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INSTYTUT MASZYN PRZEPŁYWOWYCH

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

102

GDAŃSK 1997

THE TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machines

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poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

Wydanie publikacji dofinansowane zostało przez PAN ze środków DOT uzyskanych z Komitetu Badań Naukowych

EDITORIAL OFFICE – REDAKCJA

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ISSN 0079-3205

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

1997 No. 102

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Techno-economic advantages of operation of pumped-storage plants within the power system[2]

The paper presents functions of pumped-storage power stations operating within the power system. These functions can be divided into two categories – direct functions which have a direct and immediate effect on the production curve and indirect functions which indirectly influence the operation of the system. The following direct functions are discussed among others: energy transfer, intervention function, control function, spinning reserve, operational stand-by reserve and compensation work. Amongst the indirect functions of pumped-storage power stations, there should be mentioned settling down the operation of thermal power stations, limitation of break-down occurrence in thermal power units, reduction in consumption of fuel used at start-up, power generation at or near optimum efficiency and other techno-economic advantages for co-operating thermal power stations as well as global advantages in terms of the whole power system. The aim of the paper is to give systematic insight, gained from a literature review, into advantages and disadvantages coming from the operation of pumped-storage power plants.

1. Introduction

Pumped-storage power stations serve numerous functions within the power system both at peak and off-peak load. Operation of pumped-storage power plants within a power system of middle-southern states of the US [1] has brought a series of the following advantages in terms of load distribution:

- transfer of energy from near-peak and on-peak to basic units and reduction in unsteady peak load (from 30% to 20% of the peak power),
- reduction in unsteady power generation in near-peak and on-peak units (from 10.9% to 8.1% of the total generation of the system) and decrease in minimum unsteady off-peak load (from 6% to 4% of the peak power),
- increase in minimum load of the system owing to pumping work (from 57% to 66% of the peak power),
- increase in minimum load of basic units at low demand periods (from 81% to 94% of the unit power).

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It should be noted that the possible advantages coming from reduction in unsteady generation can be more significant than the advantages due to energy transfer.

The functions of pumped-storage power stations operating within the power system can be divided into two major categories: direct functions having a direct and immediate impact on the form of the production curve and indirect functions which do not influence the system immediately but have a delayed long-term impact on the power system. The indirect functions of the pumped-storage plants encompass a series of technical and economic advantages for co-operating thermal power stations as well as global advantages in terms of the whole power system.

2. Direct functions

2.1. Energy transfer

The objective of this function is to transfer energy from low to peak demand periods. The energy transfer consists in accumulation of energy (pumping up water to the upper reservoir using power from the system) during low demand periods and releasing it back to the system during high demand periods (generation work). The full cycle of the pumped-storage power plants (pumping and generation work) takes place at a certain level of efficiency. This cycle can be daily, weekly or seasonal, depending mainly on the hydrological conditions and capacity of water reservoirs. The weekly cycle of the pumped-storage power plant means intensified pumping work during holidays and week-end days. The reservoir is filled up before Monday mornings then gradually emptied on working days, getting the lowest level on Friday evenings. Mid-week pumping work is limited only to low demand night periods, and therefore the energy used for pumping is lower than generation work. The seasonal (yearly) cycle means intensified pumping work during summer months and, in turn, intensified generation work in winters. It happens in some countries, for example in Switzerland, that power generation of pumped-storage plants in winter is ten times higher than in summer [2]. The pumping regime is of particular importance for pumped-storage plants where natural tributaries are not capable of filling up water reserves lost during generation of power. In these cases special water intakes are built on lower tributaries, beyond the main water course of the pumped-storage plants, from which water is pumped back to the upper reservoir. Such solutions can be found, among others, in the power plants of Schluchseewerk [3], Lünersee [4] and Grand Maison [5].

The energy transfer function for the pumped-storage plants has become especially significant in countries with increasing share of nuclear energy. The pumping function is called then enforced pumping [6].

2.2. Power function

The objective is to increase the power capacity of the system to meet peak loads. The power and energy transfer functions are two main objectives of the pumped-storage power plants [7].

2.3. Intervention function

The function makes use of one of the main advantages of the pumped-storage power plants, which is low time requirements for start-up, shut-down and change of the operating regime in emergency cases, including breakdown of turbosets or transmission and dispatching units, sudden unpredictable changes in power demand, or a combination of these factors. The intervention function is accomplished both during generation and pumping work.

2.4. Control function

This objective, in a similar way to the one listed previously (the intervention function), takes also advantage of low time requirements for start-up, shut-down as well as for changing the operating regime at high slopes of the load curve when maintenance of the energy balance can not be kept solely by means of conventional thermal power stations. The function consists in controlling interaction, within the power system, of one or a group of pumped-storage plants after their connection for generation work as well as disconnection. This control was called by the author in [8-9] *start-up/shut-down control*. Another suitable name for this type of control, which can be met in Polish literature, is *intervention power control* [10-11]. In world-wide literature this control is called *pick-up duty* [12] or *Lastrampen Funktion* in German-speaking literature [6]. The control function does not refer only to transient regimes – between low and peak demand periods – but also to these periods when the connection of a pumped-storage power plant for generation work (or its disconnection) does not carry the character of intervention.

Due to the close similarities in intervention-type and control-type interactions between the pumped-storage plants and the power system and the same reasons that underlie these functions, and often due to a difficulty in recognition whether the situation has the character of intervention or control, they are often given one common name – *intervention-control function.*

Establishing quotas for foreign trade of electric power The quotas are established based on co-operation accords. The power output of the national power system should take account of the power exchange programme in order to maintain the balance with the foreign partners (in the case of synchronous work of the neighbouring power systems). Any imbalance in foreign energy trade should be quickly answered which is often done by means of pumped-storage power plants, provided they are available in the power system of the country. Regulation of the foreign trade balance as regards electric power is one of the objectives of power generation control. Due to its particular significance this function has been specified separately. The function plays an important role both for technical reasons (maintaining the frequency, assuring stability of the connected international systems) and in economic terms because it enables the country to take advantage of a special system of discounts and penalties, while settling accounts, set up to assure proper functioning of the connected international systems.

2.5. Primary control (frequency control due to contribution of pumped-storage plants)

The primary control whose objective is to prevent frequency decrease is a domain of thermal and water-storage power plants equipped with regulators of the turbine rotational speed [13-14]. It should be noted that for water storage and pumped-storage power stations under operation the amount of reserves taking part in the primary control depends on the load of turbosets and current water level in the upper reservoirs. Nowadays many pumped-storage power stations participate in the primary control within 1-6% of their power capacity [14]. Data concerning the share of power capacity available for the purpose of primary control for selected West European pumped-storage plants belonging to the UCPTE system and two Polish power plants [15] are collected in Table 1.

Table 1. Share of unit power capacity available for primary control for selected pumped-storage plants in Europe [14-15]

Pumped-storage plant	Country	Generated power P_{max} [MW]	Share of unit power capacity available for primary control [$\%P_{max}$]
Veytaux	Switzerland	60	6
Roncovalgrande	Italy	125	5
Bargi	Italy	169	5
Revin	France	180	5
Coo 1 + 2	Belgium	150, 207	5
Torrao	Portugal	72	5
Żarnowiec	Poland	179	5
Porąbka-Żar	Poland	125	5
Rosshag	Austria	57.5	4.5
Malta	Austria	220	4
Mapragg	Switzerland	93.3	4
Montezic	France	228	4
Wehr	Germany	227.5	4
Säckingen	Germany	90	4
Vianden 1-9+10	Luxembourg	100, 196	4
Dinorwig	Wales	300	1-4
Estany Gento S.	Spain	112.75	3
Aguieira	Portugal	90	1

2.6. Secondary control (load frequency control - l.f.c.)

Power plants taking part in this type of control are equipped with regulators of turbine power, controlled by means of a central controller of the system. Hydro-power plants, including pumped-storage plants have the largest range of load frequency control. This range is determined through the width of the l.f.c. half band. This value related to the unit power capacity for different types of power plants is as follows [16]:

- nuclear power stations (PWR) – ±2.5%,
- conventional thermal power stations – ±15%,
- hydro-power stations – ±40%.

In reality many units of modern hydro-power plants have a possibility of l.f.c. within 50% half band, that is the secondary control can be performed within a range of 0-100%.
The half band width for pumped-storage units is usually smaller (with the exception of the pumped-storage power plant of Herdecke, Germany [17]) than for reversible hydrosets where the full range of power control is possible as for three-machine irreversible hydrosets.

The contribution of Polish pumped-storage power plants to primary and secondary control is considerably large and forms a significant share of the global balance of control power in the national power system which fulfils technical requirements for UCPTE members.

2.7. Spinning reserve function

This function is often accomplished as synchronous compensation work. The spinning reserve, being a component of the break-down reserve, is accumulated in pumped-storage units and plays a particularly significant role in maintaining the break-down reserve of the system (called also the intervention reserve). The reserve of the system consists of the spinning unloaded reserve concentrated in pumped-storage and hydro-power (mainly water-storage) plants, the spinning reserve concentrated in operating thermal power plants and partly loaded water-storage and pumped-storage plants (corresponding to the l.f.c. reserve), and the stand-by reserve, called also the cold reserve, concentrated mainly in water-storage and pumped-storage plants and gas turbines belonging to the structure of the system and operating in thermal power plants.

2.8. Operational stand-by reserve (cold reserve)

This function is as important as the spinning reserve function. A hydroset of a pumped-storage plant represents a specific power capacity and even when it is shut down it plays a vital role for the power system. In general it forms an important element of the system reserve necessary to assure the required reliability of electric energy production, particularly in the case of long-time disturbance in the system like, for example, failure of a power unit or short-term mistake in demand forecasting. The dispatcher of the system has to take action then and modifies the plan for energy production, that is increases or decreases the power of working units in order to meet actual needs and compensate the disturbance (or deviation). This can be done partially or totally by means of the secondary control reserve. This reserve usually suffices for about 5 min., which is a relatively short time. In order to reconstruct the secondary control power band, the operational reserve is created. The control system which makes use of this reserve is called the tertiary control, [13]. The operation reserve is divided between operating thermal plants and hydrosets being on stand-by. Remote control of load of thermal power plants within the country is performed by the National Power Dispatching by means of a system of hand-operated power control for hard coal power stations and a system of teleinstructions for power stations running on brown coal and the station of Pątnów running on mazout. This type of tertiary control functions on a basis of economic load distribution. The tertiary control and teleinstructions system for thermal power stations is supplemented with the teleinstructions system for hydro-power plants, among which the pumped-storage plants of Żarnowiec, Porąbka Żar and Żydowo play the key role.

2.9. Compensation work

The objective of this function is the production of reactive energy and the possibility of voltage control within the system.

2.10. The static and dynamic functions

Bearing in mind the principles of control of a power system by means of power dispatching, the direct functions mentioned above can be divided into two categories: static and dynamic functions.

Amongst static functions are the energy transfer, power function, cold reserve, compensation work. Dynamic functions encompass the intervention function, control function, contribution to the primary control, contribution to the secondary control, maintaining the spinning reserve.

3. Indirect functions as technical and economic advantages for the electric energy system in terms of co-operation between thermal and pumped-storage power stations

The indirect functions should be considered as secondary to the direct functions. Pumped-storage power plants considerably improve the balance of the power system and increase its general reliability. Many advantages coming from the contribution of pumped-storage plants to energy production are of technical nature and economic profits are not easy to estimate.

3.1. Advantages for the thermal power plants coming from their co-operation with pumped-storage power stations

Amongst the most important techno-economic factors in thermal power stations which can reduce costs of their operation are:

- *settling down* the operation of thermal power stations,
- limitation of break-down occurrence in thermal power units,
- reduction in modernization costs in thermal power stations,
- increase in the availability factor of thermal power stations,
- power generation of thermal power stations at or near optimum efficiency.

3.1.1. Settling down the operation of thermal power stations

This process is expressed by a decrease in the number of start-up and shut-down operations for big power units and thus leads to an improvement in technical and economic parameters of the thermal power station operating on the basis of the daily load curve. The above factors have an effect on:

Limitation of considerable heat losses due to the decrease in the number of shut-downs (bringing thermal power units to reserve) and start-ups Start-up losses of Polish 200 MW power units operating on hard coal vary with power stations from 2.1 TJ in the power station of Polaniec up to 3.1 TJ in Ostrołęka after 48 hour breaks. Heat losses after 8 hours of break (night reserve) vary from 1.1 TJ in Rybnik up to 1.4 in Ostrołęka B [18]. Average values for thermal power units of other power stations are near 2.4 TJ after 48 hour breaks and 1.2 TJ after 8 hour breaks. The biggest power units installed in Poland – 500 MW in Kozienice 2 require as much as 7.0 GJ after 48 hours and 4.2 TJ after 8 hours of breaks.

Reduction in consumption of liquid fuels used at start-up In most Polish power stations the main auxiliary liquid fuel used at start-up is mazout. In some power stations gas is used, for example in the stations of Stalowa Wola, Zabrze and Bielsko. The start-up of 200 MW power units after 8 hour breaks takes 11.7 tons of mazout in Połaniec and 27.3 tons in Ostrołęka B. On average the consumption of mazout for this type of power units in other power stations is about 14 tons. After 48 hour breaks the consumption rises by as much as twice.

Slowing down the process of wear of power unit elements Repeated bringing of thermal power units to reserve and start-up deteriorates their technical condition due to thermal deformation of elements, which leads to the occurrence of internal stresses in materials and consequently to shorter life-time of the devices. A considerable elimination of interrupted operation of thermal power units can by accomplished by the introduction of pumped-storage power plants into the system.

3.1.2. Limitation of break-down occurrence in thermal power units. Reduction in the modernization costs in thermal power stations. Increase in the availability factor of thermal power stations

Title problems are strictly interconnected, therefore they will be discussed beneath together. The influence of settling down the thermal power units operation on increase in their availability factor due to the introduction of pumped-storage plants into the power system was visible over late seventies and early eighties. In 1974-81 the breakdown factor of power units of 120 MW and 200 MW was near 10%, whereas since 1982 it has been reduced down to 4% [19]. The reduction in the breakdown factor has been possible owing to the introduction in 1982 into the national energy system of the pumped-storage plant in Żarnowiec and an increase in the availability factor in Porąbka Żar - the pumped-storage plant which at that time managed to overcome technical problems. It should be also noted that this breakthrough took place when Poland was under severe social and economic crisis which hit badly our country in 1980-1981.

3.1.3. Power generation of thermal power stations at or near optimum efficiency

Introduction of pumped-storage plants into the power system enables full loading of a certain number of thermal power units during pumping work and their operation at optimum efficiency, that is at the lowest level of fuel consumption. It was calculated in [20] that when the pumped-storage plant of Moty operates in the pumping regime of 810 MW (3×270) during 2200 hours a year, then 16 thermal power units of 200 MW each running on hard coal can operate at full power capacity instead of operating under minimum power condition, which brings net profit of 2640 TJ of energy – about 15% of the total yearly energy used for pumping in these power units.

3.1.4. Reduction in running costs in thermal power stations

The amount of savings made in points 1-5 should be considered a global reduction in running costs in the thermal power station.

3.2. Benefits of operation of pumped-storage plants for the power system

3.2.1. Increase in the flexibility of operation of the power system

This means an increase in the ability to adjust the system to cope with fast changes of generated power in response to changing demand. One of indirect effects is increase in the flexibility of operation of the national power system within the connected power systems [21]. This fact combined with financial tariffs set up so as to stabilise operating conditions within the connected power systems brings considerable economic profits thanks to improvement in the energy balance of the country. Increase in the flexibility of the system due to the operation of pumped-storage plants also reduces the occurrence of separation of the systems, thus reducing the time of their individual incoordinate operation following the separation. In case of separation, the separated system is usually hit by a sudden power deficit which in turn incurs significant economic losses. The losses can be reversed by operation of pumped-storage plants, which can considerably minimise the time of separated work of the systems. The systems separation happened very often in eighties when the Connected Power Systems automatically separated from the Common Power System of the former USSR following overloaded power transmission within the node of Lwów.

3.2.2. Replacement of old inefficient power stations

Pumped-storage plants newly introduced into operation within the power system eliminate inefficient thermal power stations from the process of energy production. These old thermal stations, already amortised running on high-carbon (rich) coal and remaining in reserve, are put into service for a short time during on-peak periods in order to meet the demand for power. Pumped storage plants can be an alternative for inefficient thermal stations, thus pushing them out of the system. In Polish conditions this is the fate of heat and power stations where the cost of production of 1 kWh is several times higher than in most efficient block stations [18]. For this reason units of heat and power stations are placed into reserve in first place and put back into service in the last resort.

3.2.3. Improvement in the efficiency of energy production in the whole power system

Settling down the operation of power stations described above has an effect on the efficiency of electric energy production in the whole system and also reduces the consumption of fuels needed for the production process. Assuming that the efficiency of the system rises by 1% due to introduction of pumped-storage plants into the system, as it was assumed in [22], and that the gross production of energy is of the order of 130.1 TWh, as in 1993 [23], then the savings can amount to 1.3 TWh - an equivalent to 0.8 million tons of hard coal. It should be also noted that these savings do not involve any additional investments.

3.2.4. Increase in the security factor of the system

Security of operation of the power system depends on the amount of the break-down reserve (called also the intervention reserve) of the system, which in turn depends on the production structure and availability factor for the power units operating within the system.

3.2.5. Decrease in the break-down frequency and costs of modernisation, increase in the availability factor of the power system

The limitation of interrupted operation of thermal power units leads to a decrease in the break-down frequency and lowers costs of modernisation of thermal power stations. As a consequence, inefficient and old thermal power stations, subject to frequent failures, are pushed out of the system and replaced by pumped-storage plants. Therefore, global costs of modernisation of the system are diminished. Containing the break-down frequency of thermal power units and at the same time increase in the availability factor have a clear effect on a decrease in the break-down frequency and increase in the availability factor of the whole power system as well as on an increase in the reliability of energy supplies.

3.2.6. Improvement in quality parameters of electric energy and in local conditions of energy supply

Lack of appropriate power reserve leads to a decrease in quality of electric energy supply, which manifests itself in failing to maintain guaranteed levels of frequency and voltage. A sudden power deficit caused by the loss of generated power in the aftermath of a break-down of turbosets or failure of high-voltage transmission lines connecting neighbouring systems or large power stations can shake the balance between the demand and supply potential followed by a frequency decrease. The deficit duration depends on how fast power reserves of the system are turned into generation work and on the effectiveness of primary and secondary control. In modern power systems, the time of frequency fall usually does not exceed a dozen or a few dozens of seconds [13]. Pumped-storage plants play a particularly important role in maintaining all kinds of reserve - primary, secondary, spinning and stand-by reserves.

The absence of power limitations in the national power system with the beginning of 1982 did not result from extending the power capacity of the system. The unexpected but desired change for the better which took place that time (1982). After several years of slow steady rise in production, the national economy collapsed again in 1990 following the transformation of the political system and foundation of the market economy, which brought a dramatic decline in industrial production. From the point of view of power industry, the situation of ensuing low demand for power from industry was relatively easy to cope with - the demand was satisfied. Nevertheless, in 1983-1986 due to insufficient investment feeding of the energy sector, power deficits were recorded and handled by lowering the energy quality during on-peak hours (lower voltage). As a result about 10% of consumers got voltage below the guaranteed level and about 7000 villages were not given the permission to extend their power demand by introducing new high power machinery [25].

3.2.7. Reduction in transmission losses

Reduction in transmission losses can be achieved by preventing overload of transmission lines. The control of power distribution is accomplished by means of large pumped-storage plants, localised at the nodes of the high-voltage transmission grid [26]. The examples of this kind of localisation in Europe are Vianden (1100 MW) in Luxembourg, Schluchseewerk (1884 MW) in Germany at the Swiss border or the complex of water-storage and pumped-storage plants in Illwerke (1244 MW) in western part of Austria next to the border with Switzerland, Germany and Italy – being an important node of the UCPTE system.

3.2.8. Reduction in running costs of the system

All indirect benefits achieved in thermal power stations combined with indirect benefits obtained in the energy system are decisive for decreasing global running costs of the system. However, the total amount of these savings is very difficult to estimate.

4. Conclusions

The operation of pumped-storage power plants brings a series of advantages for the power system. Besides their main function - transfer of energy and power from low to peak demand periods, these power stations carry other important functions like the intervention function, control function (including "start-up/shut-down" control, primary control, load frequency control), spinning reserve and operational stand-by reserve. Depending on the configuration of system connections, pumped-storage power stations perform also compensation work, producing reactive energy and controlling voltage in transmission lines.

The functions mentioned above bring a series of advantages for the power system as a whole. Amongst these advantages are: settling down the operation of thermal power stations which has an effect on the limitation of break-down occurrence in thermal power units, reduction in the consumption of fuel used at start-up by off-peak loading of thermal power units with pumping work, power generation at or near optimum efficiency, increase in the availability factor of the power system and in the reliability of energy supplies, reduction in transmission losses and raising the quality parameters of electric energy.

Manuscript received in August 1996

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Korzyści techniczno-ekonomiczne systemu elektroenergetycznego z tytułu pracy elektrowni pompowych

Streszczenie

Omówiono funkcje elektrowni pompowych w pracy systemu elektroenergetycznego. Podzielono je na dwie grupy umowne: na tzw. *funkcje bezpośrednie* (bezpośrednio oddziałujące na kształt krzywej wytwarzania w systemie) i na *funkcje pośrednie* (pośrednio oddziałujące na pracę systemu). Spośród funkcji bezpośrednich omówiono: pracę programową, funkcję interwencyjną, funkcję regulacyjną, utrzymywanie rezerwy wirującej i operacyjnej rezerwy stojącej oraz pracę kompensacyjną. Spośród funkcji pośrednich opisano *uspokojenie pracy elektrowni cieplnych*, ograniczenie ich awaryjności, zmniejszenie zużycia paliwa na skutek dociążenia bloków cieplnych w okresie pompowania i pracę tych bloków w pobliżu optimum sprawności, oraz inne korzyści techniczno-ekonomiczne systemu elektroenergetycznego niekiedy trudno, bądź w ogóle niewyliczalne w sensie finansowym. Artykuł stanowi globalne usystematyzowanie zalet i korzyści wynikających z pracy elektrowni pompowych zebranych na podstawie różnych źródeł literaturowych.