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на тему

ПРОБЛЕМЫ ГИДРАВЛИЧЕСКИХ ТУРБОМАШИН

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PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

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Analysis of the Operating Conditions of Polish Pumped-Storage Water Power Plants in View of the Needs of the Country's Electric Power System

An analysis has been given regarding the operation of three Polish pumped-storage water power plants at Żydowo, Porąbka-Żar and Żarnowiec from the point of view of taking advantage of their working periods at generating, pumping and compensation work, the number of switchings of the turbine sets, changes in the power plant loads per week, degree of using the capacity of the upper storage reservoir, power plant time model during a 24-hour day as well as availability.

In the second part of this paper an analysis has been given of the intervening and regulating operation of these power plants according to the needs of the Polish electric power system.

1. Introduction

The Polish electric power system is based mainly on thermal power plants. The power installed in water-power plants amounts to less than 7% of the country's total power system. Such a low share of quickly available power causes the water-power plants to practically play a key role in the Polish power system by regulating the changes in the power load appearing during the day. Seventy percent of the power generated in the whole Polish water power system is concentrated in the three existing pumped-storage water power plants at Żarnowiec, Porąbka-Żar and Żydowo. The generating power of these plants is as follows: Zarnowiec — 700 MW, Porąbka-Żar — 500 MW, and Żydowo — 150 MW. In Poland there are two more water-power plants with pumping units, namely at Solina with 140 MW and Dychów with 80 MW.

The results, as given below, of investigations of the pumped-storage water power plants with regard to their operation and regulating and intervening function have been based on readings taken from power reports and daily load observation diagrams at the power plants involved.

2. Analysis of Turbine Set Working Conditions at Pumped-Storage Water Power Plants

2.1. General

The analysis of the investigations carried out embraces variation in the work of the power plants in the seasons of the year, months, particular days in the week as well as during the whole day. The year has been subdivided into four power seasons: winter (November to February), spring (March to May), summer (June to September) and autumn (October).

2.2. Power Plant Availability

The absolute power plant availability time factor d_E i.e. without giving consideration to scheduled major and periodical repairs is calculated by the following formula:

$$d_E = \frac{nT_c - \sum_{i=1}^{n} T_{ci}}{nT_c} \cdot 100\% \tag{1}$$

where: T_c — month time in hours, $i = 1, 2, ..., n$ — number of the hydro-generator in the power plant, T_{ci} — total shut-down period of i-th hydro-generator in hours in month

It is possible to determine on the basis of these studies that the pumped-storage water power plants have their highest availability in the winter season i.e. the very period when the power demand is highest and that it oscillates within 98 to 100%. The lowest availability appears in the spring-summer season, which is favourable because it is the time for repairs and periodical surveys and thus the time of lowest demand for power in the system.

At that time the availability amounts to 72% at Porąbka-Żar and 85% at Żarnowiec.

2.3. Most Frequent Breakdowns and Repairs

In addition to the availability considered in a general manner the number of emergency shut-downs i.e. turbine set failures in the breakdowns have been analyzed. On the average approximately 8 breakdowns take place per 1000 runs. Emergency shut-downs were caused mainly by excessing the permissible temperature of turbine or generator bearings, excessively high generator cooling air temperature and appearance of inflammable gas in the transformer. Other causes of shut-downs and most frequent repairs include earthing of the poles and generator excitation circuits, replacement of damaged carbon glands, replacement of brake ferrodes, damages to the seals at the working spherical valve or to the butterfly valve actuator or sluice valve, adjustment of oil distribution unit of the controller.

The most frequent cause, however, of putting the machines out of their pumping duty are automatic shut-downs associated with frequency drops. They follow from the specific working conditions in the COMECON interconnected power systems, the cause of lowered frequency being beyond the borders of our country.

2.4. Power Plant Working Time and Number of Runs

The total mean generating time of all the four turbine sets at Porąbka-Żar during a 24-hour day in winter amounted to 16 h 21′ (4 h 5′ per one machine), and the pumping time to 21 h 21′ (4 h 20′ per one machine). Porąbka-Żar does not work at all as compensating plant, which follows from its position in the system. The sum of the working times in both directions amounts to 37 h 42′ i.e. 9 h 25′ of work per each machine during a 24-hour day. Owing to the lower availability factor and smaller power consumption the above given times are shorter in summer: the mean total generating time amounting to 14 h 40′, and the pumping time to 18 h 30′, a total of 33 h 10′, which converted into time per each turbine set gives 8 h 17′, with 3 h 40′ of generating time and 4 h 37′ of pumping time.

In the second year of service of the Żarnowiec power plant each turbine set worked there on the average for 6 h 26′, with 2 h 41′ of generating work 3 h 13′ of pumping and 0 h 32′ of compensating work.

At the Żydowo power plant (3 turbine sets, only two of them reversible) the above times were as follows: 9 h 02′ — total, 3 h 39′ — generation, 4 h 25′ — pumping (in reality 6 h 37′ for each of the two pumps) and 0 h 38′ — compensation.

A comparative analysis of operation times of the three power plants shows that Porąbka-Żar and Żydowo work nearly in the same way — on the average 1.400 to 1.450 h of generation per turbine set. Because of the fact that the Żarnowiec power plant entered into full operation not earlier than in 1984, it could not be taken into account in this comparative analysis, although there are indications that it will have similar operating characteristics.

Use of the Żydowo power plant for compensation has contributed to the fact that this plant has the highest number of working hours per year per one machine.

It is also essential that compensation work during a 24-hour day in the summer season is at Żarnowiec approximately 3 times longer and at Żydowo approximately 6 times longer than in the winter season.

The average number of runs of one turbine set at the Porąbka-Żar power plant during a 24-hour day amounted to 3.0, with about 1.6 for generation, and 1.4 for pumping. During the whole year the number of runs was equal to about 1.090, 580 of them used for generation and 510 for pumping.

In the case of the Żydowo power plant the number of runs amounted to 3.7 per 24-hour day: 1.9 for generation, 1.7 for pumping, 0.1 for compensating work; per year: 1.350, with generation in approximately 690 runs, pumping in 620 runs and compensating work in approximately 40 runs.

For all the power plants the number of runs for either generation or pumping was in the winter season approximately 15% higher than the average for the year while in the summer season it was 15% lower. As far as the compensating work is concerned, the number of runs in the summer season was approximately 3 to 5 times higher than in the winter season.

2.5. Weekly Load Distribution in Pumped-Storage Water Power Plants

During the week the pumped-storage water power plants operate under variable loads. Magnitudes of the generating or pumping and compensating loads are functions of the system needs and availability on the day involved. The investigations have shown that Monday is the workday characterized by the highest load of the pumped-storage water power plants. On Tuesday and Wednesday the load is lowest. On Thursday and Friday it rises a little, but does not reach the power generation and compensation level of Monday. The Saturday-Sunday weekend at the Żarnowiec power plant is used for repairs of turbine sets, and this is the cause of lower load on these days when compared with that of the other days in the week. The situation at the Porąbka-Żar power plant is opposite. The weekend period is the time of highest load there. Surveys and repairs at Porąbka-Żar are carried out on workdays. On the other hand, Saturdays and Sundays are a typical repair-survey period for thermal power plants, often extending till Monday. At that time the Porąbka-Żar power plant plays a very important role in the system, covering the additional power demand, especially in the evening peak hours on Saturdays and Sundays and in the morning peak on Monday. At Porąbka-Żar the load during the weekend including Monday is approximately 10 to 15% higher than in the period from Tuesday to Friday.

2.6. Work of the Power Plants during the 24-hour Day

Calculation has been carried out on the basis of the 24-hour day load diagram of the mean working times in the pumped-storage water power plants in the individual days of the week for all the seasons in the year when working with a different number of machines simultaneously. From the models prepared in this way it follows that, for instance, in 1983 the Porąbka-Żar power plant had on the average 7 h 59′ per 24-hour day of generating work: only 20′ of operation of all 4 turbines while operation with 3 turbines lasted 1 h 17′, with 2 turbines — 2 h 56′, and with one turbine — 3 h 36′. For pumping the figures were: 9 h 12′, with 4 pumps working simultaneously for 8′ only, 3 pumps — 2 h 07′, 2 pumps — 4 h 16′, and 1 pump — 2 h 41′. The stand-by period of the power plant was 6 h 49′.

The model of operation of the Żarnowiec and Żydowo power plants is similar to that of Porąbka-Żar with regards to the duration of the generating and pumping phases is similar to the work at Porąbka-Żar with the exception that at Żydowo the respective times of simultaneous operation of several machines are different due to the smaller number of turbine sets, of which one is not reversible. The stand-by period is in both these power plants approximately 1.0 to 1.5 shorter than at Porąbka-Żar. This is caused by use of both these power plants for compensation work, the duration of compensation at Żarnowiec being more frequent and longer lasting than at Żydowo. The compensation power plants work most often with one machine. For instance, in 1983 the so-called "pure" compensation lasted on the average 1 h 27′, including 1 h 14′ of single-machine operation and 0 h 13′ of operation of two machines simultaneously (no compensation work with 3 or 4 machines). In addition, the power plants often work in compensation simultaneously with a turbine or pumping service. In the case of Żarnowiec the average duration of those compensation periods amounted to 0 h 22′ per year.

2.7. Upper Reservoir Operation

A diagram of the upper reservoir operation is given in Fig. 1. On the basis of calculated volumes of water pumped into the reservoir or discharged during turbine operation factors α of the upper reservoir utilization have been calculated from formulae given below

a) α_{R-P} — reservoir utilization factor for the morning-afternoon period

$$\alpha_{R-P} = \frac{V_{TR} + V_{PP}}{2V} \cdot 100\% \tag{2}$$

b) α_{W-N} — reservoir utilization factor for the evening-night period

$$\alpha_{W-N} = \frac{V_{TW} + V_{PP}}{2V} \cdot 100\%. \tag{3}$$

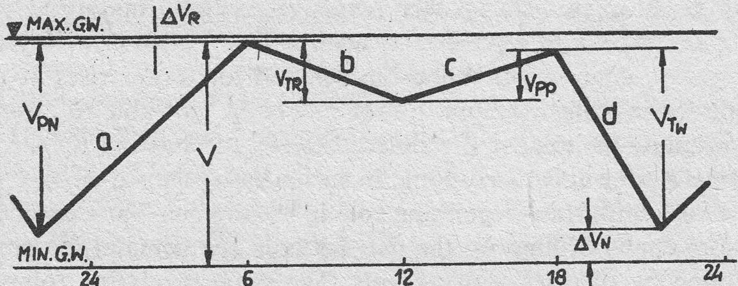

Fig. 1. Upper reservoir operation diagram

V — total useful volumetric capacity of the upper reservoir, V_{PP}, V_{PN} — capacities of pumped fillings in the afternoon and night off-peak, V_{TR}, V_{TW} — volume of reservoir water used at morning and evening peaks, V_N, V_R — night off-peak and morning peak reserve; a — night off-peak period, b — morning peak, c — evening off-peak, d — night peak

An analysis of the upper reservoir work at Porąbka-Żar shows that α_{W-N} in the winter season amounts to some 90% (average for January 1984: even 91.2%), and in the summer season it drops down to 60%. This is an indication of a high degree of utilization of the power plant's reservoir in the evening-night period. The quantities of the reservoir reserve in winter amount to: ΔV_N — 5.0 to 7.5% and ΔV_R — 0.2 to 1.5% of the total volumetric capacity, and in the summer season they are higher, amounting to ΔV_N — 14.5 to 17.7% and ΔV_R — 5.0 to 10.9%.

During the day the situation is quite different. In the morning-afternoon hours the values of the α_{R-P} coefficient are highest in the summer season (the average of approximately 31%), and in the winter season the α_{R-P} coefficient drops down to several percent (5 to 8%).

3. Intervening and Regulating Role of the Pumped-Storage Water Power Plants in the Polish Electric Power System

Poland works within an interconnected power system of European COMECON countries. The USSR, the biggest producer of generated power, is connected with the other member-countries by the so-called Lvov section and the Moldavian section (transit connection with Bulgaria through Roumania). The Lvov section comprises a total of seven different high-voltage lines, of which the 750 kV line is the most important one. Any automatic cut-off of this line due to its overload leads to separating the USSR system from the interconnected systems of the other countries inclusive of the Lvov region. This leads to a rapid drop of frequency even by 1 Hz in the system which connects the countries involved.

It is possible to distinguish three kinds of pumped-storage water power plant operation: programmed, regulating and intervening work. The programmed work is to be understood as a classical work of a pumped-storage power plant consisting in generating power in the morning peak hours with no more than two turbine sets and in the evening hours with no more than three turbine sets, and in stable (continuous) regular pumping at the off-peak periods (at night and in the day time) when there is an excess of power in the system (see example in Fig.2). Regulating work in pumped-storage water power plants takes place mainly at the transient passage from an off-peak to a peak or vice versa. The Polish power system is based on thermal power engineering. When the demand for power rises at the morning or evening peak the Polish thermal power plants are not able to cover the highly increased consumption because the time necessary for starting up the rotating reserve of thermal power units is too long. In such a case pumped-storage water power plants play a very important regulating role in the system. Their excellent elasticity (quick start-up) enables filling up the gap between the demand for power and the power generated by thermal power plants. The same regulating role is played by the pumped storage power plants together with other water-power plants in case of rapid drops of power consumption during the passage from a peak to an off-peak. The operating principle at a pumped power plant in the night off-peak consists in

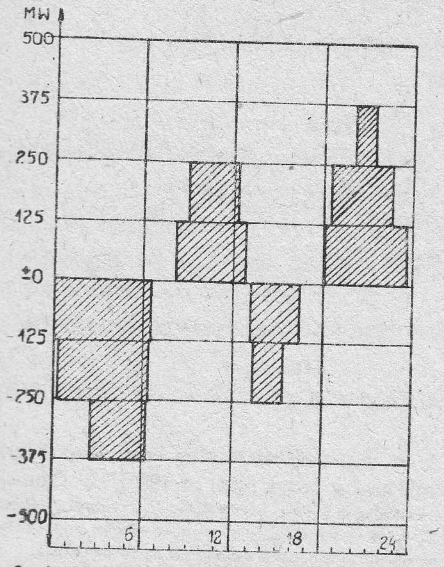

Fig. 2. An example of programmed work: loads at the Porąbka-Żar power plant on 1983.08.06 (Saturday)

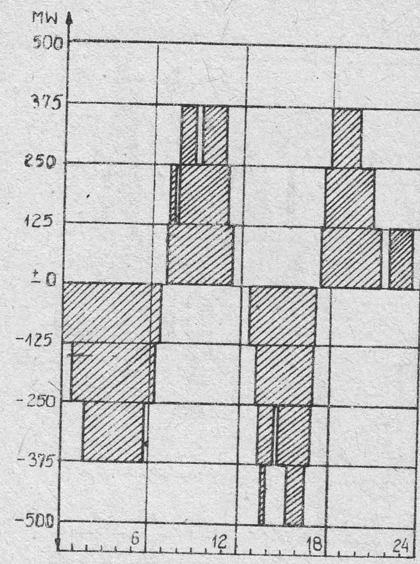

Fig. 3. An example of regulating work: loads at the Porąbka-Żar power plant on 1983.10.13 (Thursday)

filling the upper reservoirs to a maximum level by 06:00 in the morning. Often the whole complement of pumps is started before 06:00 a.m. (before the morning peak). This allows to start the reserve in the thermal power plants. After 06:00 a.m. the consumption of power begins to rise quickly. Step by step the pumps are stopped every several minutes, by which more and more portions of power are given to the system and consecutive turbines are being started. On the other hand, the regulating role of the pumped-storage water power plants during the transient passage from power peak to off-peak consists in stopping the turbines step by step and consecutive starting the pumps. An example of regulating work is given in Fig. 3.

Regulation of the exchange rate of energy with other countries has a great influence on the work of the system and consequently on the work of pumped-storage power plants. In the exchange of electric power between countries on the basis of a multilateral contract there are financial reasons for keeping up the frequency and the rate of planned and agreed deliveries of electric energy.

Further, here are economic incentives aimed at keeping up the planned rates between the USSR system and the interconnected system of the other countries in order to maintain the Lvov section in its readiness for normal work (avoiding its becoming overloaded).

3.1. Intervention Work and its Causes

The general principle accepted during the investigation was the assumption that each short-lasting start-up (for work lasting not longer than 30′) of a turbine set for generating or pumping work has a character of an intervention following from the

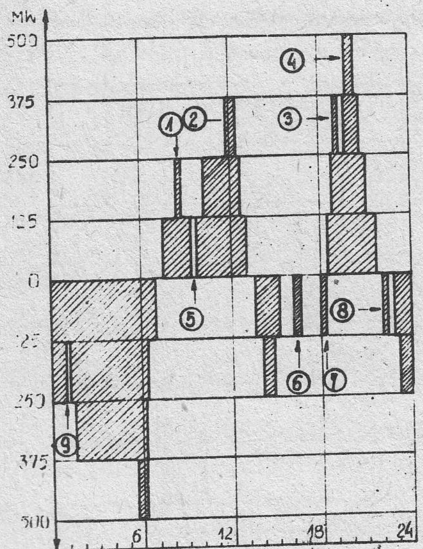

Fig. 4. An example of intervention work: load diagrams at the Porąbka-Żar power plant on 1983.09.01 (Thursday)
1, 2, 3, 4 — switching-in turbine interventions; *5* — switching-off turbine intervention; *6, 7, 8* — switching-in pump interventions; *9* — emergency cut-off due to temperature rise in the generator bearing

needs of the system. In addition, each generation work outside of the peak regardless of the time of its duration as well as the pumping work outside the night and afternoon off-peak is of an intervening character. Every short-lasting cut-off of a machine from work has the same meaning for the system as an intervention start for work. In such a case an intervention cut-off of a turbine bears the same character as if it were a pump intervention, and an intervention cut-off from pumping work as if it were a turbine intervention (see example in Fig. 4). From the principles of operation of the Polish system by the State Power Board it follows that each switching-on of a third set or more in the morning peak, and of a fourth set (only in the case of Żarnowiec and Porąbka-Żar) in the evening for generating work plays practically the role of intervention.

The basic causes of intervening operation of pumped-storage water power plants are as follows:

a) separation of the systems in the Lvov section,

b) a deficit in the planned export,

c) regulation of the exchange balance with other countries in dependence on economical incentives,

d) orders from the central dispatcher from Prague for the interconnected system,

e) sudden drop-out of a unit e.g. of 200 MW from a thermal power plant,

f) high running inertia of the rotating reserve in thermal power plants,

g) power control in the system in compliance with the demand,

h) supply of coal of inferior quality to the thermal power plants,

i) sudden worsening of meteorological conditions, temperature drop or appearance of clouds during daytime,

j) sudden switching-on of TV receivers at the end of the evening-peak e.g. in the case of an interesting TV program,

k) other causes.

3.2. Frequency and Duration of Interventions, Interventional Energy

In Fig. 5 a histogram of frequency is given as well as curves showing frequencies, of switching-on and switching-off interventions for one year of operation of the Porąbka-Żar power plant. The frequency of interventions that take place in the respective hours of the 24-hour day changes in dependence on the season of the year together with the changes of the time boundaries between the power peak and off-peak zones. On the average in 1983 the duration of turbine switching-on interventions amounted to 38′, the interventions being shortest in the morning peak — 24′ on the average, and longest in the afternoon off-peak — 55′, while in the evening peak they amounted to 45′. The frequency at which turbines are switched on is higher in the evening

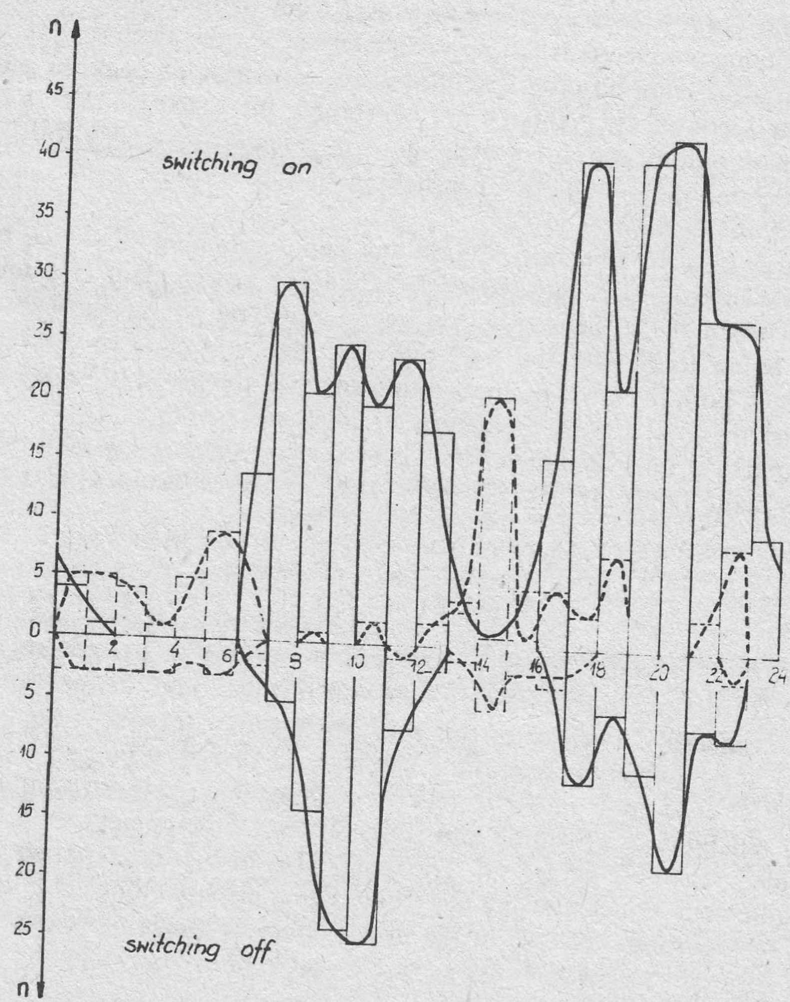

Fig. 5. Daily distribution of intervention rates at Porąbka-Żar power plant for one year
——— turbine interventions, – – – – pumping interventions

peak (48%) than in the morning peak (39%). In the afternoon off-peak 13′ (13%), in the night off-peak — 0%. The highest number of interventions at peaks takes place at the beginning and at the end of their duration. Pumping interventions are much shorter, lasting on the average 19 minutes. In the afternoon peak there is 46% pump switching-on engaging intervention, most frequently between 14:00 and 15:00, in the night off-peak — 45%, in the evening peak — 6%, and in the morning peak — 3%.

Turbine switching-off interventions last on the average approximately 19′, the morning ones being slightly longer — about 21′ and there are more of them (57%).

The evening ones are shorter — approximately 16′ (43%). The highest number of turbine switching off interventions takes place in the middle of the peak duration, which is the result of turbine switching off because of the excess of power in the system coming from full development of power from thermal power plants. Switching-off pumping interventions last approximately 21′ on the average, with approximately 62% in the night off-peak and 38% in the afternoon off-peak. In general, as far as all the kinds of interventions are concerned, the highest numbers of interventions are as follows: turbine switching-on interventions — 60%, turbine switching-off interventions — 21%, pump switching-on interventions — 14%, and pump switching-off interventions — 5%.

The energy from turbine switching on and pump switching off should be recorded with the sign "+". In the case of Porąbka-Żar power plant is amounted to +33.128 MWh in 1983. The energy from pump switching on and turbine switching off should be recorded with the "−" sign. Its total amounted to −9.299 MWh.

The sum of both the kinds of intervention energies amounted to 42.422 MWh i.e. nearly 7% of the total annual production of the power plant.

The problem of intervention has been presented on the example of the Porąbka-Żar power plant. Interventions at Żydowo and Żarnowiec have a similar character.

4. Summary and Conclusions

Pumped-storage water power plants play a key role in the control of power delivery in the Polish electric power system which is based on thermal power plants of low controllability. Because of this they are required to have a high degree of availability and reliability in operation. The high number of turbine set switching on operations, for even up to 1.500 per year per each machine, calls for good workmanship, high reliability of operation and starts. Thus, all the circuits must be reliable (and doubled, wherever necessary). This refers also to the measurement and automation equipment. Quick starting of turbine sets is essential, but "seconds" are not deciding. An additional reserve in the upper reservoir seems unnecessary — such reserve is ensured by operation of one turbine set kept in reserve by the dispatcher, and it is he who decides on starting it.

Of all the start-ups 13% are interventional ones. This amounts to approximately 5 to 7% of the total energy supplied by the power plant.

Analiza warunków pracy turbozespołów polskich elektrowni pompowych w aspekcie potrzeb krajowego systemu elektroenergetycznego

Streszczenie

Polski system elektroenergetyczny bazuje w przeważającej mierze na elektrowniach cieplnych. Wymaga to znacznego udziału elektrowni pompowych. Obecnie w system włączonych jest pięć elektrowni pompowych. Trzy z nich: Żydowo, Porąbka-Żar i Żarnowiec o mocy zainstalowanej 150, 500 i 700 MW służą jako główne elektrownie szczytowe, interwencyjne i rezerwowe. Każda z maszyn odwracalnych jest uruchamiana przeciętnie cztery razy na dobę, co oznacza 1500 uruchomień rocznie. Ponad 5% całkowitej energii dostarczanej do systemu elektroenergetycznego to energia interwencyjna, której wartość i cena są, jak wiadomo, bardzo wysokie.

Analiza potwierdziła znaczenie elektrowni pompowych dla wspomagania systemu w soboty i niedziele i w okresach nocnego spadku zapotrzebowania mocy, szczególnie niewygodnego dla elektrowni parowych.

W opracowaniu można znaleźć wiele danych liczbowych dotyczących czasów załączania, pracy oraz gotowości do pracy.

Podsumowując, z analizy wynika, że każda jednostka elektrowni pompowej jest uruchamiana 4—5 razy na dobę, co wymaga krótkich czasów rozruchu takich jednostek. Ważniejsza od czasu rozruchu jest jednak wysoka dyspozycyjność, narzucająca w szczególności wymóg bardzo wysokiej jakości działania wszystkich urządzeń pomocniczych.

Анализ условий работы турбоагрегатов польских насосных электростанций в аспекте нужд электроэнергетической системы страны

Резюме

Польская электроэнергетическая система базирует по большей частии на тепловых электростанциях. Это требует значительного участия насосных электростанций. Сейчас в систему есть включеных пять насосных электростанций. Три из них: Жыдово, Поромбка-Жар и Жарновец работают как основные пиковые, интервенционные и резервные электростанции.

Каждая из отвратимых машин вводится в движение в среднем четыре раза в сутки, что обозначает 1500 движений в год. Свыше 5% всей энергии отдаваемой в электроэнергетическую систему — это интервенционная энергия, которой стоимость и цена, как известно, очень высоки.

Анализ подтверждил значение насосных электростанций для вспомогания системы в субботы и воскресения, а также в периоды ночного падения употребления мощности, особенно неудобного для паровых электростанций.

В работе можно найти много численных данных, касающихся времён включания, работы и готовности к работе

Подытоживая, из анализа следует, что каждая единица насосной электростанции вводится в движение 4÷5 раз в сутки, что требует коротких времён разгона таких единиц. Более важной, чем время разгона, является высокая работоспособность, набрасывающая в особенности требование высокого качества действия всех вспомогательных устройств.