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Predictive energy management, control and communication system for grid tied wind energy conversion systems

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ABSTRACT

This paper presents forecast-based predictive energy management, control and communication system (PEMCCS) for grid tied (GT) wind energy conversion system (WECS) plus battery energy storage system (BESS). The proposed PEMCCS model first uses predictively estimated WECS potential over 24-hour (24 h) horizon with BESS to establish day ahead commitment (E_{DAC}) with 24 hourly energy estimates (E_{HEE}). Then the proposed PEMCCS model provides an integrated solution to the issues faced by the modern grid operators, ensuring (1) minimum RE curtailment, (2) E_{DAC} delivery, and (3) compensation of forecast errors (FE) while injecting grid coordinated smoother power into grid. Power injection level is defined dynamically whenever planned injection is disturbed due to FE or change in operational scenario across the grid. Focusing on curtailment minimization and E_{DAC} delivery, an optimal power injection magnitude is defined and system status is communicated with the grid operator for the next operational unit ($\Delta t = 5$ min) for coordinated operation. The proposed PEMCCS model, (1) increases revenue for wind system owner through DAC delivery error minimization, (2) minimizes curtailment/waste of WECS generated RE, therefore, increasing RE proportions while minimizing grid operator energy cost, and (3) improves grid reliability through "on-demand" power injection magnitude control. The proposed model also minimizes grid stress associated with injection of highly varying WECS power while compensating for FE. The proposed PEMCCS model is simple and realistic. It successfully delivers 125.47 MWh day ahead committed energy with 34–35 injection levels while accommodating grid operator requests and compensating for FE.

1. Introduction

Global energy generation canvas is changing and by 2035 renewable energy (RE) will be the world's primary source of global electricity [1]. Solar and wind power are the fastest growing RE sources [2,3], with solar power doubling every two years, reaching a total of 450 GW by 2017 [2] and wind power reaching a total of 1900 GW by 2020 [3]. Between 2000 and 2010 the cumulative global renewable electricity capacity grew by 97% from 748 GW to 1470 GW [4].

Use of wind energy is not new and have been used for centuries [5] and are widely used for generating electricity in the present era, to meet the ever growing demand and new environmental standards and codes. However, WECS is inherently non-dispatchable due to irregular or intermittent generation caused by the irregular wind resources. Intermittency, uncertainty and variability can be short- or long-term. Short-term intermittency causes power fluctuation while long-term intermittency results in energy supply issues. Intermittency impacts components sizing and placement, operations and control, energy supply and management, units scheduling and commitment, and power quality and service reliability [6,7]. Nameplate or rated capacity can only be relied upon under peak production conditions [8] and irregular wind resources often cause energy supply and demand balance issues [9]. Energy shortage causes load shedding [9] while energy surplus causes curtailment and waste [10]. Mai et al. [10] report that surplus curtailment can reach as high as 30% of the rated capacity. In 2014, 376 GWh of wind energy was curtailed due to, (1) surplus baseload generation, (2) supply and demand balance issues, and (3) congestion along transmission lines [11].

The literature is cluttered with solutions for the aforementioned power intermittency related issues. Power fluctuation causing issues such as frequency fluctuations, voltage flickers, and system instability [6,7] has been tackled with some sort of energy storage (ES) [12–17]. Geographical dispersion [18], supervisory control with BESS and forecast [19] and wind forecast-based model predictive control [20] have also been used to smooth power fluctuations.

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Syed et al. [12] proposed an algorithm that establishes a power reference level for injecting fluctuation-free power into grid; however, a static reference level does not take into account the forecasts or the forecast errors and thus can only be relied upon with ideal forecasts. In addition, the system proposed by Syed et al. [12] does not have any real-time communication with the grid operator. A solution proposed by Javier et al. [18] is only applicable to wind farms, and other proposed solutions [18–20] are not based on communication and forecast-based energy management and control (EMC).

The literature also suggests multiple solutions for energy related issues. Barote and Marinescu [21] proposed BESS-based EMC system (EMCS) for real power balance and power quality control in isolated areas to improve WECS power supply reliability. Tewari and Mohan [22] reported peak shaving by shifting WECS energy through BESS for integration into grid. Bunker and Weaver [23] reported optimal control of grid tied WECS assisted by BESS. Dali et al. [24] proposed EMCS to ensure control and energy supply by BESS. Shajari and Pour [25] reported reduction of BESS size based on complimentary photovoltaic (PV) and WECS; while Sebastián and Alzola [26] suggested using EMCS with fossil fuel generator (FFG) to bridge the supply and demand gap. However, all these proposed schemes [21–25] are (1) based on conventional EMCS which does not use forecasts in its decision making process and often causes surplus curtailment. In addition, the scheme proposed by Sebastián and Alzola [26] results in environmental pollution and has high operational and maintenance costs. Furthermore, the schemes proposed by Shajari and Pour [25] and Sebastián and Alzola [26] require higher capital investments due to complimentary PV and FFG, respectively.

Khalid and Savkin used model predictive control (MPC) to control BESS placed near wind farms to either smooth the combined power output [27] or control grid frequency [28]. However, as reported by Sharma et al. [29], Khalid and Savkin did not explicitly considered electrical dynamics, BESS size, and state of charge (SOC) constraints in either of their studies. Qi et al. [30] proposed MPC supervisory control for optimal management and operation of standalone (SA) hybrid PV-WECS with BESS, but with load shedding. None of the schemes proposed by Khalid and Savkin [27,28] or Qi et al. [30] provides RE curtailment and E_{DAC} delivery integrated solution. Parisio et al. [31] and Marinelli et al. [32] reported predictive EMCS for a grid tied PV and WECS hybrid system with BESS to balance day ahead committed supply of RE into grid using BESS on hourly basis. However, they overlooked curtailment and communication with grid operator. Hence the solution proposed does not resolve the issues faced by modern grid operators as highlighted above [11].

Modern grid operators require RE resources, including WECS, to submit a 24- to 48-h energy output forecasts, hour by hour ahead of real-time delivery to establish their day-ahead-commitment (DAC) of energy supply. However, depending on the geographic location, installation dispersion, and the forecast method used, the typical 24 h/day-ahead forecast error (FE) for wind ranges from 12 to 25% of rated capacity [33]. FE is smaller for shorter periods [11,33].

Use of energy storage for power quality control, power smoothing, peak shaving, time-of-use consumption reduction [34], strategic scheduling [35] and bridging supply and demand gap is an established field. However, solutions proposed in literature are insufficient and there is a room for improvement. Need for improvement and scheme proposed in this paper can be re-enforced by (1) energy wastage reported by Independent Electricity System Operator (IESO) [11], (2) use of static reference levels for power smoothing lacking FE compensation mechanisms, (3) surplus curtailment, and (4) no real-time communication between EMCS and grid operators to support grid operations and non-predictive controls. Predictive energy management, control and communication system (PEMCCS) proposed in this paper on the other hand, provide an integrated solution to the issues faced by the modern grid operators. Main focus is RE curtailment minimization while ensuring E_{DAC} delivery, supporting grid operations, and smoothing power on the fly compensating for FEs. The rest of the paper is organized into 4 sections: (II) system model, (III) the proposed predictive model, (IV) simulation and results, and (V) conclusions. Independent Electricity System Operator (IESO) [11] is used as a case study of power wholesale market and interested readers are referred to it for detailed operations. Wind resources forecasting is outside the scope of this paper; interested readers are encouraged to refer to references [36–38].

2. System model

WECS generated power (P_W, wind power) at any instant is given by Eq. (1), where ρ, r, and V are air density, rotor radius, and wind speed, respectively.

$$P_W = 0.5\rho\pi r^2 V^3 \tag{1}$$

Multiplying Eq. (1) by time t gives WECS electrical energy (E_W), given by Eq. (2), which can be used with turbine power curve to estimate wind energy for a given V.

$$E_W = 0.5\rho\pi r^2 V^3 t \tag{2}$$

BESS is connected across DC link of WECS and thus output of the model is limited to WECS rated power ($P_{w\text{-rated}}$) given by Eq. (3), where P_o is output, P_w is wind, and P_B is BESS power.

$$P_O = P_W + P_B \le P_{W-\text{rated}} \tag{3}$$

IESO electricity market operates based on DAC with 24 h ahead forecasts. Thus the theoretical maximum energy needed to be stored/supplied, if the forecast goes completely wrong (100% FE), is given by Eq. (4), where t = 24 h.

$$E_{B-\max} = P_{W-\text{rated}} t \tag{4}$$

However, since the maximum FE is limited to 25% of rated capacity over 24 h horizon [33], 100% FE is not probable. Therefore, BESS size can be reduced as in Eq. (5), where $E_{B\text{-DAC}}$ is BESS energy required in 24 h. Note that it is unlikely that FE will cause only surplus (or only shortage) over 24 h, therefore, one might seek to further reduce BESS size even at the expense of limiting "on-request" grid support. Therefore, 0.375 MWh energy storage is considered in this work for 1.5 MW WECS with t = 1. With a depth of discharge of 80%, required $E_{B\text{-DAC}} \approx 0.45$ MWH.

$$E_{B-\text{DAC}} = 0.25 P_{W-\text{rated}} t \tag{5}$$

3. Proposed PEMCCS model

At present, IESO sends one-way dispatch instructions (IESO-DI) to WECS, when there is surplus baseload generation, supply and demand balance issue (supply > demand), and transmission line congestion. However, the 2WC, a part of the proposed PEMCCS model, enables WECS to "offer" and IESO to "bid." In other words, PEMCCS not only provides IESO with the required DAC and hourly estimated energy (HEE) forecasts in advance for the upcoming 24 h cycle, but also pro-actively communicates and coordinates operations every Δt (5 min) for next Δt, 288 times ($24 \times 60/\Delta t = 288$) a day. The PEMCCS and IESO cooperative approach allows optimal utilization of resources through RE curtailment minimization, E_{DAC} delivery assurance, power injection magnitude control, and FE compensation. On the fly power smoothing is not the focus of the process, but rather its by-product. Five-minute Δt operational unit is selected for PEMCCS to match IESO 5-min operational resolution.