Economic Principles of Cross-Border Power Flow Control

N.A. Yusifbayli[1], R.R. Alizade[1,*]

[1] Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute, Baku, Azerbaijan

***Abstract* — The paper explores the economic principles underlying the control of cross-border power flows in interconnected electricity markets. Emphasizing the dual role of national control centers, it presents a framework where both engineering constraints and market dynamics guide operational decisions. Using real-world data from the Azerbaijani power system, the study analyzes supply and demand curves, equilibrium pricing, and the cost-effectiveness of domestic versus imported electricity under various load conditions. A practical methodology is proposed for integrating incremental cost analysis into supervisory control systems, enhancing real-time decision-making capabilities. The findings offer valuable insights into optimizing capacity allocation and ensuring economically viable power exchanges in modern energy systems.**

***Index Terms* — Power system, interconnections, electricity, electricity market.**

I. Introduction

In accordance with the current legislation of many countries, including the Republic of Azerbaijan, the energy sector has undergone drastic structural changes. The state monopoly in the electric power industry was abolished and some of its branches completely changed their form of ownership [1, 2].

In this context, economic principles of control are integrated with basic engineering principles. Moreover, the two types of principles are not independent, but closely interrelated and interdependent. Their joint implementation in general improves overall performance. Behind this is the imperative to optimally satisfy the economic interests of both energy producers (electric power industry) and consumers. This must be achieved while complying with numerous process and economic constraints, as well as advancing the interests of the state and society to ensure the energy security of the country [3].

II. National Control Center

In a market economy, the National Control Center (NCC) has to consider multiple criteria when making decisions. The NSCC safeguards efficient operation not only of the electric power industry, but also of the entire economy.

The past experience of North American and European associations (UCTE, NORDEL, CENTREL) shows that the NSCC exercises almost independent control over the operation of their power systems, ensures their reliable and economical operation, and manages technological and economic links within the power system interconnection [4].

Economic aspects of supervisory control in the past were mostly limited to optimal power flow control, aiming to minimize costs while meeting the existing constraints. This is an optimal capacity allocation problem [5].

The market environment presents a much broader range of objectives to be achieved [2], one of which is discussed in this paper through guidance criteria.

Interconnectors function as a platform for the exchange of electricity between the power systems that are part of the power interconnection. In this context, a specific market is formed, where both the volumes of transmitted capacity

* Corresponding author.
E-mail: rena_alizade@mail.ru

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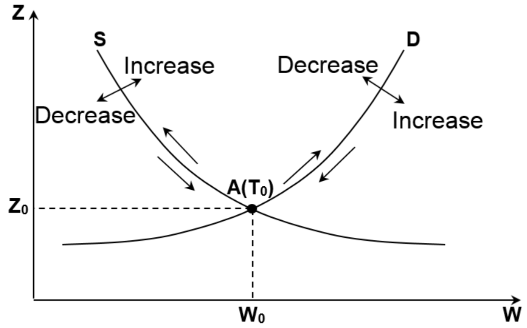

Fig. 1. Demand and supply curves, Z – costs, W – product quantity.

and the corresponding price conditions are determined. Power systems participating in intersystem flows act as economic agents – suppliers or consumers – depending on the current state of the load and generation.

Similar market mechanisms manifest themselves within the power systems themselves. Here, substations connecting transmission and distribution networks act as local trading hubs, redistributing electricity between the primary market participants: generating sources and end consumers. Such processes also obey the laws of supply and demand and are managed on the basis of a combination of technological and economic factors [6–8].

In both cases, the regulators of these processes are supervisory control centers that reconcile technological and economic criteria. The operation of supervisory control centers under these conditions should be guided by two main considerations:

1. In electric power systems, optimal capacity allocation should be ensured to minimize costs and respect constraints [5, 6].
2. NCC actions should comply with the basic laws of market economy, i.e., the laws of supply and demand [4].

Moreover, both of these considerations are inextricably linked. The former consideration is well known and has been successfully applied in power system control across all hierarchical levels of automated supervisory control system (ASCS). Therefore, our paper focuses on the latter consideration.

III. Laws of Demand and Supply

The laws of demand and supply are represented by the corresponding curves shown in Fig. 1 [4, 9, 10]. The direction of the curve slope reflects the logic governing the market laws:

The higher the price of a good, the less it is demanded (*S* is the demand curve), and vice versa.

The higher the market price, the more goods the producer is inclined to supply to the market (*D* is the supply curve), and vice versa.

In the market environment, the price that would satisfy both parties is found at the intersection of the curves, where the so-called equilibrium price is established. The market players are power systems, each of which, depending on the load profile, can be either a seller or a buyer of electricity, i.e., power flows through interconnector can be reversible.

In the electricity market, the demand and supply curves can be represented as relationships between incremental costs (fuel or expenses) and the supplied active power. Power systems do exhibit such relationships. What is unique to them is that these properties are subject to change due to a variety of factors. These factors can be divided into two groups. The first group of factors leads to an upward or downward shift of the demand and supply curves, whereas the second requires a movement of “operating point” from one point to another without altering the positions of the curves (Fig. 1).

The first group of factors includes the following:

- predicted changes in loads;
- changes in fuel prices;
- changes in equipment prices;
- seasonal factor;
- changes in the mix of electricity generation, etc.

The effect of these factors should be taken into account

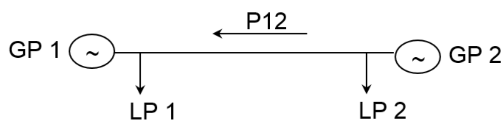

Fig. 2. Parallel operation of the two power systems via interconnector.

by control centers mainly in long-term and, to some extent, in short-term planning.

Changes in the number of consumers or producers with subsequent load fluctuations result in the “operating point” moving along the corresponding curves. It is essential to consider this phenomenon in both the short-term planning and real-time control.

Demand and supply curves in the case of power systems illustrate the relationship between incremental costs and the increase in generated power. Some studies [3] introduced the notion of the selling cost price, which is the value of system-wide incremental costs (fuel or expenses) under optimal conditions of power system operation. In other words, it is the cost incurred per additional 1 MWh of electricity produced.

When making decisions on the sale/purchase of electricity, the operating personnel should be guided by the ratio of the existing wholesale rate of electricity to its selling cost price within the power system.

IV. Parallel Operation of Power Systems

As an example, consider the parallel operation of two power systems linked through interconnector (Fig. 2). Both power systems have a power reserve. This means that each of the power systems can sell or buy surplus power. However, the operating costs of these systems are different.

If we assume that the wholesale electricity rate is stable within the timeframe covered by short-term planning and real-time control, then the $T_{wh}(P)$ relationship is linear and runs parallel to the horizontal axis. The degree to which buying electricity from the wholesale market is economically (un)feasible can be estimated by combining this curve with a similar curve of the power system $T(P)$. Under the initial optimal operating conditions, the loads are equal to P_0, given the cost $Z_0 = T_0P_0$.

When the loads of the power system increase by ΔP, consumers can be supplied either by additionally loading their power plants (the cost will increase to $Z_1 = T_0(P_0 + \Delta P)$, or by purchasing electricity from the wholesale market (the cost will be equal to $Z_{wh} = T_{wh}(P_0+\Delta P)$.

In what follows, a practical implementation of this idea will be presented through a case study.

V. Case Study

The deficient “Absheron” node (Fig. 2) is powered by its own generation sources (Shimal thermal power plant (TPP), Baku TPP, Sumgait TPP), and receives power from the Azerbaijan TPP through the “Sharg” cutset and from the UES of Russia through the 330 kV overhead line “Yashma – Derbent,” which serves as the interconnector. In the case of increased loads at the “Absheron” node, it can be fed either from the Azerbaijan TPP (at the internal electricity rate of 3.88 US cents per kWh), or via the interconnector (at the wholesale electricity rate of 3.0 US cents per kWh) [11].

Control engineers will need to answer the following questions as part of their real-time control operations: “When is it appropriate to stop loading the units of the Azerbaijan TPP for operations to remain economically feasible?” and “When does purchasing electricity from the wholesale market become a more cost-effective option than relying on Azerbaijan TPP?”

Table 1 below summarizes the input and calculated data for the 300 MW unit of the Azerbaijan TPP.

The Table uses the following notations: E is an incremental increase in fuel consumption:

$$E = 0.26 + 0.000121P;$$

Z_1 is an incremental cost, USD:

$$Z_1 = EKC_2;$$

C_2 is the specific cost of gas, thousand m^3 (\$69); K is the conversion factor for converting reference fuel to m^3 of gas (0.87); C_1 is the electricity rate, given the incremental cost per additional kWh;

$$C_1 = C_0 + Z_1$$

Table 1. The INPUT and Calculated Data for the 300 MW UNIT of the Azerbaijan TPP

P, MW	E, g per kWh	Z_1, US cents	C_1, US cents per kWh	Z, mln USD
150	18.41	0.1105	3.99	23.94
200	24.46	0.1468	4.03	32.21
250	30.51	0.1832	4.06	40.63
300	36.56	0.2195	4.10	49.19

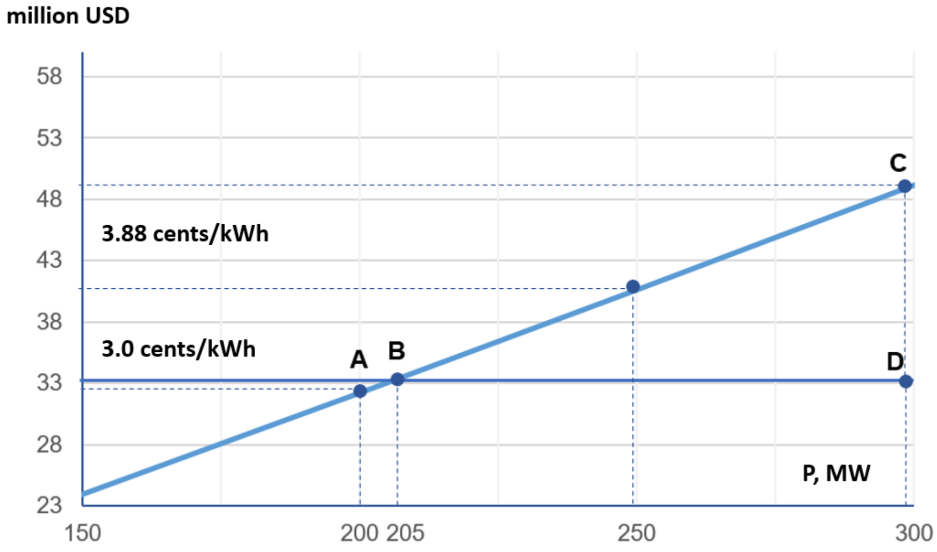

Fig. 3. Economic (in)feasibility of buying electricity from the wholesale market.

(C_0 = 3.88 US cents per KWh); Z is costs:

$$Z = PTC_1.$$

Given the interconnector capacity limit of 400 MW, the number of its utilization hours equal to 1 960, and a wholesale electricity rate of 3.0 US cents per kWh, the costs are as follows:

$$Z = 400 \cdot 10^3\,\text{kW} \cdot 2750\,\text{h} \cdot 0.03\,\text{USD/kWh} = 33\text{ mln USD}.$$

Figure 3 plots the relationship between the costs and internal/wholesale electricity rates.

Under initial operating conditions, the Azerbaijan TPP unit operates with a capacity margin of 15–16%, i.e., the unit's capacity is 250 MW.

The control engineer can increase the capacity of the *AB* unit up to 205 MW if the load in the system increases. Meeting additional demand becomes more economically efficient when relying on power flow through the interconnector (*BC*).

In the case of the cost-effective operation under internal electricity rate, the control engineer has the range *AB* on the graph.

Whether the operation is economically feasible is determined by the ratio of the area under the wholesale curve to the area under the power system's curve. Point *B* is the equilibrium point: at this point a mutually beneficial power exchange is ensured and the entities involved are ready to enter into contractual agreements, for behind this point, $S_{BC} > S_{BD}$, and the power system benefits from buying electricity from the wholesale market at the equilibrium rate (T_0) per MWh.

Thus, both principles are at work: optimal capacity allocation to minimize costs, along with the fundamental laws of supply and demand.

A similar result can be obtained by equating the following costs, US cents:

$$Z_1 = PTC_1 \ (1)$$

– electricity production costs,

and

$$Z_2 = PTqC_2 \ (2)$$

– fuel costs, where q is consumption per kWh.

At the same time, C_1 refers to the fuel component of the electricity rate, which is about 80%.

From equalities (1) and (2), it follows that

$$C_1 = qC_2. \ (3)$$

Table 2 shows the results of the calculation and their comparison with those produced by the first technique (q = 320 g per kW, C_2 = 69 USD /thousand m^3).

As seen in the Table, the difference in the results is negligible.

A similar technique can be applied to both a single power plant and the entire power system. In either case, technique II is preferred. We can determine the electricity

TABLE 2. Comparison of Calculation Techniques

P, MW	Costs, mln USD		Difference, %
	Technique I	Technique II	
150	23.94	24.26	1.3
200	32.21	32.35	0.4
250	40.63	40.44	0.5
300	49.19	48.52	1.4

rate based on the data reported by Azerenerji OJSC for 2023:

$$C_1 = qC_2 = 3.1 \text{ (US cents per kWh).}$$

Increasing the cost of 1 000 m^3 of gas up to the selling prices of natural gas abroad (i.e., by 2.7 times) leads to an electricity rate increase up to 8.37 US cents per kWh. This indicates that the current rate of 3.88 US cents per kWh is understated, which corresponds to q = 320 g per kWh.

The special point B on the curve moves during the operational cycle of power system load control in accordance with the supervisory control load profile and is controlled by the control engineer. This also occurs in the case of changes in the specific fuel consumption, percentage of the fuel component in the electricity rate (60–65%), and fuel price.

Making the curves analytically tractable and entering them into a computer system enable real-time power flow control following technical and economic criteria.

VI. Conclusion

In the context of liberalization of electric power markets, effective management of intersystem electricity flows requires the integration of both technological and economic principles of management. This study has demonstrated that the use of fundamental laws of supply and demand in combination with methods of optimal capacity allocation can significantly improve the efficiency of energy systems participating in cross-border electricity markets.

The analysis performed using the example of the power system of Azerbaijan confirms the possibility of practical implementation of the proposed methodology. This includes the use of marginal cost calculations, the determination of points for economically viable electricity purchase and sale, as well as the construction of supply and demand curves for automated control.

The methodology facilitates informed decision-making regarding optimal capacity allocation and utilization of external supply sources, aiming to minimize costs and balance the interests of market participants.

Further development of the approach requires automation of obtaining economic characteristics of generating units and systems in real time, as well as the introduction of a single algorithm for forming supply functions for both producers and consumers. The national control center should have tools for continuous monitoring and adjustment of these functions, which is especially important in a volatile market environment.

The introduction of this methodology into the supervisory control system will ensure more precise and economically sound regulation of power flows, will increase the transparency of processes at intersystem and intrasystem levels and, ultimately, will contribute to strengthening energy security and sustainability of energy systems.

References

[1] N. Yusifbayli, V. Nasibov, A. Huseynov, R. Alizade, K. Suleymanov, “Strategy of provision of energy security of Azerbaijan under conditions of peculiarities and intensive development of the electric power system,” AIP Conf. Proc., vol. 2552, no. 1, Art. no. 020001, 2023. DOI: 10.1063/5.0112959.

[2] A. M. Huseynov, N. A. Yusifov, “Economic principles of economic management of electric power systems,” Power Engineering: Research, Equipment, Technology, no. 2, pp. 20–23, 2000. (In Russian)

[3] C. R. McConnell, S. L. Brue, S. M. Flynn, Economics: Principles, Problems, and Policies. Moscow, Russia: INFRA-M Publishers 2011, 1041 p. (In Russian)

[4] A. B. Osak, A. V. Domyshev, I. V. Sorokin, “Automation of supervisory control systems of electric power facilities based on SCADA-ANARES,” in Systems Studies in Energy. Irkutsk, Russia: Melentiev Energy Systems Institute, SB RAS, 2005, pp. 230–237. (In Russian)

[5] V. A. Venikov, V. G. Zhuravlev, T. A. Filipova, Optimization of power plant operating conditions in power systems: A textbook for power engineering majors. Moscow, Russia: Energoizdat,1981, 466 p. (In Russian)

[6] N. A. Yusifbayli, V. H. Nasibov, R. R. Alizadeh, “Power consumption management and flattening of load profiles in the Azerbaijan power system,” in Proc. the 94th meeting of the International Scientific Seminar “Methodological issues of reliability studies of large energy systems,” Alushta, Russia, Sep. 19–23, 2022, vol. 73, pp. 611–622. (In Russian)

[7] V. M. Letun, I. S. Gluz, “Optimal control of power plants operation in the market environment,” Elektrical Stations, no. 3, pp. 8–12, 2003. (In Russian)

[8] I. O. Volkova, D. G. Shuvalova, E. A. Sal'nikova, “Prosumers in intelligent energy systems: opportunities and prospects.” [Online]. Available: https://publications.hse.ru/mirror/pubs/share/folder/xnto5eu7bd/direct/71899800. Accessed on: Jan. 20, 2025.

[9] S. Pazouki, A. Mohsenzadeh, M. R. Haghifam, “Optimal planning of parking lots and DLC programs of Demand Response for enhancing distribution networks reliability,” in 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, USA, Jul. 27–31, 2014, pp. 1–5. DOI: 10.1109/PESGM.2014.6939499.

[10] X. Zhang, et al. “Hourly electricity demand response in the stochastic day-ahead scheduling of coordinated electricity and natural gas networks,” IEEE Trans. Power Syst., vol. 31, no. 1, pp. 592–601, 2015. DOI: 10.1109/TPWRS.2015.2390632.

[11] N. A. Yusifbayli, A. M. Huseynov, H. B. Guliyev, A. F. Aliyev, O. B. Azadkhanov, “Monitoring of dynamic security indicators of the power system of Azerbaijan in the context of the energy transition,” in Proc. the International Scientific Seminar named after Yu. N. Rudenko “Methodological issues of studying the reliability of large energy systems,” Cholpon-Ata, Kyrgyzstan, Sep. 11–15, 2017, vol. 68, pp. 357–362. (In Russian)

Nurali Yusifbayli was born on March 28, 1963. He attended Kiev Technical Academy from 1980 to 1986 and graduated on the specialty of “Electrical systems cybernetics” from the Power Engineering faculty. He received his degrees of Candidate of Technical Sciences in 1995 and Doctor of Technical Sciences in Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute in 2004. In 2011 he became a professor. Since 2021 he is a vice-rector of Azerbaijan Technical University. He has been awarded honorary titles “Honored engineer”, “Honored Scientist” of the Republic of Azerbaijan and “Honored Power Engineer” of CIS member countries.
E-mail: yusifbayli.n@gmail.com