Application of Pumped Hydroelectric Energy Storages for Improvement of Power System Flexibility

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ABSTRACT

Besides many benefits deriving from the energy transition process, it is not uncommon for modern power systems to be faced with difficulties in their operation. The issues are dominantly related to the non-dispatchable nature of renewable energy sources (RES) and mismatching between electricity generation and load demand. As a consequence of a constant peak load growth, this problem is particularly pronounced during the daily peak hours. Therefore, it is of great importance to conduct all necessary activities within the system in order to preserve the system stability and continuity of operation. The typical solution to this problem lays in the use of gas power plants and diesel engine power plants. However, these units are characterized by high operating costs and they are not in compliance with modern environmental protection aspirations. Instead of expensive and outdated generation capacities, peak load shaving can be achieved through the engagement of pumped hydroelectric energy storage (PHES), and this is the primary focus of the paper. In addition to presenting the fundamental characteristics and operation principles of PHES, a new algorithm for peak shaving is developed. The traditional operation algorithms rely on complex optimization techniques and they are based solely on the day-ahead load forecast, meaning they don't take into account the volatility of RES. The developed algorithm overcomes the aforementioned drawbacks of the existing algorithms and its validity is confirmed through performed simulations on the modified version of the IEEE 30 bus system.

KEYWORDS: peak load shaving, pumped hydroelectric energy storage, storage management, renewable energy sources

INTRODUCTION

The consumers' needs for electricity change throughout the day. As a result of a growing trend in the number of end-users, the peak demand is increasing continuously, implying the possibility for occurrence of power outages and raising of the marginal cost of power supply [1]. Taking this into consideration, peak load management is one of the most important problems the electric utility is faced with. The commonly used approach in the addressing of this problem lays in the use of gas power plants and diesel engine power plants. However, these units are characterized by high operating costs [2,3] and they are not in compliance with modern environmental protection aspirations. On the other hand, the presented issue may be treated through peak load shaving, sometimes referred to as load levelling. Namely, peak load shaving represents the process of eliminating the peaks and the valleys in the daily load profile, thus flattening the load curve. The benefits of load levelling, both for the grid operator and for the end-user, are various and have been elaborated in a large number of studies [4-6]. Thus, different methods for peak load shaving are being developed and a large number of these methods are currently in use. Three different strategies for peak load shaving, which have been thoroughly reviewed in literature and implemented in practical power systems, involve the integration of Energy Storage System (ESS), smart use of Vehicle-to-Grid (V2G) technology and Demand Side Management (DSM). Electric Vehicles (EV) have not been widely deployed yet, especially in the Third World countries, and since a single EV is incapable of meeting the peak load alone, it is quite challenging to synchronise the operation of a large number of EVs in order to implement the V2G technology efficiently. On the other hand, implementation of DSM implies the use of advanced Information and Communication Technologies (ICT) which are only partially implemented in the undeveloped power systems. To bridge the gap between present power systems and modern power systems in the future, ESS is the only reliable option. The development of storage technologies is one of the most challenging fields of research in electrical engineering. The current research in this area is mostly directed towards Battery Energy Storage Systems (BESS). However, BESS have a short lifespan, require additional maintenance infrastructure and have limited power output, so they can only be used for peak shaving in the distribution grid. Therefore, in this paper, the possibility of using Pumped Hydroelectric Energy Storage (PHES) for peak shaving is investigated because this type of storage is widely accepted in developed power systems and it overcomes the disadvantages of BESS. What originally motivated pumped storage installations was the inflexibility of nuclear power plants [9]. Nuclear plants' large steam turbines run best at full power. Pumped storage can defer the excess nuclear power generated overnight when consumption is low, thus help meeting the next day's peak load. However, in the 21st century, the situation has completely changed with the integration of Renewable Energy Sources (RES) into the power grid, and different storage system technologies are widely used to enable the higher penetration of RES. Different methods for optimal operation scheduling of storage systems have been developed and are available in the literature. However, these methods mostly rely on complicated optimization techniques such as dynamic programming [7] and particle swarm optimization [8], which presume high processing power and large memory requirements. In this paper, in addition to presenting of fundamental characteristics and operation principles of PHES, a new algorithm for peak shaving using PHES is developed, and the application of this algorithm is tested on the standard IEEE 30 bus power system. The developed algorithm is also extended to match the non-dispatchable nature of RES. As it will be shown in the upcoming chapters, the main advantage of the developed algorithm in comparison with the traditional operation algorithms is its simplicity and execution speed, which makes it ideal for real-time monitoring and redispatching of the PHES in order to meet the system requirements.

FUNDAMENTAL CHARACTERISTICS OF PHES

Pumped hydroelectric energy storage is a type of storage which stores energy in the form of the gravitational potential energy of water, pumped from a lower to the higher elevation reservoir, as shown in Fig. 1. During peak hours, the stored water is released through the turbine from the upper reservoir and used to produce electric power. On the other hand, during the periods of low demand, excess generation capacity in the system is used to pump water from the lower to the higher elevation reservoir. Through this simple concept, energy is transferred from the peak part of the daily load curve to the base, thus flattening the load curve. The first application of PHES dates back to the early 20th century, and the units which were used were conventional synchronous-speed units. Then, in the late 20th century, Japan's utilities chose to install variable-speed pumps so that the plants could also help stabilize the grid frequency because the variable-speed induction motor-generators can adjust the plants charging and discharging to simultaneously balance electricity generation and load demand. These units provide wider operating range in generation mode, because of the possibility to optimize operating efficiency by adjusting the speed. On the other hand, conventional single-speed units in pumping mode can only operate with constant power, while variable-speed units can operate within a wide range, thus allowing them to store excess energy from various sources. Although variable-speed units have higher capital costs, the benefits they provide for the power system flexibility could make them a crucial resource for balancing modern power systems [10]. All pumped hydroelectric energy storages can be classified as closed or open-loop systems. While open-loop PHES is continuously connected to a naturally-flowing water source, closed-loop systems are usually preferred because of the fewer environmental impacts associated with their construction.

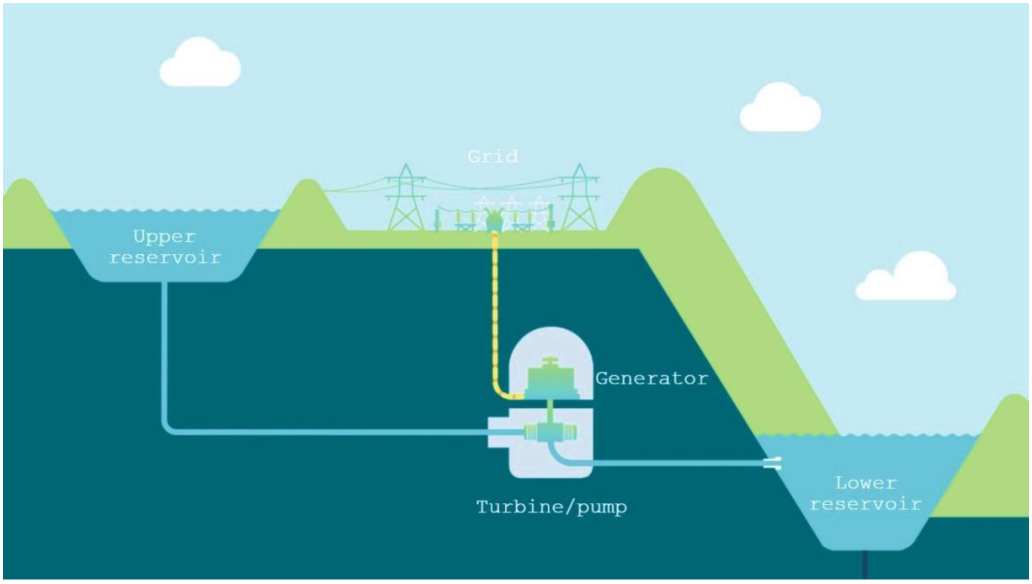

Fig. 1. Closed-loop pumped hydroelectric energy storage

Because of the high capital costs and grave impacts on the environment resulting from the need for two reservoirs, severe techno-economic analysis has to be conducted prior to the construction of PHES.

THE PROPOSED ALGORITHM FOR PEAK LOAD SHAVING

The developed algorithm is intended for peak load shaving of the daily load profile, so the starting assumption for the analysis is that the day-ahead load profile $P_{load}(t)$ is predefined. Let the 24-hour period be uniformly divided into a number of intervals.

For an arbitrary interval i, like in the Fig. 2., the energy W_i which should be provided by the PHES in order to flatten the daily load curve can be calculated as:

$$W_i = \int_{t_i}^{t_i+\tau} (P_{load}(t) - P_{avg})dt \quad (1)$$

where P_{avg} is the average daily load and τ is the length of the interval.

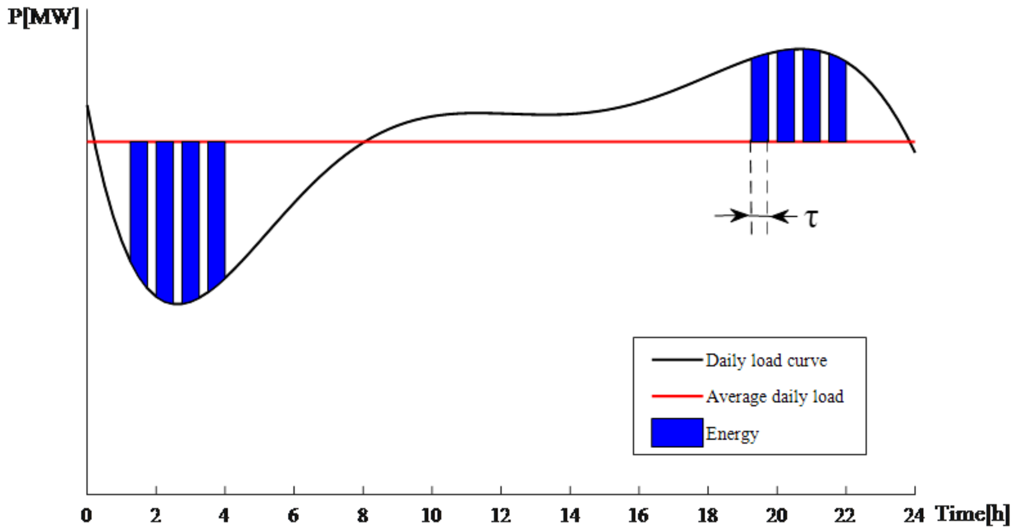

Fig. 2. Basic principle of the operation algorithm

If the load during the observed interval is higher than the average daily load, the calculated energy will be positive, which corresponds with PHES working in generating mode. Otherwise, if the load during the observed interval is lower than the average daily load, the calculated energy will be negative, meaning that the PHES should be dispatched to work in pumping mode. For real-time monitoring and operation of the PHES, the State of Charge (SOC) of the upper and the lower reservoir has to be updated for every interval τ, where the round-trip efficiency of the PHES needs to be taken into consideration. The SOC(%) has to be kept within the predefined threshold limits:

$$SOC_{LTh} \leq SOC \leq SOC_{UTh} \quad (2)$$

where SOC_{LTh} and SOC_{UTh} are the lower and the upper threshold values, respectively. The SOC can be updated as:

$$SOC = SOC_0 - \frac{W_i}{\eta W_{max}} 100 \quad (3)$$

where SOC_0 is the initial state of charge at the start of the observed interval, W_{max} is the energy equivalent of the water in the upper/lower reservoir when it is full and η is the efficiency of the PHES in pumping or generating mode. The efficiency of the PHES operating in generating mode η_g differs from its efficiency when operating in the pumping mode η_p.

The efficiency of the PHES operating in the generating mode ranges from 71.6 to 86.4 per cent, while the efficiency in the pumping mode ranges from 85.4 to 88.8 per cent. Lower efficiency in the generating mode is a direct consequence of lower turbine efficiency compared to pump efficiency. The round-trip efficiency of the PHES ranges from 75 to 85 per cent [11].

The power output of the PHES during the observed interval τ should be:

$$P_{st,i} = \frac{W_i}{\tau} \quad (4)$$

and the calculated power has to satisfy the condition:

$$-P_{p,max} \leq P_{st,i} \leq P_{g,max} \quad (5)$$

where $P_{p,max}$ is the maximal power in pumping mode and $P_{g,max}$ is the maximal power in generating mode. If the required power output exceeds the defined limits, it should be set to the corresponding limit value.

As it was stated in the introduction, the developed algorithm for operation scheduling of the PHES is extended to match the non-dispatchable nature of renewable energy sources. For the sake of simplification, the basic principle of the operation algorithm will be explained assuming the power system contains a solar power plant. However, it should stress out that the proposed algorithm can be evenly applied on systems with any type of RES. The idealized power output of the solar power plant can be described with a Gaussian function $P_{solar}(t)$ as shown in Fig. 3. With the predefined approximation of the solar plants power output and the day-ahead load curve, the daily load profile, as seen by the other generators in the system, can be defined as:

$$P_{gen}(t) = P_{load}(t) - P_{solar}(t) \quad (6)$$

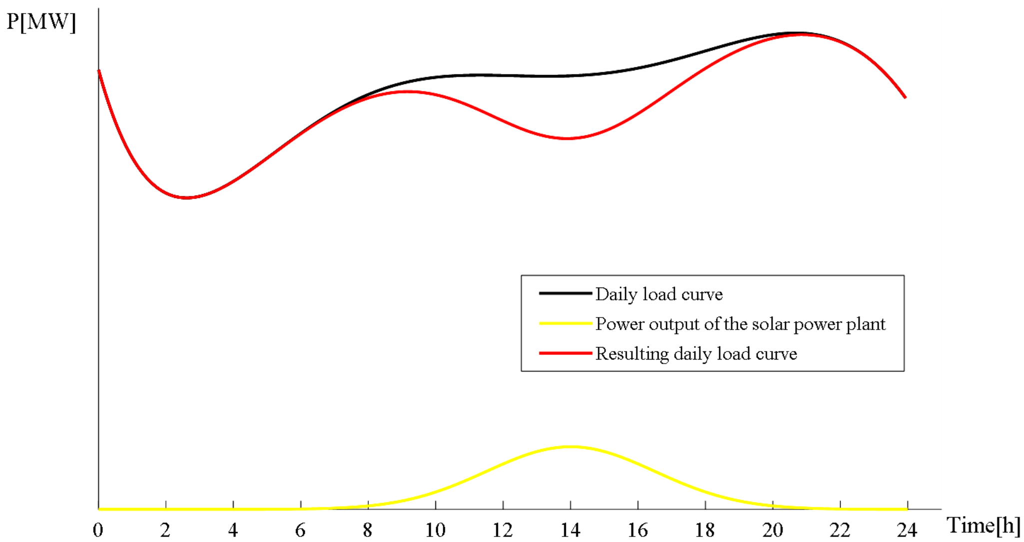

Fig. 3. Basic principle of the operation algorithm with integrated RES

Operation scheduling of the PHES in this case is performed in the practically identical manner as in the case when the power system doesn't contain renewable energy sources.
The only difference is that in this case, W_i is calculated in respecting of $P_{gen}(t)$ instead of $P_{load}(t)$. In Fig. 3., daily load curve is shown, along with the idealized solar plant power output and their corresponding load profile $P_{gen}(t)$.
The production of renewable energy sources strongly depends on weather conditions, so the day-ahead operation scheduling of the PHES relies heavily on the quality of the RES production forecast. In real-time operation, the newest data about the actual operating conditions of the RES needs to be taken into account so the PHES redispatching can be done. One of the conclusions deriving from Fig. 3. is that, in this case, the forecasted peak production of the solar power plant partially matches with the peak load in the system, meaning the operating power of the PHES can be reduced, thus saving the valuable stored energy for later use. Also, in case the peak production of the solar power plant occurs during the periods of low demand, it can be used for powering the PHES which operates in pumping mode.

THE ANALYSIS OF THE PROPOSED ALGORITHM

The developed algorithm was tested on the modified version of the IEEE 30-bus system shown in Fig. 4., which differs from the original version because of the PHES with nominal power S_n = 100MVA is connected in the 28th node. The 28th node was chosen empirically, after performing the tests for all available nodes in the system. The alternative approach is to choose the node and size of the PHES in order to reduce the transmission and distribution losses [12], however, this would result in minor benefits regarding peak load shaving.

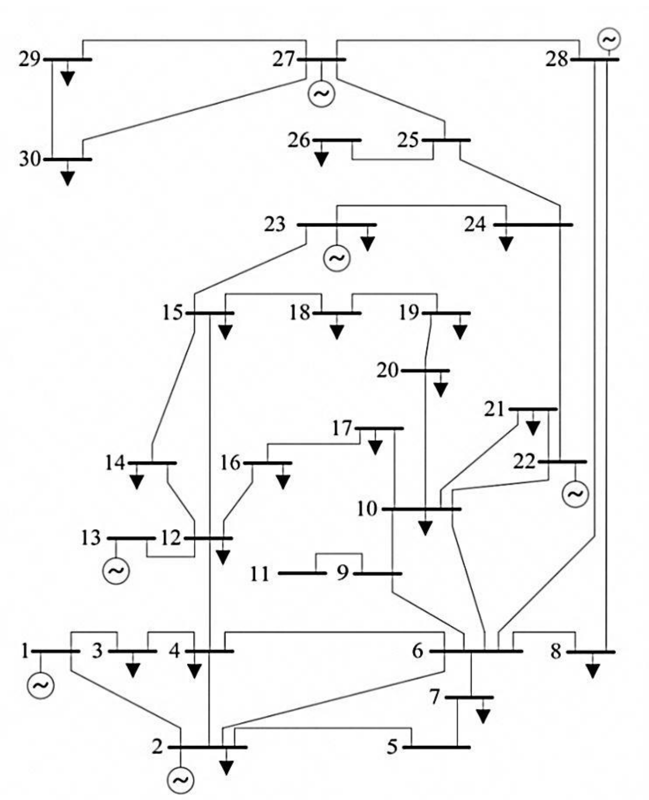

Fig. 4. Modified IEEE 30-bus system

The daily load profile was aggregated using the data provided by the Transmission System Operator (TSO) of Montenegro, however, it should be noted that the developed algorithm can be evenly applied to an arbitrary daily load profile. All loads in the system were treated as constant power loads during the time interval $\tau = 15\, minutes$, which corresponds with the resolution of measurement in the Montenegrin power system. To be in compliance with the adopted daily load profile, let the initial SOC of the PHES be set to its lower threshold value.
The test results, which include the daily load profile before and after the engagement of the PHES and the power output of the PHES are shown in Fig. 5. Analysing the load profile before the engagement of the PHES, it's obvious that the difference between the daily peak load and the load in the off-peak hours is almost 100MW. After the strategic operation of the storage system using the proposed algorithm, it can be noted that the load variations, as seen by the generators in the system, don't exceed the value of 10MW.

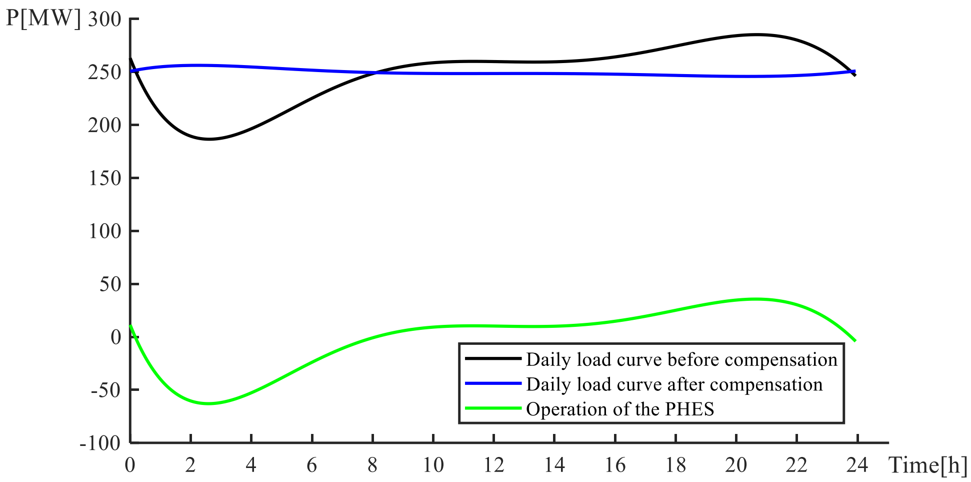

Fig. 5. Test results

Before the connection of the PHES, some of the nodes had voltage issues, especially during the peak hours. Figure 6. depicts the voltage regulation benefits arising from the strategic operation of the PHES during peak hours.

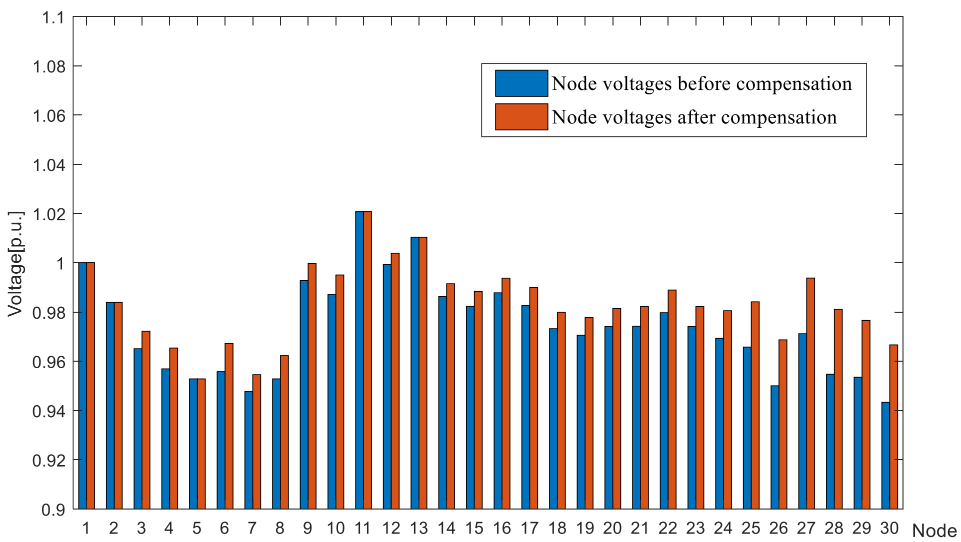

Fig. 6. Node voltages before and after the compensation during the peak load

To demonstrate the application of the developed algorithm for the operation scheduling of PHES in case of the power system with renewable energy sources, let the generator connected in the 27th node be replaced by a solar power plant. The 27th node was chosen because it's electrically closest to the location of the PHES, so the transmission losses will be minimal when the PHES is operating in pumping mode thanks to the power produced by the solar power plant. The test results are shown in Fig. 7.
As stated earlier in the paper, for the adopted load profile and idealized daily production curve of the solar power plant, the PHES can operate in the pumping mode solely using the peak production of the solar power plant. The strategic operation of the PHES helps to achieve a better matching between electricity generation and load demand. Thus, the complete benefits of this synergy have been reaped. The load variations after the strategic operation of PHES don't exceed the value of 10MW so the purpose of the developed algorithm is more than achieved.

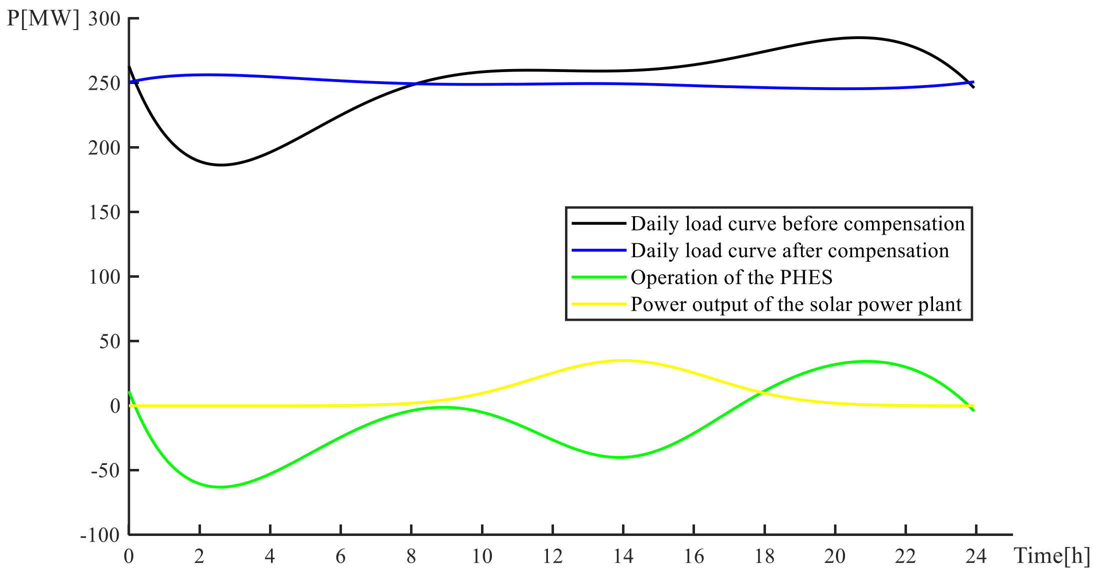

Fig. 7. Test results

CONCLUSION AND FURTHER WORK

As can be seen in the paper, the developed algorithm is very simple and effective for the optimal scheduling of the PHES. Since it relies only on load flow calculation and simple mathematical operations, the developed algorithm is fast and reliable and it doesn't require high processing power, which makes it ideal for real-time monitoring and redispatching of the PHES. The benefits of the PHES for peak shaving and voltage regulation are undeniable. Further work will be oriented towards the adaptation of the developed algorithm for peak shaving using different types of storage technologies like Battery Energy Storage System (BESS) and Vehicle-to-Grid (V2G) technology in order to create a universal solution for an unlimited application in practical power systems.

ACKNOWLEDGEMENT

This paper is a result of the authors research conducted within the CROSSBOW project. The project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 773430.

NOMENCLATURE

Symbols

$P_{load}(t)$	the day ahead load profile
τ	length of the interval
W_i	the energy provided by the PHES in the *i*-th interval
P_{avg}	the average daily load
W_{max}	the energy equivalent of the water in the upper/lower reservoir when it is full
η_g	efficiency of the PHES operating in generating mode
η_p	efficiency of the PHES operating in pumping mode
$P_{st,i}$	power output of the PHES during the *i*-th interval
$P_{p,max}$	maximal power of the PHES in pumping mode
$P_{g,max}$	maximal power of the PHES in generating mode
$P_{solar}(t)$	idealized power output of the solar power plant
$P_{gen}(t)$	the resulting daily load curve
S_n	nominal power of the PHES

Abbreviations

SOC	State Of Charge of the upper and the lower reservoir
SOC_{LTh}	lower threshold value of the State Of Charge
SOC_{UTh}	upper threshold value of the State Of Charge
SOC_0	the initial State Of Charge at the start of the *i*-th interval

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