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Need for Adjustable Speed Pump Storage Turbines in the Systems Having Large Capacity of Conventional and Pumped Storage Power Plants: A case study for Turkey

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SUMMARY

Considering the whole power system, a Pumped Storage Power Plant (PSPP) is distinctive from other types of power plants for its storage capacity in case of any imbalance between supply and demand which is taken into action in a short time, thus, helping peak shaving and valley filling in the power grid. The current study aims to evaluate the importance of the presence of s in a large power system and to explain the need for PSPPs when current state and future development plans of Turkish Power Grid, which has large capacity of conventional storage power plants, are taken into account. Moreover, penetration of the Adjustable Speed Pumped Storage Power Plant (AS-PSPP) in Turkish power system is also verified. In addition, the question of whether AS-PSPPs are required in a power system with large storage capacity as in Turkey is investigated thoroughly. The feasibility of AS-PSPPs is studied through focusing on the current state and projecting on the future conditions of Turkish Electricity System when both conventional storage HEPP and pumped storage power plant's technical characteristics are taken into consideration. According to the results obtained in the current study, it is seen that the presence of AS-PSPPs could be more conducive in operation condition with a high fluctuation factor which is a result of the increase in the penetration of renewables like wind and solar power plants.

KEYWORDS

Flexibility of electricity grid, adjustable speed pumped storage, Turkish power system, Renewable Energy Resources

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1. Introduction

Turkish Electrical System is a developing system with average annual growth rate about 5.6%, considering the electricity consumption covering the years 2005 - 2015. In addition to this growth rate, the portion of renewable energy sources (RES) in the electricity production is increasing due to technological advances, supply diversification and policies related to environmental measures. In coming future, this rate is expected to increase further [1]. However, the increase in the penetration of RES in the electricity grid, with the intermittent generation characteristics, negatively affects the supply and demand balance of the grid and deteriorates power quality of the system. The only way to increase RES rate in the power system without compromising electricity supply-demand balance and the power quality, as targeted in the strategic plan, is to utilize sufficient capacity of flexible power plants which are capable of compensating the imbalances through the grid [2],[3].

The installed capacity of hydroelectric power plants (HEPP) in Turkish power system is about 19 GWs. meaning flexible and a large conventional storage capability today [1]. However, whether this large flexible hydroelectric capacity responds to the all compensation needs of the current and the targeted future conditions of electricity network, and in terms of flexibility which amount of flexible hydroelectric capacity will be needed in the future is an important question.

Adjustable Speed Pumped Storage Power Plants (AS-PSPP) could be a good solution for storing excess RES energy during off-peak hours in the grid in which high penetration of RES would be a potential problem [4],[5].

The aim of this study is to overlook the Turkish Electricity System's current situation and to provide some insights for its expected situation in the near future by predicting the amount of ASPSPP power needed in the Turkish Electricity System's in 2025, through the consideration the prescience of targeted amount of RES powers enter in to the system with expected production and consumption amount. Being in line with the targeted aim, this study seeks for the answers to the following questions:

1) Can existing and planned large scale HEPP's fulfill all balancing request of Turkish electricity grid system?
2) What is the secure and sustainable way of resolving the missing function that may occur in the systems?

2. Conventional Storage and Pumped Storage Hydro Electrical Power Plants

Just as Pumped Storage Power Plants (PSPP) have undertaken the compensation role for the unbalances caused by the inflexible steam driven power plants in electricity grid in the past, presently problems arising from the unbalances caused by high penetration of RES such as wind and solar power which has intermittent characteristics, could be handled by PSPPs. It is expected that as the portion of RES in the electricity grid increases, compensation needs in the grids would increase, as well. PSPP's are secure, sustainable and highly efficient technology, thanks to its flexible characteristics, which has the longest term use in the supply and demand compensation of electricity grid systems [6], [7].

In terms of daily grid operation, Conventional HEPP and PSPP, in generation mode, have the same technical characteristics. Both power plants are capable of providing stable and flexible power which is extremely important for the system stability. Both power plants provide added value to the system by using the stored hydraulic potential through introduction of the power required in peak hours [7]. There are some differences between them in terms of resources. Conventional Storage Power Plants generate electricity by utilizing naturally running water into the basin. While Pump Storage Power Plants generate electricity by pumping the water to upstream reservoir through the surplus electricity provided by thermal and renewable sources in the system. Simulated daily operation of PSPP in the multi resourced electricity system is shown in Figure 1.

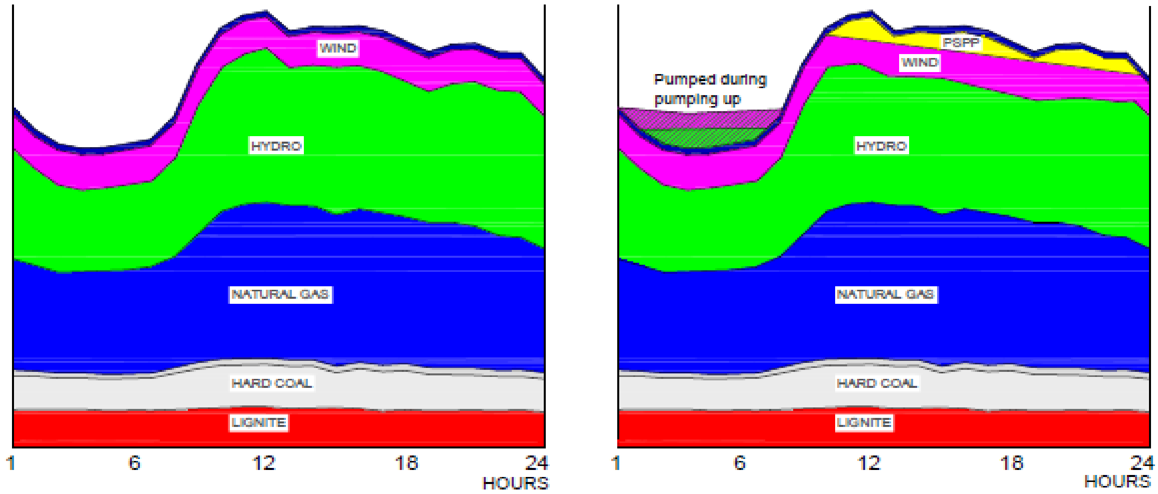

Figure1: Simulated daily operation of PSPP in the multi resourced electricity system.

2.1. Conventional Pumped Storage Power Plants

There is a considerable difference in the amount of electricity consumption during the day and night. Hence, it is important to make effective use of the generating equipment that produce a surplus during the night. Generating electricity by pumped water uses following process. The electricity generated at night by thermal, nuclear, and wind power generators is used to pump water from the lower reservoir to upper reservoir, and during the day time hours of peak demand this water is used to generate electricity. While it is not possible to store electricity in large amount, it can be stored by transforming it into water energy [2], [8]. In Figure 2, the operation methods of a PSPP is shown.

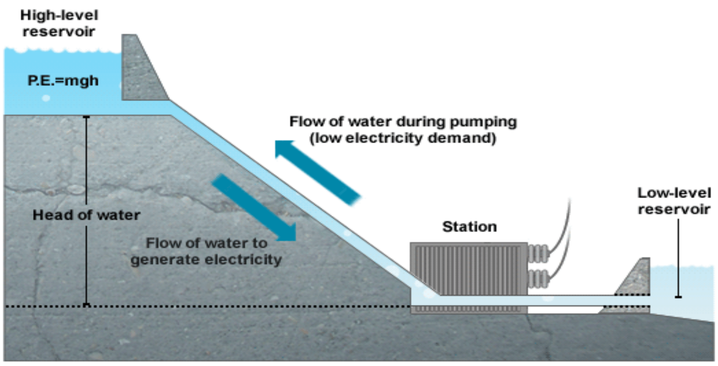

Figure 1: Operational Principle of a PSPP [8].
Source: http://www.bbc.co.uk/bitesize/standard/physics/energy_matters/generation_of_electricity /revision/3/

Conventional PSPPs could wait stand-by mode or run in full power in the pumping mode by consuming energy produced by the system. In other words, while operating in pumping mode, conventional PSPP's, in the case of frequency fluctuations, cannot contribute to the frequency control system by adjusting their input power received from the grid. This means that PSPPs are inadequate in compensating the instability induced by the electricity generation of renewable sources in the off-peak hours [9], [10], [11].

2.2. Adjustable speed pumped storage plants

AS-PSPPs has unique characteristics among the PSPPs where in pumping mode, they are capable of operating in partial loads and presenting flexibility to the electricity grid. Adjustable speed pump turbines were commissioned starting in the early 1990s. Developed for the problem arising from base load operation mode of nuclear power plants in the night where the demand decreases, AS-PSPP has provided great extent of flexibility capability to the grid which they are connected in since then [10], [11].

The structural differences between adjustable speed machines and conventional fixed speed machines are shown in Table 1. These structural differences bring advantageous and flexible operation characteristics to owner who have power plants with adjustable speed machines.

Table 1: Comparison of conventional machine and adjustable speed machine [10].

System	Conventional Machine	Adjustable Speed Machine
Pole	Salient Pole	Cylindrical
Rotor Coil	Low Voltage(DC)	High Voltage (AC)
Excitation	DC Excitation	AC Excitation
Speed	Fixed	Adjustable

Adjustable speed pump storage power plants can control pump input power by adjusting the rotating speed of pump thus participating to Automatic Frequency Control (AFC) of the grid during night and day-offs when the demand is low. This operation mode is not possible with conventional fixed speed pump units. Highest number of planned and operational installed AS-PSPP units are in Japan. Typically, adjustable speed units and fixed speed units are constructed in the same site in Japan. Vendors note that adjustable speed units have longer operational time compared to fixed speed units. When compared in terms of availability, adjustable speed units operate in the pumping mode whereas fixed speed units operate in the generating mode. This means that adjustable speed units are commissioned for power grid system stability. Operators take into account the advantage of operation free from speed regulator and AFC mode [11].

An appropriate speed can be adjusted in speed spectrum of the machine by considering pump-turbine efficiency in adjustable speed units. Consequently, pump-turbine efficiency can be improved compared to conventional units. As an example, efficiency has been improved by 5% at partial loads in Yagisawa Unit 2 [11]. In another study, fixed speed units have been renewed by adjustable speed units during refurbishment of Kadamparai pump storage power plant in Tami Nadu district of India where the results have been analyzed. The results of analysis show that the increase in efficiency, which takes into account the amount of water mass pumped from down reservoir to upper reservoir, is 5.89% compared to original configuration [12].

Load change speed i.e. response time of adjustable speed (AS) units for frequency control is better compared to conventional units. This response can be denominated as instantaneous response. Figure 3 represents the depiction of the variations of response time at the same unit. In adjustable speed units, the combination of flywheel effect and governor effect provided a fast and continuous response characteristics for power change [13].

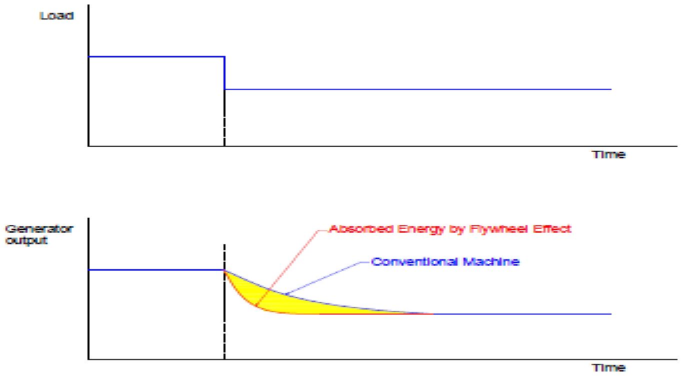

Figure 2: Comparison of response time between conventional machine and AS machine

As an example of response speed of AS-PSPP, it is stated that a 400 MW adjustable speed pumped storage unit for Ohkawachi Power Plant can change power in steps of at least 32MW in the generating mode and at least 80MW in the pumping mode, within 0.2 s, which in turn means the fastest response among its kind [10].

2.3. Comparison of Operation Characteristics between AS-PSPP, Conventional- type PSPP regarding the frequency control

An adjustable speed machine possesses all the functions that a conventional-type fixed speed machine possess. Moreover, they also have additional functions for the improvement of the quality of electricity at the off-peak hours. However, a drawback is the rise in the construction cost, which includes additional equipment and a large space for installation [11].

In the generating operation mode, the width of the change is wide and the speed of the change is also fast because it is possible to change the output by a change in the rotational speed and a change of the water volume. In the pumping mode, the AS-PSPP can adjust the input with a change in the rotational speed; the input cannot be adjusted in the conventional-type PSPP at all [11].

Tokyo Electric Power Company's Kazunogawa PSPP have both fixed speed machine and adjustable speed machine. A comparison of the operation characteristics of both machines in Kazunogawa PSPP is shown in the Table 2 [5].

Table 2: Comparison of Operation Characteristics between AS-PSPP and Conventional-type PSPP

	Width of output change in generating operation mode	Width of input change in pumping operation mode
AS-PSPP	130MW – 400MW	320MW – 470MW
Conventional-type PSPP	260MW – 400MW	470MW (Constant)

The AS-PSPP has large control width in generating operation and pumping operation. Thus, it is seen in the table that AS-PSPPs frequency control range is excellent.

3. Frequency Control System (FCS) and Utilization of HEPPs in the FCS in Turkey

The reference frequency in Turkey is 50 Hz and frequency is controlled between 49.8 and 50.2 Hz. Figure 4 shows ancillary services method for frequency control of grid that includes primary frequency control by demand fluctuation from a few seconds to a few minutes, secondary frequency control by demand fluctuation over fifteen minutes and tertiary control by demand fluctuation over more than fifteen minutes [14].

Various flexible power plants have very similar ancillary services functions, but only AS-PSPP and buying power from other countries have frequency control function during off-peak periods. AS-PSPP's can move power very fast by using flywheel effect of the machine. Reservoir type hydro also has frequency control function during off-peak periods, but it is very uneconomical to operate during hours with low marginal price. Combined-cycle thermal power plants can participate in frequency adjustments, but the response speed is much slower than hydro power plants [5].

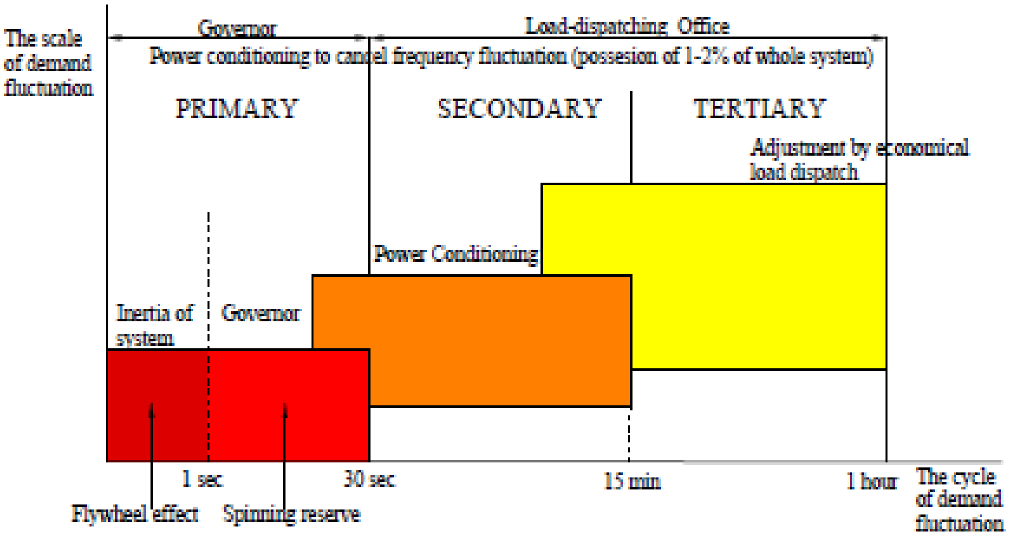

Figure 3: Corresponding method to demand Fluctuation

Contrary to other type of units, power variations in Turkey are ensured via large hydraulic units through the use of large mass and volume of water or by controlling the energy sources, which in turn leads to higher delays in terms of FCS response time. Main servomotors, inertia of the rotating parts, physical extension and large amount of water mass of large hydraulic units lead to delays in response time during abrupt power changes. Although faster response time can be obtained via mechanical systems, this causes efficiency losses. In another words, frequency control mode operation of large hydro units eventually leads to decrease in efficient operational domain and thereby reduces the efficiency of the plant considering the amount of water mass flowing through the turbines. Execution of such process via hydroelectric power plants during off-peak hour is not considered as an economically sound method.

4. Case study for Turkish Electricity System:

4.1. Turkish Electricity System's Current Situation and Short Term Forecasts

Currently, no pumped storage power plant exist in Turkey because of the high share of hydroelectric power with large scale reservoir in Turkish Electricity Grid. Although the increases of RES share in current grid system, alternative flexible power plant construction is revealed in Turkey due to the fact that exhaustion of the new HEPP potential and the particular increased need of flexibility on demand side at off-peak hours.

As of the year 2015, Turkish electricity grid installed capacity by resources and percentages are given in Table 3 [1].

Table 3: The distrubution of installed capacity of resources in Turkish Electricity Grid, 2015

Type of Resource	End of the year 2015		
	Installed Capacity (MW)	Percentage %	Number of Power Plant
Natural Gas + LNG	21.222,1	29	233
Hydraulic with reservoir	19.077,2	26,1	109
Hard Coal + Lignite	9.013,4	12,3	28
Hydraulic run of river	6.790,6	9,3	451
Exported Coal	6.064,2	8,3	8
Wind	4.498,4	6,1	113
Multi fuel (Liquid+ LNG)	3.684,0	5	46
Other	2.796,8	3,9	526
TOPLAM	**73.146,70**	**100**	**1.514**

Presently, RES input is not at critical level in terms of balancing of Turkish Electricity Grid System. However, the integrated power in the grid has reached 22 percent of the total installed capacity with Renewable Energy Sources Support Mechanism aiming at maintaining the supply balance against increase in demand side. Power plants supported by RES support mechanism should be run continuously when they are capable of supplying the required power to the grid. According to 2015 data, some stability problems were observed in grid when minimum to maximum load level is about 50%, due to higher generation of RES support mechanism in minimum load hours. For example, although disconnected to the system, approximately 750.000 MWh energy equivalent was paid to the operators due to leveling problems in 2015 [15].

As of the water income in spring season is increase, so generation also increases in the eastern part of Turkey. This surplus power has to be conducted to the western part due to high consumption. Moreover, spring is also the period for scheduled maintenance and repair of transmission lines, which causes overloading the transmission lines from east to west.

Table 4 provides an estimation of Turkish Transmission System Operator (TEIAS) for the next 10 years and includes renewable energy resources' installed capacities and their estimated available power in a minimum season in accordance with projections based on 2025. (Contribution to the generation on minimum conditions are simulated according to current availability/capacity factors of that kind of power plant). These values can be considered as the worst case scenario. A total 16.850 MW inflexible renewable power will be in the system according to this estimate.

Table 4: Estimated Renewables Installed Capacity for Turkish Electricity Grid System by 2025[15].

Type of Resource	Estimated Installed Capacity Year 2025 (MW)	Contribution to generation on min. condition. (MW)
Wind	16.000	4.800(%25)
Hydraulic run of river	12.000	9.000(%75)
Solar	9.000	900(%10)
Geothermal	2.000	1.500(%75)
Other renewable	1.300	650(%50)
Total	40.300	16.850

According to Turkish electricity system 2025 projection, peak demand load, instantaneous minimum demand load and average minimum demand load values are expected to be 70.000 MW, 26.500 MW and 30.000 MW, respectively. In addition, installed capacity of storage hydroelectric power plants is planned to reach up to 25.000 MW. A total of 2.400 MW of nuclear power installed capacity; a plus of 63.000 MW installed power of natural gas; coal fired power plants will be in the electricity grid. Considering the Renewable Energy Resource in Table 3 this accounts for a total 130.700 MW of installed power in the Turkish Electricity Grid System by 2025. This number leads a result of 31.850 MW of total power in the grid with an approximate total power of 16.850 MW renewable power, which must run, while another 15.000 MW minimum thermal power considering peak load power requirement from other sources[15]. According to the aforementioned scenario an imbalance is expected between 1.850 MW and 5.350 MW generation-demand profile of 2025. Moreover, only some part of this imbalance can be eliminated through power import.

4.2. Discussion:

Looking at the current state and future projections of Turkey, the electricity grid system will face the following challenges, and system operators will likely have considerable difficulty in adjusting frequencies during off-peak hours. This means that frequency adjustment function during off-peak hours will be of high value.

The problems for power plants in supplying frequency adjustment functions are:

- A majority of conventional hydropower plants of large and medium capacity (50 MW or larger) are shut down during off-peak hours.
- Combined-cycle thermal power plants owned by private companies aim at operating at the maximum output as much as possible rather than making output adjustments.

Need for frequency adjustment reserve will increase due to the introduction of large amount of wind turbines, whose output fluctuates greatly over short durations. Introduction of nuclear power plants, on the other hand, is expected to operate constantly at base load mode, in the near future.

Conventional large hydroelectric power plants in Turkish electricity grid cannot meet the flexibility requirement by eliminating excess energy occurring in off-peak hours. PSPP power can play an effective role in Turkish electricity market due to its storage capability where excess supply causes to either zero or very low prices at minimum load periods today.

Presently, a solution for the issue of transmitting power from the east to west direction by PSPP in Turkey can be achieved by shifting high power transmission from peak hour to off-peak hours that will provide a relaxation in the interregional transmission lines.

Increased RES share with the intermittent character in electricity power systems can cause increased risk of the stability of the system. Adding enough flexible power plants such as AS-PSPP which is capable of achieving balance in both supply and demand side, will be helpful to minimize the risk.

In order to reach the objective of resource diversification and increasing the share of renewable energy into the system referred in Turkish electricity strategy plan, inclusion of ASPSPP system and realizing the large scale projects in 10 years may enable a reliable and smooth transition to intended energy system structure in the future.

Considering with the advantages of the AS-PSPP described in Section 2, the presence of AS-PSPPs could be more fruitful in operation condition with a high fluctuation factor which is a result of the increase in the penetration of renewables like wind and solar power plants.

5. Conclusion

An analysis of the current Turkish Electricity Grid System generation characteristics yields that 20 percent of this generation originates from renewables, which are discrete in character. Within this regard, operationally there are no effective balancing systems employed particularly during the minimum load conditions taking place in spring. Therefore, integration of AS-PSPP systems to electricity grid increase flexible load amount in demand side and effectively provide a remedy to this problem.

Although peak hour load is estimated to be compensated by projected installed power system according to 2025 Turkish electricity system demand-supply projection, there will be a need towards flexible load during minimum system loading hours. System leveling problems will increase due to flexible power, system reliability and stability requirements in minimum loading periods. There is a need for integration of flexible power of AS-PSPP capable of operating at minimum load, in place of conventional hydroelectric power plants which are in stand-by mode during minimum load periods.

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