Efficiency Improvement of Pumped Storage System for MW Scale Off-grid PV Plants

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Abstract—**The photovoltaic market has been growing at a fast rate in the last two decades, and in 2014 reached a global capacity of about 180GW. Due to the increasing penetration level, large-scale energy storage systems that can compensate for its fluctuations become increasingly important. In case of off-grid systems, suitable energy storage is naturally a necessity. In areas with favorable geographical properties, pumped storage has an excellent potential to be applied with large-scale PV plants. The performance of a pumped storage system at MW power level, connected with an off-grid PV plant, is analyzed in this paper, considering the variable character of the PV power. An efficiency increase of the pumped storage system is obtained by means of an improved control of the motor for pump's drive. The system is tested and validated on a RTDS (Real Time Digital Simulator) platform.**

Keywords-photovoltaic energy; pumped storage; efficiency; control

I. INTRODUCTION

The photovoltaic sector experienced a strong growth of the installed power in the last years. In 2014, at least 40 GWp of PV systems were installed globally and is reported that the installed cumulative worldwide capacity was 178 GWp by the end of the year [1].

New PV technologies have been developed, and their energy conversion efficiency can reach 40%. In addition, the price of the PV systems is decreasing. Solar Power Europe estimates a decrease of around 75% in the next 10 years [1]. It is obvious that the PV integration level will increase even more considering these premises.

Even in grid-connected applications, stability problems, equipment overloading, power quality degradation, increased power losses, and even blackouts can take place due to grid overloading. Appropriate energy storage technologies can overcome the problem of an ineffective grid penetration. Spinning reserve, frequency and voltage regulation, peak curtailment and levelling are just a few important functions that can be met by storage [2]-[3].

Among different storage technologies available, pumped storage can significantly contribute to PV energy integration. This storage technology has gained attention especially in the countries with high potential of hydropower. High capacity, along with long period of storage, are the most attractive features of this technology [4]-[8].

Many studies, which consider pumped storage for wind penetration increase are made, but photovoltaic-based pumped storage system were found in the literature only for very small applications such as load of a few houses. Ma et al. [9] presented a study of the pumped storage with PV systems for small autonomous systems in remote areas. Manolakos et al. [10] presented the implementation of a standalone PV plant in which the battery storage was replaced by a micro-hydraulic turbine. Margenta and Glasnovic [11] proposed a hybrid power system consisting of PV energy generation in combination with pumped storage to provide continuous energy supply. Javanbakht et al. [12] evaluated the transient performance of a small-scale plant consisting of a PV and a pumped storage system.

The analysis of PV based pumped storage at MW power level is important, as this kind of system can facilitate the increase of PV energy integration.

The performance of a PV - pumped storage system at MW power level is analyzed in this paper. The variable operating conditions of such a system due to the fluctuating solar irradiation, and consequently the power provided by the PV system are taken into account. The efficiency of the system is the focus of the current study, even though also the dynamics can be considered. For e.g. there may be situations of a sudden load increase, but this can be the subject of another analysis. The efficiency increase of the pumped storage system is presented in this paper. This is obtained by means of using an improved control method for the pump's drive.

II. PV-PUMPED STORAGE SYSTEM DESCRIPTION

This paper considers a standalone system, which consists of a PV plant, a pumped storage system, and a variable load (consumers). During the daytime, the energy from the PV plant is used to satisfy the load, while the extra energy will be used by the pumped storage system. During the night, the pumped storage system assures the energy for the consumers. In addition, the pumped storage system can provide the energy for the peak periods of the daytime or in case of low irradiance conditions.

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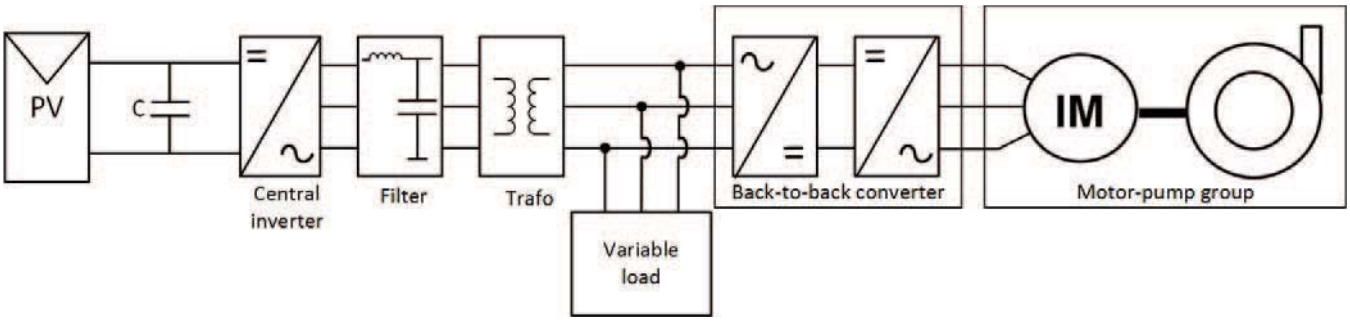

Fig. 1. Standalone PV system with pumped energy storage

A back-to-back converter, which interfaces the storage system with the PV plant and the variable load, is included.

The block scheme of the system is presented in Fig. 1, and a short discussion considering the most important aspects of each of the system's elements is given in the following.

A. PV system

The PV system's installed power is 2.5 MWp. Panels with 250 Wp were chosen for the analyzed system. Their technical characteristics are given in Table 1. In order to reach the 2.5 MWp power, 10575 panels were needed.

A PV plant layout with central inverter is considered in the current study. The losses in the PV systems were neglected, as we focus on the efficiency of the pump storage system.

B. Back-to-back converter

The back-to-back converter assures the power circulation from the PV plant to the pumped storage group and from the pumped storage group to the variable load. The motor side inverter facilitates the variable speed operation, which is very important for the pumped storage systems performance.

C. Motor-pump group

The efficiency of the pump system is around 80% (for MW power order) [13]. The motor-pump group have a great impact on the system efficiency. The induction motors have an efficiency of about 90% at MW power level, but their efficiency decreases as the load increase.

On the other hand, in pumped storage applications, their load torque is dependent on the square of the speed, while the pump's power is dependent on the third power of the speed [14]. This means that the loading of the motor is lighter at lower speeds than at nominal speed. Therefore, variable speed operation with different loading levels can lead to an efficiency increase of the system. The pump's torque is presented in Fig. 2.

In [15] the authors established the motor's most efficient operating points in pumped storage systems, and the analysis concluded that the most efficient operating zone of the induction motors turns to be between 25 and 35 Hz of the supply voltage for MW power order (Fig. 3). The correlation between the motor-pump group's mechanical speed and the frequency of the supply voltage by means of motor's number

TABLE I. PV PANEL CHARACTERISTICS

Parameter	Value	SI
Watt peak	250	W
V_{oc}	37.2	V
I_{sc}	8.87	A
V_{mpp}	30.1	V
I_{mpp}	8.3	A

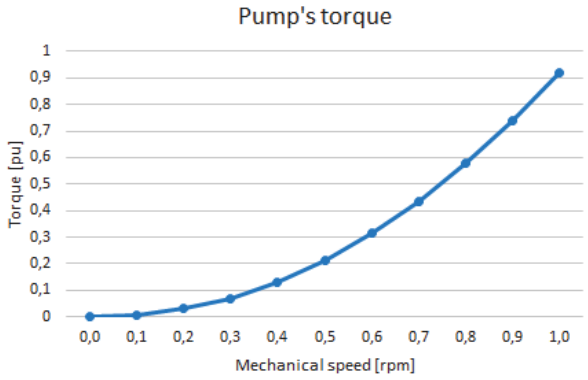

Fig. 2. Pump's torque

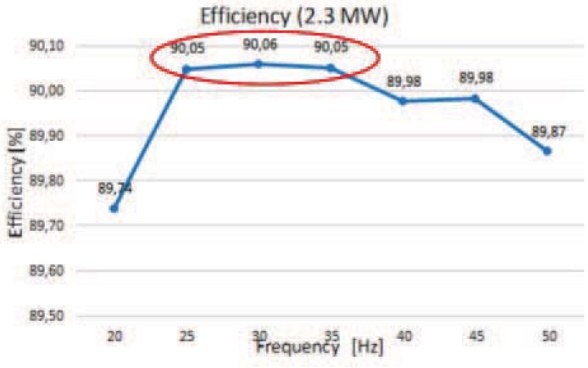

Fig. 3. Induction machine most efficient operating points in pumped storage applications

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of poles has been considered.

The impact of the motor efficiency on the pumped storage system can also be seen for the system presented in this paper, because the motor has to operate under 50 Hz for reduced levels of solar irradiance. This will be presented in the System evaluation and results section of this paper. It is noted that the same type of system as in [15] is used in the current study.

III. Efficiency Improvement of the PV-Pumped Storage System

Moreover, by means of the motor side inverter, an improved control of the motor was implemented. This considers a third grade polynomial dependency of the motor's phase-to-neutral voltage on the stator frequency (V/Hz^3). The control method was proposed by the authors in [17], and it was implemented for pumped storage systems for wind systems. This control leads to a better exploitation of the low speed zone, which is characterized by low efficiency especially for the pump's operation. Also, increased power available for pumping is obtained compared to classical motor control. However, this paper will not go into details regarding the control methodology, but the efficiency increase obtained in the case of the PV-pumped storage system using this control is worth to be presented.

IV. System Evaluation and Results

The MW power study is facilitated by the RTDS (Real Time Digital Simulator) platform, on which the system is tested and validated. The RTDS is capable of simulating complex systems including power converters in real time and it is a well-established tool for power system studies.

The RSCAD software was used for interfacing the RTDS Simulator hardware. The standalone PV-pumped storage system has been modeled in the RSCAD/Draft module. The system monitor and the variation of the operating conditions in real time were performed by means of the RSCAD/RunTime module. The RTDS platform can be seen in Fig. 4.

The 2.5 MW PV-pumped storage system is analyzed in the case of different levels of solar irradiation, from 200 W/m^2 to 1000 W/m^2, to take into account the stochastic nature of PV energy.

The DC available power of the PV system is lower as the solar irradiance decreases. Therefore, the system's frequency needs to be decreased below 50 Hz, thus the motor for pump's driving will operate on different points on the mechanical characteristic.

Moreover, the motor can operate at higher frequencies considering the same input conditions, if implemented the V/Hz^3 control, fact shown in Fig. 5.

The pumping power versus supply/input voltage frequency is presented in Fig. 6 for V/Hz control, and in Fig. 7 for V/Hz^3 control. It can be seen that the latter method of controlling the electrical machine leads to higher available power for pumping, as the pump's mechanical power is proportional with the third power of the speed.

The pumping power depending on the solar irradiance is presented in Fig. 8. It can be seen that around 0.2 MW are available for extra-pumping if the proposed control (V/Hz^3) is implemented, compared to classical V/Hz control method. The powers available for pumping the water are almost equal for both control methods in the case of 1000 W/m^2. This is because the motor operates on the same point of the mechanical characteristic for both control methods.

The system efficiency can be seen in Fig. 9. The maximum efficiency reached by the pumped storage system is 90.05% at 600 W/m^2. Moreover, an efficiency increase of up to 1% can be noticed with V/Hz^3 control for all the cases analyzed.

The increased efficiency for 400, 600, and 800 W/m^2 obtained with both control methods considered is influenced by the motor's efficiency. As it was previously stated, the efficiency of the motor is affected by its loading. In pumped

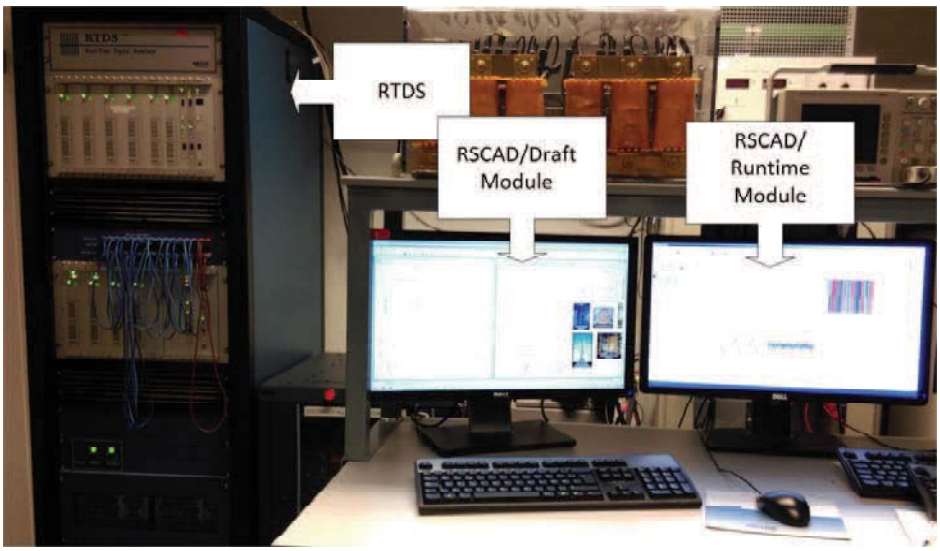

Fig. 4. Real time digital simulator (RTDS)

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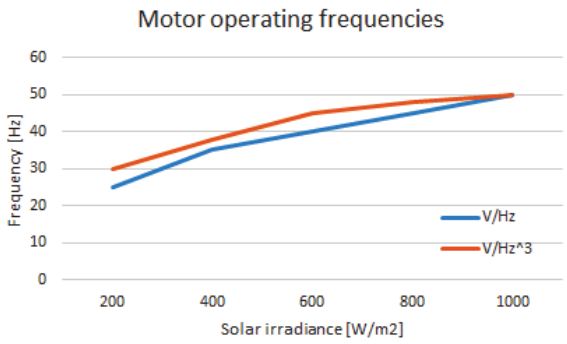

Fig. 5. Pump's motor operating frequencies in V/Hz and in V/Hz^3 control

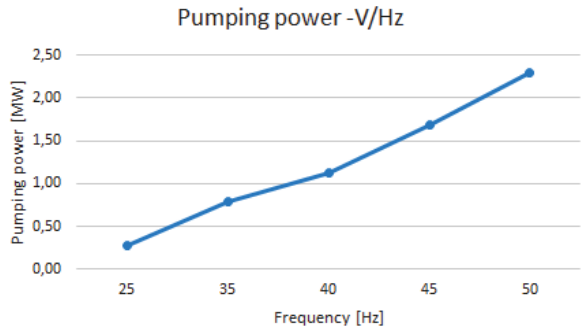

Fig. 6. The available power for pumping for the PV pumped storage system depending on the supply frequency in the case of V/Hz control

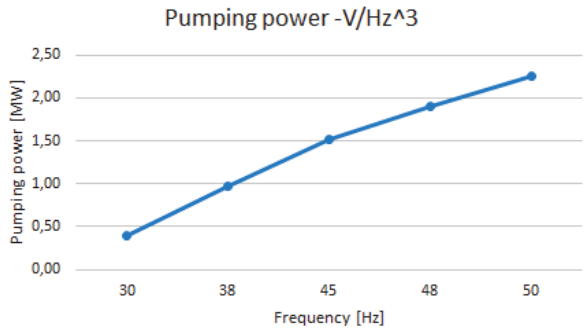

Fig. 7. The available power for pumping for the PV pumped storage system depending on the supply frequency in the case of V/Hz^3 control

storage applications, the load of the motor is lighter at lower speeds and frequencies than at nominal speed.

Therefore, the motor has a better performance at lower speeds. This happens also in the PV-pumped storage system, where for lower level of irradiance, the system has to operate at lower frequencies.

Moreover, a study case considering a specific site situation is included in this paper. The hourly energy profile of a PV system based on the solar irradiance is the input in analyzing the PV-pumped storage system performance. Two situations are presented, considering the irradiance level of two representative days: one with high irradiance level and one with low irradiance level (cloudy day).

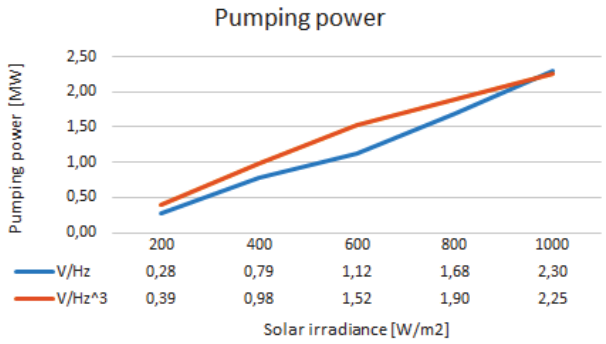

Fig. 8. The available power for pumping for the PV pumped storage system in the case of V/Hz and V/Hz^3 control methods

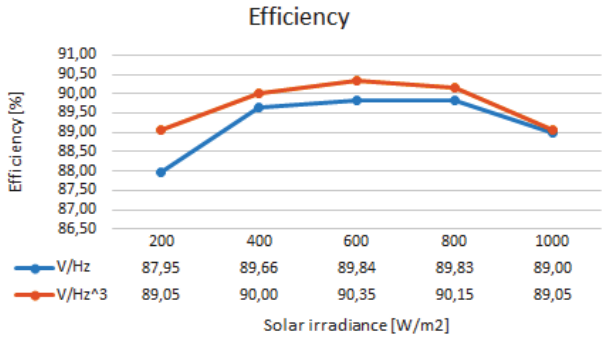

Fig. 9. The efficiency of the PV pumped storage system in the case of V/Hz and V/Hz^3 control methods

In Fig. 10 and Fig. 11, the system's pumping power for both days is presented. The results are given in a comparative way for both control methods analyzed in this paper. It can be seen that a higher power available for pumping is obtained with the proposed control method.

Furthermore, in Fig. 12 and in Fig. 13 the hourly power difference between the case in which the system is controlled with the V/Hz^3 method, and the one in which the classic control is used, is given.

Thus, the energy gain by using the proposed control method is established. For a day with high irradiance level, the energy yield is 2.57 MWh, while for a cloudy day, with low level of irradiance, 1.88 MWh are gained.

V. Conclusion

Appropriate energy storage technologies can overcome the problem of an ineffective grid penetration. A potential candidate for PV integration is pumped storage considering its valuable characteristics (high efficiency, high quantities of energy which can be stored).

This paper demonstrates the good operability of a PV plant with a pumped storage system at MW power level. The gain in the power (and efficiency) of the pumped storage system for various levels of solar irradiance is established. The pumped storage system's efficiency is up to 90.05%, without considering the PV energy conversion factor.

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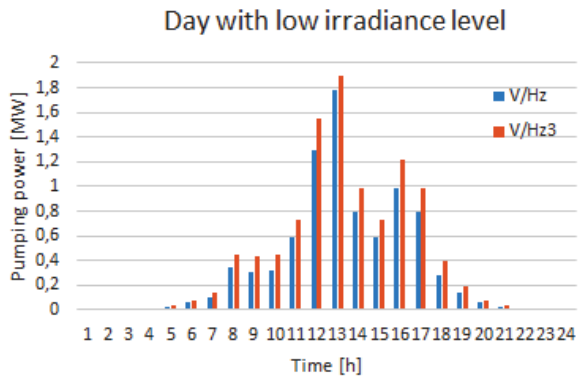

Fig. 10. The available power for pumping for the PV pumped storage system in the case of V/Hz and V/Hz^3 control methods for a day with low irradiance level

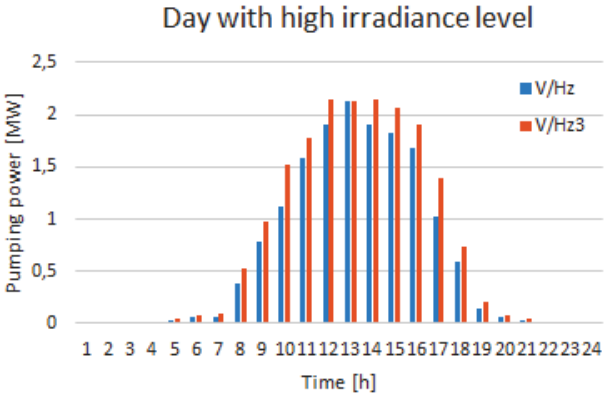

Fig. 11. The efficiency of the PV pumped storage system in the case of V/Hz and V/Hz^3 control methods for a day with high irradiance level

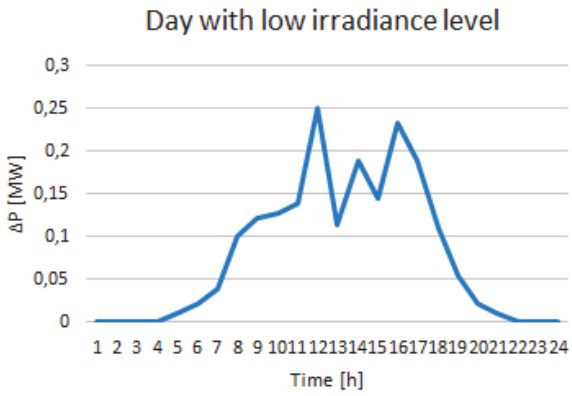

Fig. 12. The hourly power difference between the case in which the system is controlled with the V/Hz^3 method, and the case in which the classic control is used

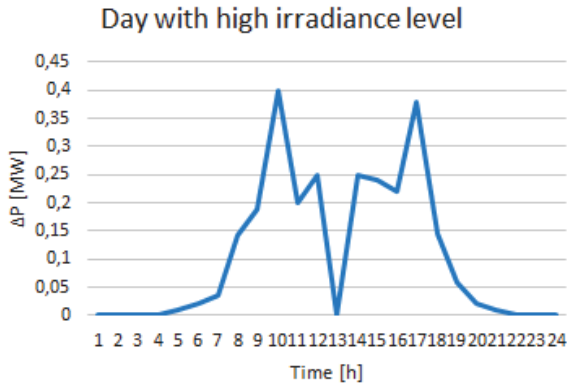

Fig. 13. The hourly power difference between the case in which the system is controlled with the V/Hz^3 method, and the case in which the classic control is used

Moreover, an optimized control for the pump's motor drive was implemented. An efficiency gain of up to 1% was obtained. However, considering the high power of the system, losses of hundreds of kWh are eliminated.

In addition, a study case considering a specific site situation is also presented. The hourly energy profile of a PV system based on the solar irradiance is the input in analyzing the PV-pumped storage system performance. Thus, not only the gain in power is be established, but also the energy gain, for a real situation. For a day with high irradiance level, the energy yield is 2.57 MWh, while for a cloudy day with low level of irradiance, 1.88 MWh are gained, if using the proposed control based on the third grade polynomial dependency of the motor's phase-to-neutral voltage on the stator frequency.

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