THE WAVELET-BASED CONTROL ALGORITHM OF HYBRID ENERGY STORAGE SYSTEM FOR REDUCING FLUCTUATION OF PHOTOVOLTAIC SYSTEM

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SUMMARY

Since the penetration level of Photovoltaic (PV) system continuously increases, the negative impact caused by the fluctuation of PV power output needs to to be carefully managed. This paper proposes a coordinated control algorithm based on a discrete wavelet transform to eliminate both short-term and long-term fluctuations by using hybrid energy storage system (HESS). While the short-term fluctuation is mitigated by using an electric double-layer capacitor (EDLC), the long-term one is reduced by the support of a Li-ion battery. The effectiveness of the proposed algorithm has been tested by using Matlab/Simulink program. The simulation results demonstrate that the HESS with the proposed control algorithm can indeed assist in dealing with the variation of PV power output.

Keywords: *Photovoltaic System, Hybrid Energy Storage System (EESS), Discrete Wavelet Transform, Fluctuation Mitigation, Li-ion Battery, Electric Double-Layer Capacitor (EDLC)*

INTRODUCTION

Recently, the exhaustion of fossil fuels and the critical environment pollution have led to the need to develop new clean energy sources. Photovoltaic energy, a type of renewable and environmental-friendly, is considered as a prospective replacement for conventional energy sources. The presence of PV systems opens opportunities and poses new challenges. PV systems can effectively reduce power losses and on-peak operation costs, improve voltage profile, defer system upgrades, and improve system intergrity, reliability and efficiency with sophisticated control scheme [1]. However, because of the stochastic and intermittent characteristic of sunlight, the resulting fluctuation in power output is the greatest obstacle to the increasing penetration level of PV system in power grids. In order to reduce the negative impact of these fluctuations on the stability, reliability and protection of the power system, a number of control methods have been proposed. An electrical energy storage system (EESS) is regconized as an alternative technique to mitigate both short-term and long-term fluctuations. Various benefits of using EESS have been discussed in [2]. The cooperation of different storage devices with different charge/discharge characteristics makes it possible to balance both power and energy requirements. On this paper, the combination of EDLC and Li-ion Battery is used as solution to mitigate the PV power output fluctuation. EDLC is suitable for dealing with short-term fluctuation because it has a number of exception characteristics such as high power density, fast charge/discharge time, high efficiency and long life time [2]. On the other hand, Li-ion battery with high energy density is good for eliminating long-term fluctuations.

In the literature, a moving average technique and the first-order delay filter (FDF), the simplest methods, have been applied to smooth out the PV power output [3]. Some researchers have proposed intelligent approaches such as fuzzy logic, bacteria foraging technique to integrate PV system and storage systems to maintain a constant grid power output [4]. However, these methods are implemented via non-real time process, which limits the real-time application. This paper proposed a real-time control strategy based on

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discrete wavelet transform for solving the above problem.

This paper is organized as follows: Section 2 presents the modeling of PV system and energy storage devices. Section 3 introduces the real-time wavelet-based energy management algorithm (RWEMA). In Section 4, the simulation studies are carried out in the Matlab/Simulink environment to validate the effectiveness of the proposed method. Finally, some conclusions are given in Section 5.

PV-HESS SYSTEM OVERVIEW

The typical PV power system as illustrated in Fig. 1 is used for simulation studies in this research. In this system, the PV farm consists of four PV arraysin which each PV array is connected to a DC/DC converter. The output of the boost converters are connected to a common DC bus of 500V. Each boost converter is controlled by individual Maximum Power Point Tracking (MPPT) using Perturb and Observation technique in order to get maximum possible power. A three phase voltage source converter converts 500V DC to 260 AC and keeps unity power factor. A 400-kVA 260V/25kV transformer is used to connect the converter to the grid. The grid model consists of typical 25-kV distribution feeders and 120-kV equivalent transmission system.

The HESS system consists of the Maxwell Bootscap devices and Li-ion battery equivalent model. A real-time wavelet-based energy management algorithm is added to provide the charge/discharge reference signals, $P_{LB,ref}$ and $P_{EDLC,ref}$, which are then fed to the corresponding DC/DC converter. The total active power at the point of common coupling (PCC) P_{sys} is the sum of the PV farm, EDLC and the Li-ion battery power output (*P*wind, *P*EDLC, and *P*batt, respectively).

REAL-TIME WAVELET -BASED ENERGY MANAGEMENT ALGORITHM

The application of discrete wavelet transform (DWT) in the PV power system is actually a filter process, in which the PV power output is decomposed into smoothed and noised components. This process can be classified into non-real time and real-time methods. In this paper, a real-time wavelet algorithm is implemented based on a moving window function (MWF) [5]. This MWF has a length of *n* and is designed to store PV power output data as a first-in first-out buffer. The proposed RWEMA controller dynamically obtains the results from MWF and the SOC level from EDLC and Li-ion battery bank, and then determines the reference value for the corresponding DC/DC converter controller of HESS. The objective of the proposed method is to both denoise and keep the total PV-HESS power output constant during the specified time period.

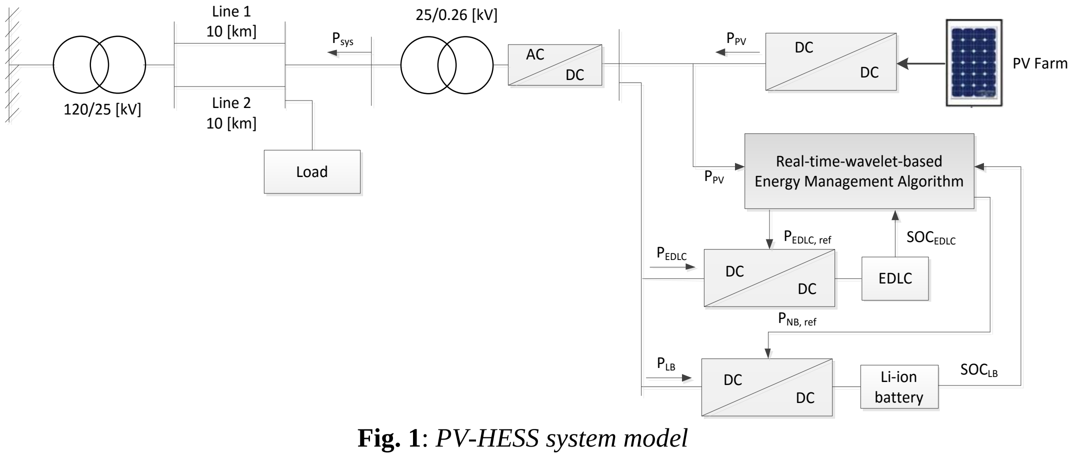

Fig. 1: *PV-HESS system model*

Data processing and discrete wavelet transform procedure

Step 1: During the first *n* seconds, the wind power output data is sampled every second and added to the MWF.

$$\left\{P_w^t \middle| t = 1, 2, ..., n\text{-}1, n\right\} \quad (1)$$

Step 2: As soon as the MWF is filled, the MWF is extended by using a short-symmetric method to deal with some of the disadvantages of real-time wavelet transform such as border distortion and the pseudo-Gibbs phenomena [5]. The length of MWF is increased, and the pre-processed wind power series becomes:

$$\left\{P_w^1, P_w^2, ..., P_w^{n-1}, P_w^n, \underbrace{P_w^n, P_w^{n-1}, ..., P_w^{n-\Delta t}}_{Short-Symmetric}\right\} \quad (2)$$

Step 3: The wind power output in the extended MWF is decomposed into two corresponding components by passing it through low-pass and high-pass filter to the l^{th} level. The level-*l* low-frequency component and the sum of the *l*-level high-frequency terms are:

$$\left\{P_A^t \middle| t = 1, 2, ..., n-1, n, n, n-1, ..., n-\Delta t\right\} \quad (3)$$

$$\left\{P_D^t \middle| t = 1, 2, ..., n-1, n, n, n-1, ..., n-\Delta t\right\} \quad (4)$$

Step 4: The n^{th} data of the high and low frequency component are sent to the average buffer. As soon as the average buffer is filled, the system output reference ($P^k_{sys,ref}$) is calculated by taking the average of the buffer. The system output reference at time *t* ($P^t_{sys,ref}$) is calculated, and finally the reference for the Li-ion battery converter controller is determined by using:

$$P_{NB,ref}^t = P_A^t - P_{sys,ref}^t \quad (5)$$

Step 5: Subsequently, the new data from the wind power output is added to the last position of MWF and the first data is removed. Repeat step 2 to step 5 with the updated MWF. A flowchart of the complete algorithm is illustrated in Figure 2.

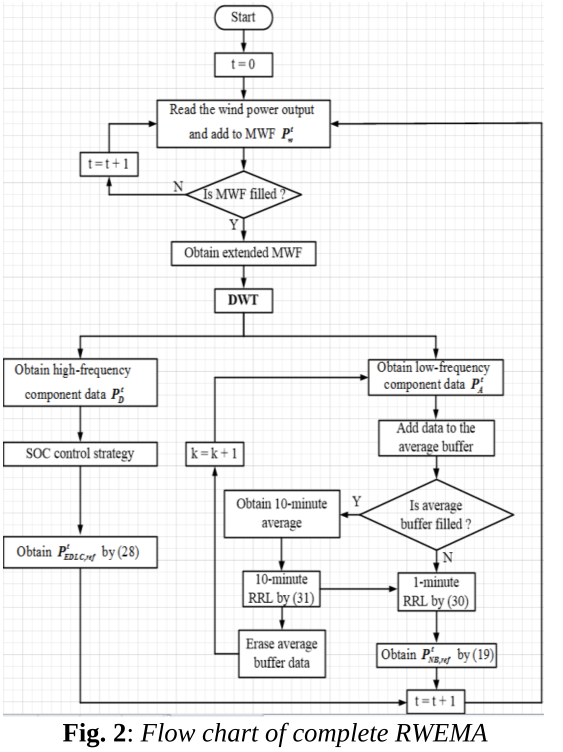

Fig. 2: *Flow chart of complete RWEMA*

Ramp rate limitation requirement

Since both short-term and long-term fluctuations have severe impact on power system quality, stability and reliability, they should be restricted within a certain limit. Several different standards for this problem are proposed in literature, depending on the recent situation of PV system of each country and policies of power utilities. In this paper, two standards that were recently used in Ireland are chosen, as shown in Fig. 3 [6].

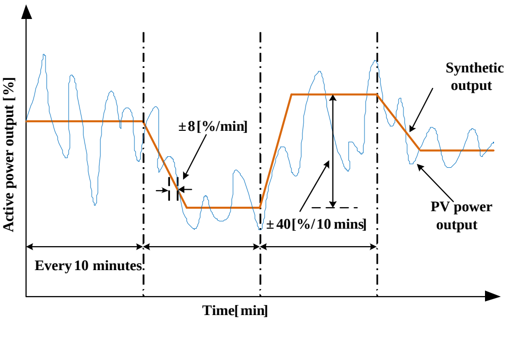

Fig. 3: *1-min and 10-min RRL requirements*

A one-minute requirement is used to limit the ramp rate of the total power output, while a 10-mininute requirement is used to prevent overshooting when the system power reference is changed.

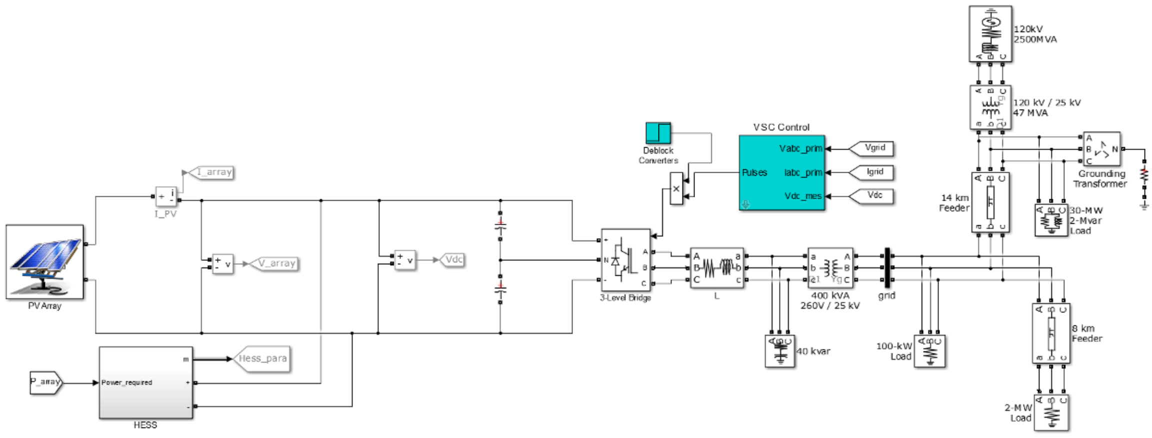

Fig. 4: *Test system model in Matlab/Simulink environment*

SIMULATION STUDIES

Configuration of the test system

The PV-HESS test system shown in Fig. 1 is implemented in the Matlab/Simulink environment. The PV farm consists of four PV arrays delivering each a maximum of 100 kW at 1000 W/m^2 sun irradiance. A single PV array block consists of 64 parallel strings where each string has 5 SunPower SP-315E modules connected in series.

The capacities of the storage are chosen based on the selected energy management algorithm. The rating of the Li-ion battery is determined to continuously supply or store 60% of the PV farm rated power for approximately 600s. The rating of EDLC is chosen so that it can supply or store 40% of the PV farm rated power for 60s. The detail parameters of the test system are summarized in table 1.

Table 1: *Test system parameters*

Component	Parameter	Value
PV farm	$P_{PV,rated}$	400 kW
Li-ion battery	$P_{LB,rated}$	240 kW
	$E_{LB,rated}$	48 kWh
EDLC	$P_{EDLC,rated}$	160 kW
	$E_{EDLC,rated}$	3.2 kWh

The proposed RWEMA including the DWT algorithm is implemented as a user-defined model in Matlab/Simulink. In order to satisfy the typical time step (50 µs) of real time simulation and to reduce the size of the component, the length of MWF was selected as *n = 16.* The length of short-symmetric extension was 4. The decomposition level of DWT was 5, with mother wavelet was "Haar" function. The simulation model in Matlab/Simulink environment is presented in Fig. 4.

Simulation case

The proposed RWEMA with RRL control strategies is applied. The Solar irradiation is assumed to change every 5 seconds. The simulation results are represented in Fig. 4. As shown in Fig. 4, the fluctuation of the PV farm power output was completely eliminated. Moreover, the total power injected to the grid was kept constant during the simulation time. The changes in power output also demonstrates that the RRL requirements have been met. The power output of the Li-ion battery and EDLC are shown in Fig. 5(b) and 5(c), respectively.

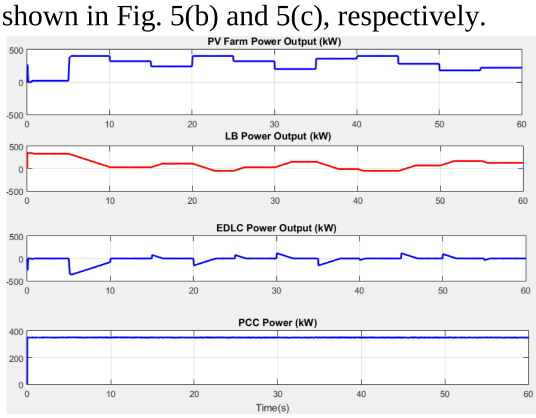

Fig. 5: *Power profiles*

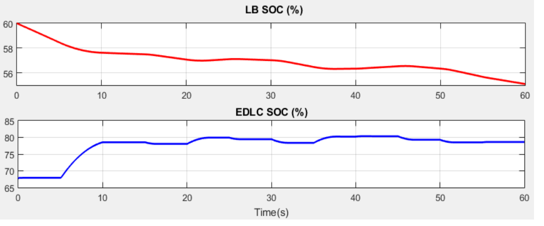

Fig. 6: *SOC profiles of HESS*

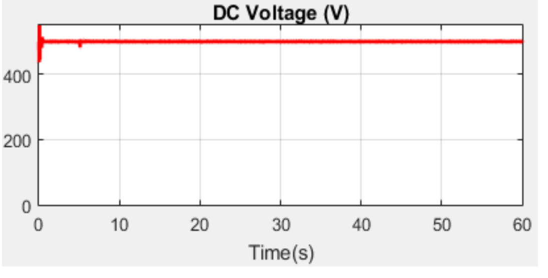

Fig. 7: *DC bus voltage curve (V)*

CONCLUSIONS

This paper proposed a RWEMA of a PV-HESS system to denoise and flatten the PV farm power output. A real time DWT was used to decompose the 1-s sampled PV power output into high-frequency and low-frequency components. The high-frequency components were used as a reference of the EDLC DC/DC converter, while the low-frequency terms were used to calculate the reference of the NB. The RRL requirements were also applied in the algorithm.

The simulation models of the Li-ion battery and EDLC energy storage system were developed in the Matlab/Simulink environment as a user-defined function. A configuration interface was also developed to modify the simulation parameters of the model. The proposed algorithm has been tested in real-time by using the Matlab/Simulink. The simulation results demonstrated the effectiveness of the proposed control algorithm in denoising and flattening PV farm power output. Since the proposed approach uses a simple DWT-based structure without any prediction technique, it can be easily implemented in real-time applications. In order to move beyond the simulation level and into the hardware implementation, many practical issues and requirements still need to be considered, such as data acquisition, communication media and protocol, data management, and selection of processor. The proposed method will be implemented as an actual hardware controller and be tested with the real PV-Hess system in the future.

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TÓM TẮT

THUẬT TOÁN ĐIỀU KHIỂN HỆ THỐNG TÍCH TRỮ NĂNG LƯỢNG LAI SỬ DỤNG PHÉP BIẾN ĐỔI WAVELET NHẰM GIẢM SỰ DAO ĐỘNG CỦA HỆ THỐNG PIN NĂNG LƯỢNG MẶT TRỜI

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Do mức độ sử dụng hệ thống năng lượng Mặt trời (PV) vẫn đang tiếp tục tăng lên nhanh chóng, ảnh hưởng xấu gây ra bởi sự dao động công suất đầu ra của hệ thống PV cần phải được quản lý một cách cẩn thận. Bài báo này trình bày phương pháp phối hợp điều khiển dựa trên phép biến đổi wavelet rời rạc để loại bỏ sự dao động ngắn hạn và dài hạn sử dụng hệ thống tích trữ năng lượng lai (HESS). Trong khi các dao động ngắn hạn bị loại bỏ nhờ sử dụng siêu tụ điện, các thành phần dài hạn được triệt tiêu sử dụng pin Li-ion. Tính hiệu quả của thuật toán được kiểm tra bằng phần mềm Matlab/Simulink. Kết quả mô phỏng chứng minh rằng hệ thống HESS với sự trợ giúp của thuật toán đã hỗ trợ tối đa trong việc loại bỏ dao động công suất đầu ra của hệ thống PV.

Từ khóa: *Hệ thống pin năng lượng Mặt trời, hệ thống tích trữ năng lượng lai, phép biến đổi wavelet rời rạc, triệt tiêu dao động, pin Li-ion, siêu tụ điện*

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