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Future Electric Power Systems: Structure and Transition Mechanism

M. Yu. Vasilyev

***Abstract*--The paper analyses structural changes in deregulated electric power systems (EPS), which should take place in the future if the current trends and conditions remain. The circumstances are considered which define the current EPS functioning and its future structural changes. The mechanism of the restructuring and the boundary conditions, which will start the mechanism, are described.**

***Index Terms*--regulation of electric power industry, unbundling.**

I. Introduction

Although EPS in different countries are restructured in different ways, the main elements of electricity markets tend to be the same. Unbundling of transmission from generation and consumption is among these common elements. The transmission networks are regulated and function as guaranteed monopolies. Some disadvantages of this kind of regulation, such as higher transmission prices and lower capacities, are discussed in [1, 2].

The cost-based regulation of the network requires that all the costs are taken into account and divided between the network users, including the costs to release congestions. The infrastructural approach to the network regulation requires that all the congestions are released. It's usually a responsibility of the network company to connect new entities to the network, sometimes including the connection costs into the transmission fees for all participants. These regulation elements can vary in different countries, but still are applied often.

Taking into account the feedback between the regulator and the regulated entity – the regulator regulates the company and the company manipulates the regulator – the transmission prices will tend to increase in many, if not all, electricity markets.

At the same time there is a long-term trend of decreasing costs of electricity, produced by photovoltaics (PV), wind generators (WG) and other alternative generating units. This trend is based both on efficiency growth and decrease of investments per 1 megawatt of installed capacity. Step by step this kind of generation becomes more competitive in comparison with conventional EPS.

Further development of these two trends should lead to essential structural changes in deregulated EPS. Part II of this paper focuses on circumstances, which define these changes. Part III describes the boundary conditions, which start the restructuring mechanism, and the mechanism itself. Probable inefficiencies are mentioned. Part IV contains a simple model and an example illustrating some essential dependences. The conclusions and references complete the paper.

II. Current Circumstances

The future structural changes are defined by the following circumstances:

– monopolistic guarantees for network but not for generating companies;
– infrastructural approach to network regulation: all the bottlenecks must be released and the costs are included into the transmission tariffs;
– the “non-discriminatory” network access, which does not allow network companies to cover all the connection costs from the entity connected;
– decrease of costs of electricity generated by PV, WG and other generating units, which can be installed close to consumers.

Let us consider the circumstances more in detail.

A. Network monopolistic guarantees

It is one of the most essential and common elements of modern electricity markets. Transmission networks are separated from generation and consumption and regulated since they are considered as “natural” monopolies. Generators and consumers can not keep away from the network company even if they do not like transmission prices.

In Russia it is organised in the following way [3, 4]. Many entities are allowed to construct new lines and connect the lines to the grid, but the line owner can not conclude contracts for electricity transmission and define the terms of the contracts. He must make an agreement with the network company and pass the rights to operate the line and to conclude contracts. The expenses of electricity transmission should be accounted separately and the transmission prices are regulated. Generating companies and consumers are not allowed to construct and own lines, except for lines 110 kV or lower which are owned by consumers and used for their own needs only.

So, the network monopoly is protected. In fact, only those consumers can avoid paying regulated prices, which construct

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M.Yu. Vasilyev is with Energy Systems Institute, Lermontov str. 130, 664033, Irkutsk, Russia (e-mail: vassiliev@ieee.org).

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their own direct lines 110 kV or lower directly to a generator. And the direct line regime is not specified explicitly by laws in Russia what makes a direct line construction quite risky. All the other entities have to deal with the guaranteed monopoly – the Federal grid company – and to pay its prices.

As discussed in [5] the prices of guaranteed monopolies tend to increase. So, in countries, where generators and consumers can not avoid paying regulated prices of transmission monopolies, we should expect long-term growth of transmission (and electricity) prices.

B. Infrastructural approach to bottlenecks

Another popular element of network regulation is the idea, that all congestions should be released. Transfer capability of any line should always exceed the power flow in this line under market equilibrium. It equalizes electricity prices and makes electricity market more efficient. To reach the desired conditions new lines are constructed and the existing ones are reconstructed. And the costs of reconstruction, inevitably, are included into regulated transmission fees.

There are two main results of releasing a bottleneck in a dispersed EPS: higher transmission prices and equalized electricity prices. For some generators and consumers the benefit from changed electricity prices covers losses from higher transmission prices. But some users lose from both price changes. If they cancel operation the transmission prices should become even higher because the same network costs are shared between fewer users.

A small example below shows a situation, in which a congestion in a dispersed EPS (low generation/consumption within a big region) should not be released, otherwise it leads to ever increasing transmission prices and, finally, to bankruptcy of the network company and some system users.

The EPS of Russia (especially, Siberia and Russian Far East) is dispersed. The infrastructural approach, announced by [3] can lift transmission prices quite high.

C. Connection of new entities to the network

One more regulatory element, which can pull the network prices up if applied in a certain way, is the “non-discriminatory network access”. “Non-discriminatory” means that the same conditions should be applied to all network users: existing and new. Different connection prices can, certainly, be understood as a kind of discrimination.

But if the connection prices are equalized a kind of cross-subsidization arises - the entities, which are close to the existing network, should cover a part of costs to connect the entities, which are far from the network.

When a new entity is connected to the network, some lines may become congested. And the costs to release the new congestions should be allocated to the entity connected. Otherwise another kind of cross-subsidization arises.

These two kinds of cross-subsidization create wrong market signals. New power plants and consuming assets will be constructed without taking into account the corresponding costs of network expansion. The costs will grow and transmission prices as well.

D. Progress in alternative electricity production

Costs of electricity, produced by PV and WG, decrease both because of growing efficiency and decreasing installation costs. Currently, PV-electricity can be produced at a cost of 8-10 cents per kilowatt/hour [6]. Within the coming years alternative generation is expected to become more and more competitive and applied widely by electricity consumers.

E. Other factors

Some other factors, which can contribute to the structural changes, should be mentioned briefly. So, high oil and gas prices make alternative generation more competitive. Also, some kinds of regulation can influence. For example, in Germany the prices of electricity, produced by WG and PV, are fixed. The corresponding costs are allocated to all consumers. Depending on how this kind of regulation is organised it can stimulate structural changes.

III. Boundary Conditions and Mechanism

A. Boundary conditions

Structural changes will become probable when the following boundary conditions will be met for many electricity consumers:

1. Costs of conventional power supply (buying electricity at the market through regulated networks) exceed costs of own generation.
2. Costs of delivering electricity through regulated network exceed costs of delivering through own lines (if possible).

When the first condition is met for a certain consumer the conventional power supply is not the best alternative for the consumer any longer. He is interested in installing an own PV or WG nearby. It depends on prices if the consumer will remain connected to the network to use ancillary services (frequency and voltage adjustment, reserves and so on).

When the second condition is met the consumer is interested in constructing his own line directly to the nearest generator to receive electricity apart from the regulated network company, if possible. Since high-voltage lines function as guaranteed monopolies, large consumers will construct medium- or low-voltage lines what means higher investments and losses for the same amount of electricity transferred.

These boundary conditions are already met for some consumers. It does not yet lead to great structural changes because the amount of such consumers is still small. Usually these consumers either are far from EPS or have good sun/wind conditions combined with high electricity prices in the region. But as the above mentioned trends remain, more and more consumers will decide for own PV, WG and networks. As soon as number of such consumers reaches a certain level the following mechanism will start.

B. Mechanism

When at least one of the boundary conditions is met for many electricity consumers they start to install own generating units and to construct own medium- and low-voltage lines to the nearest power plants. Some of these consumers disconnect themselves from the regulated network, other ones decrease electricity consumption from the network. Microgeneration and microgrids, integrated with consumers, boom.

The income of regulated network companies decreases because some users are disconnected and some other pay less. Since the prices are regulated they start to grow to cover the lack of income. The new growth forces more consumers to decide for own generation and lines. And so on.

Since consumers pay less for electricity supply and the network income is the same due to regulation, income of generators, which are not integrated with consumers, decreases. They have to decrease prices to prevent further fall of demand and to stimulate consumption growth close to the power plants. In some cases they might invest into technologies, which consume a lot of electricity, say, aluminium or hydrogen production.

As a result of this mechanism large EPS will be disintegrated into many microEPS, connected by the regulated network (some of them might be completely disconnected). The regulated network will charge very high prices and will be close to bankruptcy (hopefully, not bankrupted at all). The main function of the network is not transmission of big amounts of electricity any longer, but supply of ancillary services from/to generators and microEPS: frequency and voltage adjustment, reserves and so on.

C. Inefficiencies

The main reason of the economic inefficiency is that the existing capital (high-voltage transmission system) becomes too expensive to use because of corresponding regulatory conditions. System users try to minimize their usage of the network. There is excessive duplication – new generators are constructed while existing units can cover the demand at reasonable costs, private microgrids duplicate regulated networks.

Electricity losses grow since the electricity is transmitted on lower voltage levels.

For technical reasons smaller generating units may be less efficient, than larger units. Smaller generators win competition just because they can be installed close to consumers and, thus, allow to decrease payments for the monopolistic network.

The power plants, which fail in integrating with consumers and in developing new loads, become less profitable, and, probably, go bankrupt. These are sometimes not really inefficient plants, but those, which are far from consumers and, for some reasons, can not develop own consumption. Large off-shore wind farms are, in my opinion, quite close to this unpleasant condition. Hopefully, they will survive because of their zero marginal costs.

Possibilities for centralized optimization of generation (both operation and expansion) decrease. Nowadays market prices serve as a tool for quasi-centralized optimization of generation. Real optimization is possible in generating companies, which operate several or many power plants. As far as amount of microgeneration grows drastically, EPS become less efficient, since it is nearly impossible to optimize so decentralized systems.

Because of many inefficiencies and probable bankruptcy of network companies and some power plants new re-regulation of electric power industry will be necessary.

IV. Modelling the Changes

A. Simple Model

Let us consider a simple 2-node system with many consumers and producers connected to each node. The transmission line (or system) between the nodes entirely belongs to and is operated by the specialized network company (NC). The producers are described by their total supply functions

$$P_1(w_{g1}) = a_1 + b_1 \bullet w_{g1}, \qquad (1)$$

$$P_2(w_{g2}) = a_2 + b_2 \bullet w_{g2}, \qquad (2)$$

where P_1, P_2 are the prices in the nodes *1* and *2*, respectively;
w_{g1}, w_{g2} are amounts of electricity produced by all generators in the nodes *1* and *2* respectively;
a_1, a_2, b_1, b_2 are parameters of the supply functions.

The consumers are described by their total demand w_{c1} and w_{c2} (amounts of electricity consumed). Since the consumers are considered as inelastic the market equilibrium can be found as

$$min\left(\int_0^{w_{g1}} P_1 \, dw_{g1} + \int_0^{w_{g2}} P_2 \, dw_{g2}\right) \qquad (3)$$

with constraints

$$w_{12} = w_{g1} - w_{c1}, \qquad (4)$$

$$w_{21} = -\, w_{12} \bullet \Delta, \qquad (5)$$

$$w_{21} = w_{g2} - w_{c2}, \qquad (6)$$

$$w_{12} \le w_{line\ max}, \qquad (7)$$

$$w_{21} \le w_{line\ max}, \qquad (8)$$

where w_{12} is the energy transmitted through the line (system) from node *1* to node *2* if measured at node *1*;
w_{21} is the energy transmitted through the line (system) from node *2* to node *1* if measured at node *2*;
Δ reflects losses in the transmission line (system);
$w_{line\ max}$ is the maximum transfer capability of the line (system).

Expenses of the transmission company (E_{NC}) are covered by consumers only and, thus, the transmission price is calculated as

$$P_{NC} = \frac{E_{NC} - I_{NC}}{w_{c1} + w_{c2}}, \qquad (9)$$

where I_{NC} is the income of the network company due to the price difference between the nodes (the network is considered to buy electricity in one node and sell in the other)

$$I_{NC} = w_{12} \bullet P_1 + w_{21} \bullet P_2. \qquad (10)$$

If NC reconstructs the line to increase the transfer capability, the expenses increase proportionally

$$E'_{NC} = \frac{E_{NC} \cdot w'_{line\,max}}{w_{line\,max}} \quad , \tag{11}$$

where ' indicates expenses and transfer capability after reconstruction.

Consumers in each node have their alternative costs of generation and transmission. If the transmission price exceeds a certain value

$$P_{NC} > P_{NC\,max\,1}, \tag{12}$$
$$P_{NC} > P_{NC\,max\,2}, \tag{13}$$

consumers decide for their own direct lines to generators of the same node. If the total price of electricity supply exceeds a certain value

$$P_1 + P_{NC} > P_{1\,max}, \tag{14}$$
$$P_2 + P_{NC} > P_{2\,max}, \tag{15}$$

consumers decide for their own generation.

B. Algorithm

The algorithm is very simple: for the given initial data the prices and electricity amounts are calculated as result of optimization (3) with constraints (1)-(2) and (4)-(8). If the line (system) is congested

$$w_{12} = w_{line\,max} \text{ or } w_{21} = w_{line\,max} \tag{16}$$

the NC reconstructs it, if the constraints (12)-(15) are met the consumers construct their own transmission lines or generators. A new optimization of (1)-(8) is made for the new data. The algorithm is over when the line (system) is not congested and no a single constraint (12)-(15) is met.

C. Example

An example was calculated for the initial data given in Table 1. The step-by-step results are provided in Table 2.

Step 1. After step 1 criteria (12)-(15) are not met but the line is congested. The NC has to release the congestion and to increase the transfer capability of the line. The new transfer capability can be found from (1)-(6). It equals $w'_{12} = 20.83$ *eu*.

Step 2. The NC reconstructs the line (system) to increase its transfer capability to 21 *eu*. The price in the node *1* and the transmission price increase and the constraint (14) is met, what forces consumers in the node *1* to construct their own generating units.

Step 3. Consumers in the node *1* construct generating units, which produce 10 *eu*. The other 4 *eu* they receive from the network. After optimization we can see that the network is congested again. Now it needs 24.4 *eu* of transfer capability.

Step 4. The NC reconstructs the line (system) to increase the transfer capability to 25 *eu*. The transmission price increases and consumers in the node *2* construct lines with the total transfer capability 10 *eu* directly to generators. Since this power flows aside from the NC it should be excluded from the denominator of (9). The consumption from the grid and generation into the grid is 10 *eu* lower.

Step 5. Because of lower consumption from the grid the transmission price becomes higher, what forces consumers of the node *1* either to construct new lines directly to the generators or to install new generating units. They decide for new lines because it is cheaper (5.26 *pu* + 2.2 *pu* < 7.5 *pu*). Consumers in the node *2* also want to construct new lines to receive directly all the electricity generated by the power plants in the node *2*.

Step 6. Consumers in the node *1* construct direct lines with transfer capability 4 *eu* to the generators in the same node. Consumers in the node *2* construct direct lines with transfer capability 2 *eu* to the generators in the node. The electricity, which is transmitted through new lines, is excluded from the denominator of (9) and, therefore, the transmission price grows further. Consumers in the node *2* want to construct their own generation.

Step 7. Additionally 20 *eu* of generation in the node *2*. Transmission price becomes 46 times higher than at step *1*. The price for the consumers in the node *2* is twice higher than the alternative generation costs. NC is close to bankruptcy.

TABLE 1
INITIAL DATA

Parameter	Volume		Parameter	Volume
Generators and consumers				
a_1	1		b_1	0.15
a_2	2		b_2	0.3
w_{c1}	14 *eu*		w_{c2}	35 *eu*
Network				
$w_{line\,max}$	15 *eu*		Δ	0.95
E_{NC}	50 *cu*			
Alternative generation and transmission				
$P_{NC\,max\,1}$	2.2 *pu*		$P_{NC\,max\,2}$	2 *pu*
$P_{1\,max}$	7.5 *pu*		$P_{2\,max}$	8.8 *pu*

**eu* – electricity units, *pu* – price units, *cu* – currency units.

TABLE 2
STEP-BY-STEP CALCULATION

Variable/ Parameter	Step						
	1	2	3	4	5	6	7
w_{g1}, *eu*	29	34.83	25	28.4	28.4	28.4	7.35
w_{c1}, *eu*	14	14	14	14	14	14	14
P_1, *pu*	5.35	6.23	4.75	5.26	5.26	5.26	2.1
w_{g2}, *eu*	20.75	15.21	15.05	11.82	11.82	11.82	11.82
w_{c2}, *eu*	35	35	35	35	35	35	35
P_2, *pu*	8.23	6.56	6.52	5.55	5.55	5.55	5.55
w_{12}, *eu*	**15**	20.83	**21**	24.4	24.4	24.4	3.35
w_{21}, *eu*	-14.25	-19.79	-19.95	-23.18	-23.18	-23.18	-3.18
$w_{line\,max}$, *eu*	15	21	21	25	25	25	25
I_{NC}, *cu*	36.96	0.22	30.22	0.26	0.26	0.26	10.6
E_{NC}, *cu*	50	70	70	83.33	83.33	83.33	83.33
P_{NC}, *pu*	0.27	1.42	1.02	**2.13**	**2.86**	3.58	12.53
P_1+P_{NC}, *pu*	5.62	**7.65**	5.77	7.39	**8.12**	-	-
P_2+P_{NC}, *pu*	8.49	7.99	7.54	7.68	8.41	**9.13**	**18.08**

* The variable which starts the next step is marked bold.

The generators in the node *1* produce 4 times less electricity than at step 1. They are also close to bankruptcy although they are more efficient than generators in the node 2.

D. Analysis

From the example we can see how stable and rather efficient situation (Step 1) leads to bankruptcy of some companies (Step 7) just because of the infrastructural approach to network development. And vice a versa, if a regulator considers congestions and different nodal (or regional) prices as normal phenomena of network operation, a dispersed system will function stably with reasonable transmission and electricity prices.

More concentrated system still will be able to survive. If we assume twice lower line (system) reconstruction expenses in the example above (more concentrated system needs lower costs to improve transfer capability) and instead of (11) use

$$E'_{NC}=\frac{E_{NC}\cdot w'_{line\,max}}{2\cdot w_{line\,max}}\quad , \tag{17}$$

the calculation ends at step 2 with the following results:

I_{NC} = 0.22 *cu*,
E_{NC} = 60 *cu*,
P_{NC} = 1.22 *pu*,
$P_1 + P_{NC}$ = 7.45 *pu*,
$P_2 + P_{NC}$ = 7.78 *pu*,

all the other variables are like in Table 2 (step 2). The system remains stable with no bankruptcies.

Not only infrastructural approach to system development can make the market situation unstable. Any factor which pulls transmission or electricity supply prices up can bring the same result: new system users connected to the network without paying full connection costs, special network taxes, obligatory fees for “green” generation and, finally, monopolistic guarantees for transmission companies.

V. Conclusions

The trend of increasing transmission prices, defined by widely used regulatory approaches, combined with trend of decreasing costs of electricity, produced by photovoltaics, wind generators and other generating units, will result in structural changes in electric power systems. The main features of the new structure:

– development of generation integrated with consumers;
– development of grids between consumers and power plants;
– decreasing profitability of power plants, which have no possibility to integrate themselves with consumers or develop own consumption;
– decreasing efficiency of electric power industry because of excessive duplication, higher losses, lack of possibilities for optimization;
– growth of regulated transmission prices and decreasing profitability of regulated network companies;
– change of network function from electricity transmission to providing ancillary services.

To postpone and soften the structural changes and to prevent the corresponding inefficiencies regulation of transmission networks should be modified. Entities should be allowed to construct and operate new lines without any rights restrictions. Infrastructural approach to bottlenecks should be avoided, at least within dispersed electric power systems. Any new entity should pay all the costs of its connection to the network, including new lines and costs to release corresponding bottlenecks. Other regulatory elements, which can increase network or electricity prices, should be avoided or applied carefully.

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VIII. Biography

Mikhail Yu. Vasilyev was born in Irkutsk, Russia on October 13th, 1975. He graduated from Irkutsk State Technical University. Since 1997 he has been working at Energy Systems Institute where he received Ph.D. in electrical engineering in February, 2002. His current research interests include power system economics and regulation of electric power industry.

E-mail: vassiliev@ieee.org.