winter: from December till February;
- Summer: from May till August;
- Spring/Autumn: March, April, September and October.

The future development of the load is estimated according to the theory that the load correlates with the Gross Domestic Product (GDP) [3].

B. Generation

Because the total installed generation capacity is not available to cover the load the total disposable generation capacity (P_{disp}) is used in the model. The disposable generation capacity is obtained by deducting the non-available generation capacity due to maintenance and outages of generation units, and reservation of generation capacity for provision of ancillary services from the total installed generation capacity. Also unfavorable environmental conditions can cause a reduction of disposable generation capacity, e.g. if a thermal power plant cannot cool the working fluid on very hot summer days. P_{disp} can be also decreased through non-usable capacity resulting from deliberate decisions, e.g. capacity in conservation or mothballed capacity (P_{rest}) [4].

P_{disp} can be estimated by the equation as follow:

$$P^{i,j}_{disp} = P^{i,j}_{inst} - (P^{i,j}_{services} + P^{i,j}_{maint} + P^{i,j}_{outages} + P^{i,j}_{rest}) \qquad (1)$$

where:
i – current year,
j – current season,
P_{inst} – total installed generation capacity,
$P_{services}$ – generation capacity reserved for ancillary services,
P_{maint} – switched off generation capacity due to maintenance,
P_{outage} – switched off generation capacity due to outages,
P_{rest} – rest of non-usable generation capacity.

The disposable generation capacity represents the capacity which is available to the market to cover customers' demand, i.e. load. Both L and P_{disp} can vary during the year, e.g. the largest part of the maintenance work takes place in summer when the load is lower than in winter.

The generation reserve (P_{Res}) of a market region is defined as the difference between P_{disp} and L of the market region.

In case P_{Res} is negative and not enough generation reserve in neighboring market regions and corresponding interconnection capacity for import (P_{import}) are available the load of the market region cannot be completely covered. To keep the power system in balance an equivalent part of the load must be shed, Figure 2. Increasing P_{inst} and interconnection capacities are alternative measures to reduce the risk that such situation occurs.

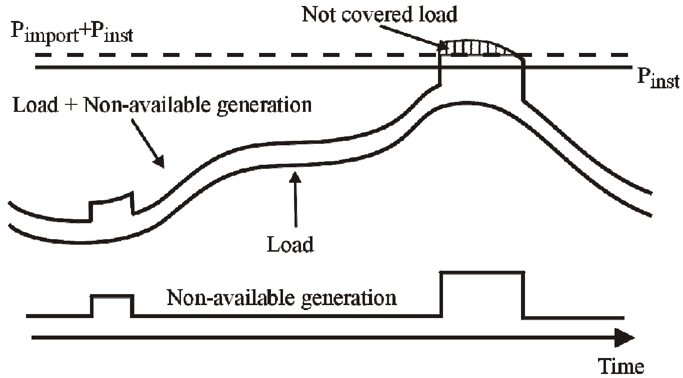

Fig. 2. Example of not covered load of a market region

III. Market Modeling

The energy exchange between the regions will be stimulated by the market prices for electricity, based on marginal costs of electricity production. Every region has an own price structure, depending on generation portfolio marked by e.g. used primary energy sources and efficiency of generation units. In regions with more or less homogeneous generation portfolio (e.g. hard coal power plants with similar efficiency) the electricity price is almost independent of the generated amount of electricity. In regions with contrary situation, i.e. with diversified generation portfolio the electricity price depend strongly on the amount of generated electricity.

The marginal costs of electricity production have been estimated for diverse technologies such as hard coal power plants; brown coal power plants, etc. For each market region which is represented in the model by a single node, the electricity production costs have been evaluated through the Levelized Unit Energy Costs (LUEC) method (2). This methodology makes it possible to evaluate the electricity production costs against the generated electricity [5].

$$C_{kWh} = \frac{I}{h} \cdot \left[\frac{r}{1-(1+r)^{-y}} \right] + \frac{M\,\&O}{E_{el}} + \frac{p_f \cdot \dot{m}_f}{E_{el}} \qquad (2)$$

C_{kWh} – average lifetime levelized electricity generating cost,
I – specific investment costs,
h – equivalent full load hours in the year t,
$M\&O$ – maintenance and operation costs in the year t,
r – discount rate,
y – life time,
E_{el} – electricity generation in the year t,
p_f – average fuel price in the year t,
$\dot{m}_f$ – consumed fuel in the year t.

The electricity production costs constitute the basis for building the regional "Day-ahead" market price for electricity. Each supplier (e.g. trader, operator of power station) will deliver offers for each hour of the following day. An offer is characterized by a price and the quantity of electricity that can be supplied at this price.

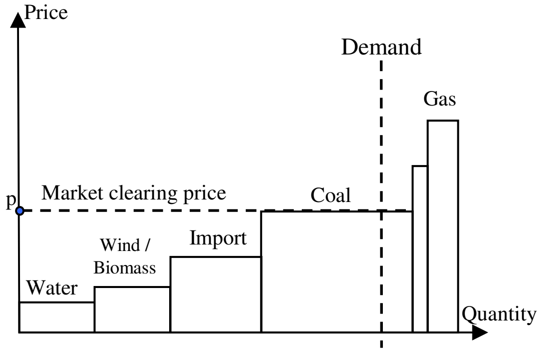

Fig. 3. Electricity price modeling

The power exchange collects all offers of all suppliers and sorts the offers according to the price in ascending order. It results in a sequence for usage of offers, the so called Merit-Order-List of the regional market, Figure 3. The price of the offer, which is needed to cover the demand, determines the regional market price. So, the market price is the point where the demand curve intersects the supply curve, Figure 3. This intersection is the market equilibrium and defines the conditions necessary to determine a market-clearing price. This equilibrium point represents a combination of price and quantity at which buyers and sellers are mutually better off by trading. Market equilibrium price is given with *p* on the vertical axis, and market equilibrium quantity traded is given on the horizontal axis, Figure 3. The equilibrium point is said to be efficient because society is making the best possible use of its resources [6].

The energy exchange (import or export) will take place depending on the regional market prices for electricity. Electricity is transferred from regions where the price is low to regions where the price is high, Figure 4.

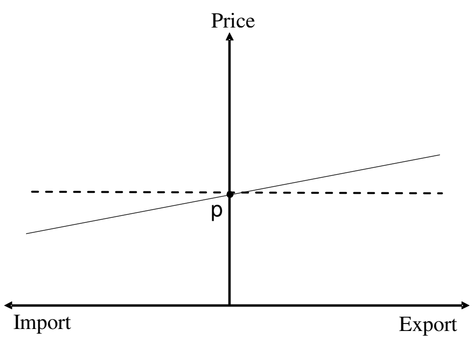

Fig. 4. Impact of energy exchange on regional market price

The formulation of the competitive energy market will determine the concentration of supply in the analyzed case. The concentration is measured with the Herfindahl-Hirschman Index (HHI). This index is defined as follows:

$$HHI = \sum_{i=1}^{N} s_i^2 \tag{3}$$

where the summation is over all N participants in the market (in this case there are eight regions), while *s* refers to the market share of each defined as:

$$s_i = \frac{E_i + E_{i(exp)}}{E_{total}} \tag{4}$$

E_i indicates the energy production to serve the demand in region *i*, $E_{i(exp)}$ indicates the energy produced for the export and E_{total} is the total energy production in the considered area. The share *s* can be expressed in per unit (in which case the maximum value of HHI is 1) or in percent (in which case the maximum value of HHI is 100) [7]. An increase in the HHI index generally indicates a decrease in competition on the market and an increase of market power (a monopolistic-oligopolistic market), while a decrease indicates the opposite (competitive market).

IV. Realization of Market Transactions

The physical realization of energy exchanges between market regions cause cross-border power flows according to Kirchhoff's laws, which means that a transaction between two market regions loads all interconnections of the network to an extent determined primarily by the impedances of the network branches. For that reason PTDF are used in the model to transfer scheduled commercial flows into estimation of real physical power flows. Each PTDF shows what relative share of an energy exchange between two market regions appears as power flow in a certain transmission line or e.g. group of cross-border lines as result of this energy exchange.

The PTDF can be calculated using a DC power flow. The calculation is based on the general equation [I]=[Y][U] where [I] is a vector of nodal current which is injected or drawn in nodes, [Y] is a nodal admittance matrix and [U] is a vector of nodal voltages.

The nodal admittance matrix is an n-by-n matrix, where *n* is the number of nodes:

$$Y_{ij} = \begin{cases} -\dfrac{1}{Z_{ij}} & \text{, if i} \neq \text{j} \\ \displaystyle\sum_{j \in n_i} \dfrac{1}{Z_{ij}} & \text{, if i = j} \\ 0 & \text{, if i = j and there is no direct i-j connection} \end{cases} \tag{5}$$

Using the equation for a current I_i which is given by:

$$I_i = Y_{ii} \cdot U_i + \sum_{j=1}^{n}{}_{j \neq n} Y_{ij} \cdot U_j \tag{6}$$

one can evaluate the power injected into the node or required from the node:

$$P_i = I_i \cdot U_i = Y_{ii} \cdot U_i^2 + \sum_{j=1}^{n}{}_{j \neq n} Y_{ij} \cdot U_j \cdot U_i \tag{7}$$

According to (7) one can calculate a base case flow for each line in the network. To calculate the PTDF for line *i-j* and for a particular transaction from market region A to market region B a DC power flow calculation is performed for an additional 100 MW transfer from the source of the transaction (node representing the market region A) to the sink of the transaction (node representing market region B). The PTDF is calculated with the following equation:

$$PTDF_{ij} = \frac{P_{ij}^{base\ case+100MW} - P_{ij}^{base\ case}}{100\,MW} \tag{8}$$

V. Exemplary Implementation

The presented methodology was applied for an exemplary area where the costs of energy supply in market region 'A' have to be minimize, Figure 5.

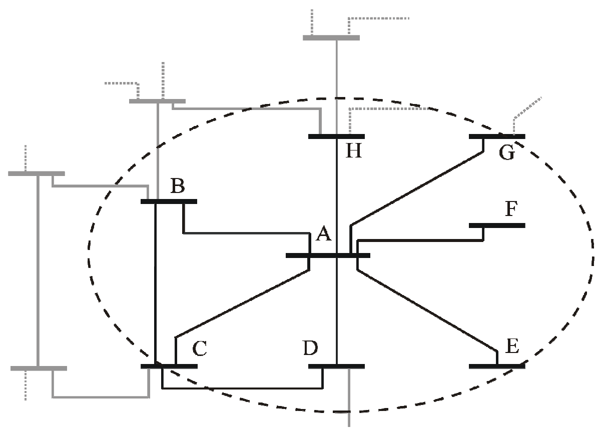

Fig. 5. Topology of interconnections of analyzed area

In this scenario, a power deficit (i.e. negative P_{Res}) in region 'A' is expected, which is mainly caused by the rapid increase of energy demand in connection with a hesitant replacement and extension of the outdated power generation sector. This deficit of energy should be compensated with energy imports from other market regions. The corresponding energy trades take place on the respective markets. Depending on the marginal costs of the power plants in region A and on the electricity prices in the surrounding regions, electricity can be both imported to and exported from region A.

The main reason for differences between market prices of the regions is the different diversification in the generation sector with regard to electricity generation technology. Energy sector of each market region is characterized in Table I.

The mathematical model evaluates the benefit of increasing interconnection capacities between regions taking into account prices and energy transmission conditions.

TABLE I
General Characteristic of the Market Regions

	A	B	C	D	E	F	G	H
P_{inst} [GW]	25	100	20	8	50	8	7	30
En.prod. [TWh/a]	144	570	75	30	170	30	14	150
En.demand [TWh/a]	130	555	60	25	140	30	9	135
CB*) [MW]	6000	3500	5300	2000	250	150	1200	600
Energy mix [%]								
Lignite	25	20	55	-	-	-	-	-
Gas	3	16	2	-	20	-	-	-
Nuclear	-	18	20	30	50	-	45	30
Solar	-	2	-	-	-	-	-	-
Hard coal	62	23	4	40	25	99	40	16
Water	9	5	12	30	5	1	15	50
Wind	1	16	7	-	-	-	-	4

*) Total Cross-Border Capacity

The power flow in the network is optimized by using a linear programming algorithm. With the aim to minimize the costs for covering load in market region 'A' the objective function is defined as:

$$z_A = p_A x_A + \sum_{n=B}^{H} p_n x_n \rightarrow min \tag{9}$$

With constraints as follow:

$$\begin{aligned} &|x_n| \le P_{line} \\ &x_n \le P_{Res,n};\ P_{Res,n} \ge 0 \\ &x_n \ge P_{Res,n};\ P_{Res,n} \le 0 \\ &0 \le x_A \le P_{disp,A} \end{aligned} \tag{10}$$

n = B, C, D, E, F, G, H – node assignment,
z_A – cost for covering load in node 'A',
p_n – electricity price (market clearing price) in node n,
p_A – electricity price in node 'A',
x_n – current exchange between node n and node 'A',
x_A – used production capacity in node 'A',
P_{line} – interconnection capacity (e.g. P_{B_A} – interconnection capacity between node 'B' and node 'A'),
$P_{Res,\ n}$ – generation reserve in node n,
$P_{disp,\ A}$ – disposable generation capacity in node 'A'.

It is also assured that each region is balanced. The power balance in the region 'A' is defined as:

$$\sum_{n=A}^{H} x_n = L_A \tag{11}$$

The constraints considering the PTDF for the analyzed network are:

$$x_B \cdot \begin{bmatrix} PTDF_{B\_A} \\ \vdots \\ PTDF_{C\_D} \end{bmatrix} + \ldots + x_H \cdot \begin{bmatrix} PTDF_{B\_A} \\ \vdots \\ PTDF_{C\_D} \end{bmatrix} \le \begin{bmatrix} P_{B\_A} \\ \vdots \\ P_{C\_D} \end{bmatrix} \tag{12}$$

where P_{B_A} represents the interconnection capacity between region 'B' and region 'A'. Because of direct connection of regions 'E', 'F', 'G' and 'H' with region 'A' the PTDF for this connections equals 1.0, Table II. Because of these constraints there is a guarantee that the increase of interconnection load, caused by realization of the transaction, will not exceed the interconnection capacities. The parameterization of the analyzed area is shown in Figure 6.

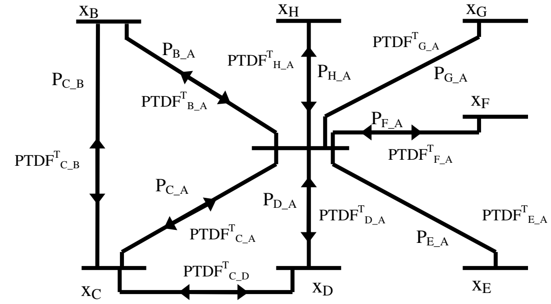

Fig. 6. Parameterization of the model

The PTDF for all interconnections and possible transactions are shown in Table II. The rows represent interconnections, whereas the columns the transactions.

TABLE II
PTDF FOR ANALYZED MODEL

	B->A	C->A	D->A	C->B	C->D	E->A	F->A	G->A	H->A
B_A	0.5	0.35	0.31	-0.15	0.04	0	0	0	0
C_A	0.35	0.47	0.36	0.13	0.12	0	0	0	0
D_A	0.16	0.14	0.33	0.02	0.15	0	0	0	0
C_B	-0.3	0.18	0.09	0.55	0.16	0	0	0	0
C_D	0.05	0.17	-0.45	0.12	0.62	0	0	0	0
E_A	0	0	0	0	0	1	0	0	0
F_A	0	0	0	0	0	0	1	0	0
G_A	0	0	0	0	0	0	0	1	0
H_A	0	0	0	0	0	0	0	0	1

In the first phase of the optimization an energy exchange takes place only between the neighbors of region ‘A’. Because only regions ‘A’, ‘B’, ‘C’ and ‘D’ are intermeshed this phase will influence the energy exchange made in step two. The energy exchanges are limited to the interconnection capacities and the generation reserves in the market region.

The second phase of the optimization concerns region ‘A’. The load of the region is covered by disposable generation capacity of region ‘A’ and imports as long as the market price of neighboring regions is lower than in region ‘A’ and the interconnection capacities are not exceeded.

Export from region ‘A’ can happen if the electricity price of the neighboring region is higher than in region ‘A’.

The estimation of price equilibrium in the analyzed network is accomplished with the help of linear programming, see Figure 8. For that, the simplex method was selected and implemented in the model. This method permitted only one goal function to be optimized, which in this case, was the cost function for region ‘A’. The solution is achieved with respect to technical and market constrains described above.

Energy trading without consideration of technical restrictions could cause an overload of interconnections. Therefore, an implementation of PTDF allows the estimation of load flow on interconnections. This consists of more than one single flow because of loop flows. The total flow will be defined using the superposition method, see Figure 7.

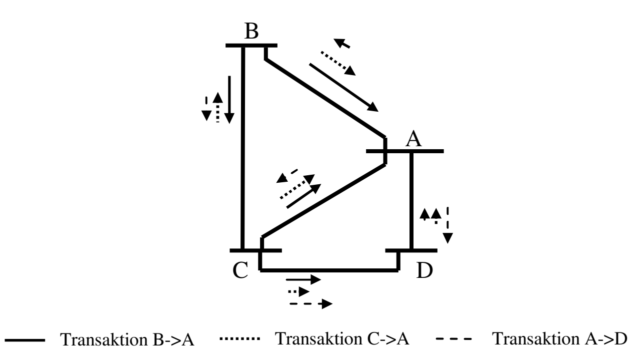

Fig. 7. Total flow resulting from the superposition method (here only for 3 transactions)

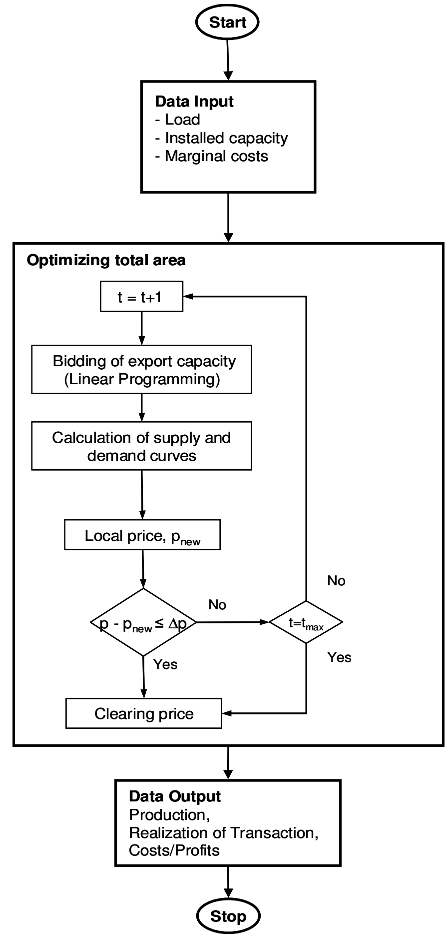

Fig. 8. Flow diagram for estimation of market equilibrium

The monitoring of total power flow, for example, on the interconnection from region B to region A (B_A) shows that the interconnection will be fully loaded 80% of the year, which the duration curve of load on this interconnection shows, Figure 9.

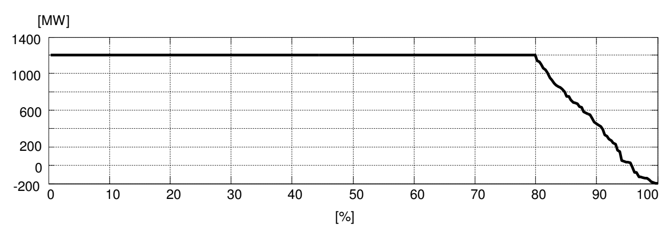

Fig. 9. Duration curve of load on interconnection B_A (P_{B_A} = 1200MW)

The simulation constrains have limited the transfer on the interconnection B_A to 1200MW, but without any transfer constraints the exchange would be much higher, just because of price differences between region ‘A’ and region ‘B’. This helps to identify bottlenecks in the network and indicates the need for extension of network infrastructure to achieve an unlimited market driven energy transport between the regions.

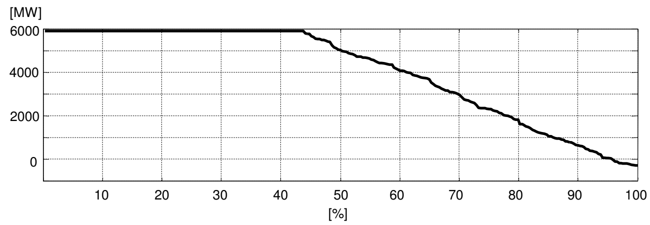

Fig. 10. Duration curve of load on interconnection B_A (P_{B_A} = 10GW)

The increase of transfer capacity on the interconnection B_A to 10 GW allows a free energy transport between regions 'A' and 'B' until the prices in both regions are equal or the transfer was limited by other line in the network. The line is loaded, during 45% of the year, with 60% of the maximal line transfer, Fig. 10.

The analyzed model considers also the market development with the time horizon of the next 14 years. The mentioned index HHI allows us to distinguish if the market has a monopoly character or a liberalized one.

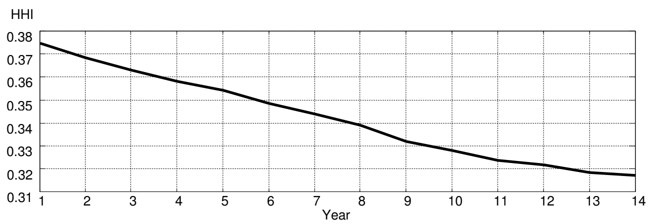

Fig. 11. Market development during the next 14 years

A high HHI index value indicates that the market has a monopoly character where one or a few energy suppliers sell all of the electricity. On the other hand, a low value of the HHI index indicates a more competitive market. Figure 11 shows the HHI index evaluated for the eight considered regions. According to the threshold level given by Federal Energy Regulatory Commission (FERC) the analyzed market is characterized by a high concentration of suppliers because the HHI is greater than 0.18.

VI. Summary

The focus of this study was the consideration of optimal interconnection planning under the influence of the different price structure between the regions. The results of the analysis show clearly that a rapid increase of the power demand in a region in connection with an insufficient development of the power generation sector can lead to an appreciable worsening of the security of supply. The results show also that if an energy deficit occurs, the transmission infrastructure will not be prepared for importing the necessary amount of energy. Because of that and the expected differences of market prices the interconnection capacity must be increased.

From the market point of view, interconnection capacities will introduce better conditions for trading between the market regions.

In this contribution the planning of the interconnections taking into account the development of the electricity prices in the regions has been analyzed. The mathematical model describes the market driven energy exchange between several market regions with consideration of technical constraints. In the model the Power Transfer Distribution Factors (PTDF) for the estimation of load flows resulting from energy exchanges were used. The simplex method was selected to solve the optimization task described by the model. As an example, the results of the analysis of an area with eight market regions were given and discussed.

Finally, recommendations for development of interconnection capacities derived by means of the proposed method have to be verified by in-depth studies taking into account all relevant aspects of transmission system planning.

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VIII. Biographies

Tomasz Smieja studied electrical engineering at the Wroclaw University of Technology, Poland. He graduated in 2005 at the Otto-von-Guericke-University Magdeburg. Since 2005 he has been with the Chair of Electric Power Networks and Renewable Energy Sources at the Otto-von-Guericke-University Magdeburg, Germany as a research assistant.

Pio Lombardi studied mechanical engineering at the Politecnico di Bari, Italy. He graduated in 2006 at the same university with degree M.Sc. He joined the Chair of Electric Power Networks and Renewable Energy Sources at the Otto-von-Guericke University Magdeburg, Germany as a research engineer in 2006. His primary field of interest is the optimization of virtual power plants.

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Swen Löppen studied electrical engineering, graduated and received in 2007 his PhD at the RWTH Aachen University, Germany. From 1999 till 2005 he worked as scientist at the Institute of Power Systems and Power Economics (IAEW) at the RWTH Aachen University. Since 2005 he has been worked for the Transmission System Operator Vattenfall Europe Transmission GmbH, Germany. His special fields of interest include network planning and operation, congestion management systems, market modeling and regulatory management.