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Research paper

Development of Complementary Operation Plan for Wind Power Fluctuation based on Small-Scale ESS

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Abstract

Background/Objectives: Various small scale power systems have considered renewable energy as core generating capacity; it has lead a requirement about certain storage capacity to impose flexibility into whole generation management process.
Methods/Statistical analysis: It is important to determine a reasonable energy capacity because the device have many controversial cost issues. Therefore, surplus power focused operation plan for storage device was analyzed.
Findings: For developing a stable combined system with a number of distributed resources including storage device, an appropriate storage operation plan must be configured based on the system components and changeable condition to handle the internal network appropriately. In this paper, a curtailment-supporting algorithm based on storage device is introduced, and applied in the capacity calculation method. The main purpose is designing basic standard for small-scaled power grid.
Improvements/Applications: Several fluctuating conditions are utilized in simulation to reflect critical situation. The analyzing process focuses on the control feasibility with applied capacity and control method.

Keywords: ESS application, curtailment, microgrid, capacity calculation, EMS

1. Introduction

For catching an efficient power extraction from renewable energy, there have been increased of renewable penetration in island area that is indirectly connected with main grid or independently operated. As large-scaled wind farm projects are developed in various offshore region, a demand about acceptability condition analysis with regard of grid integration keeps receiving attention [1], [2]. Several middle level island power grids (under 3GW) are connected with main system by using high voltage direct current (HVDC); those systems are considered as partially independent network and it can maintain frequency separately [3]. Those power grids should consider further complex HVDC management plan in addition to a central controller when relatively huge energy (compared with entire power consumption) is extracted from renewable sources [4]. In case of full independent power grid, its stabilities have to be controlled by single central generator. These networks have pursued utilizing renewable energy in various way, however, handling fluctuating condition imposed from environmental factors is still considered difficult issue. Along with fundamental study on the mainly basis of predictive method to solve this technical encounter, further compensating methods using storage devices have been receiving attention in the renewable sector because entire cost has been reduced according to the technological developments [5], [6]. Especially, there are a lot of exemplary operations on high renewable penetration grid which utilize the energy storage system (ESS) at not only power compensation for management but also handling quality issues. In case of relatively small power grids, however, appropriate capacity calculation methods are still required due to its high cost range.

The benefits of electricity from wind generation system have been higher than conventional fuel generators owing to its environmental-friendly characteristics, and certain owners take advantages from a subsidy by governments. In case of small power grid, however, connected wind generation system may be suffering a number of curtailment orders due to generated surplus power from the gap between imposed reference and real profile. This possibility had led a requirement about revaluation of wind system integration in terms of unexpected economic loss caused by grid scale; to overcome this, several researches have highlighted additional power controllability of entire wind generation system [7], [8].

Among the control options of wind system, a pitch controller for curtailment has been considered as basic application. With a developed wind farm management solution in [9], for demand response, the system operator could assign a curtailing signal that is used in pitch control to each wind turbine. In Ref. [10], an adaptive pitch controller utilized to match grid power balance. Yet, the limited energy is classified as waste energy and a rapid fluctuation can induce mechanical load to blade. Most of all, since the curtailment is application for limiting exceed power supply, further additional devices should be included if TSO demands compensating option for lacked energy. In particular, if a small power system wants to utilize renewable energy, both unexpected surplus power and complimentary supply operation have to be covered with own storage device.

Conventional applications for grid support is usable in island power system focusing on the frequency response for stability. Under this condition, however, due to the constraints at economic feasibility, large size application is hard to be considered. Therefore, a support plan should be formed with a tight and clear aim to cope with reasonable size configuration and stability-guaranteed operation. This paper deals with mentioned required issues by establishing a pitch control focused ESS compensating plan. In order to reduce mechanical loads from frequent pitch control, a combined ESS-wind hybrid control method is introduced. A power control algorithm and derived estimation plan for supporting pitch control are mainly discussed. Through an EMTDC simulation, the feasibility analysis of proposed options has been progressed.

2. Conceptual Framework

2.1. ESS-Wind Combined Control

Figure 1 displays a basic concept of proposed ESS-Wind combined control. In a centralized wind generation system, the pitch control is solely usable for operator to response the imposed order by transmission and system operator (TSO). This paper pursues a prompt supporting of power control process with a directly connected ESS. To achieve this, by consider the response rate of two different application, a combined algorithm configuration should be composed. The stored energy must concentrate complimentary operation, and through this, the economic estimation is available.

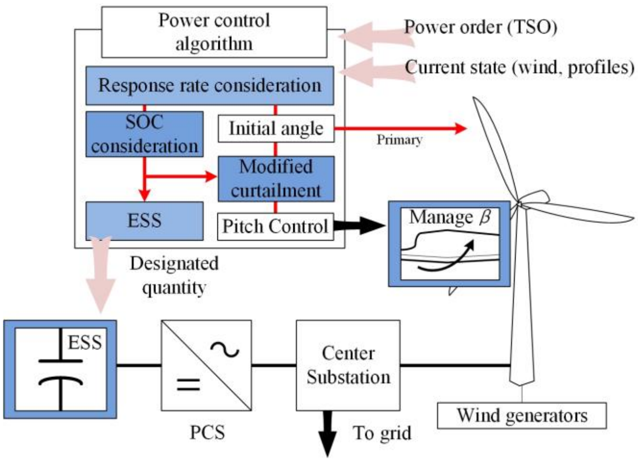

Figure 1: Power support concept of ESS-Wind system

2.2. Capacity Calculation Requirements

An ESS capacity estimation for curtailment support should focus mechanical loads during power control process. There must be response time that for electrical output convergence (within certain error bound) when we handle power profile through pitch angle modification. In here, overshoot characteristic and damping ratio of wind turbine are supposed to be utilized for expecting required capacity to handle output profile. A general transient response of wind turbine can be described as Figure 2. Without external variation, the output profile is converged in steady state after transient section. As depicted in the figure, the transient characteristics could be changed according to the response parameter. The ESS operation will be performed with two different control modes, regarding the decision about the charging and discharging mode with respect to the reference signal, irrespective of whether the state of charge (SOC) is usable or not. Since the capacity for discharging process cannot be larger than first overshoot section, a precise ESS control plan can cover the required quantity. Furthermore, as the first overshoot must be bigger than second one, we could focused on it in the calculation process. Consequently, the power capacity for ESS can be designed according to the peak power at T, and the owner could put cumulative power during maximum overshoot to energy estimation process.

As the supplementary operation of ESS in this paper is focusing on whole pitch control process, the capacity should cover the expected power fluctuations to make it smoothly. In other word, the capacity evaluation should be derived based on expected maximum surplus power. A few of possible exemplary curves are displayed in Figure 2.

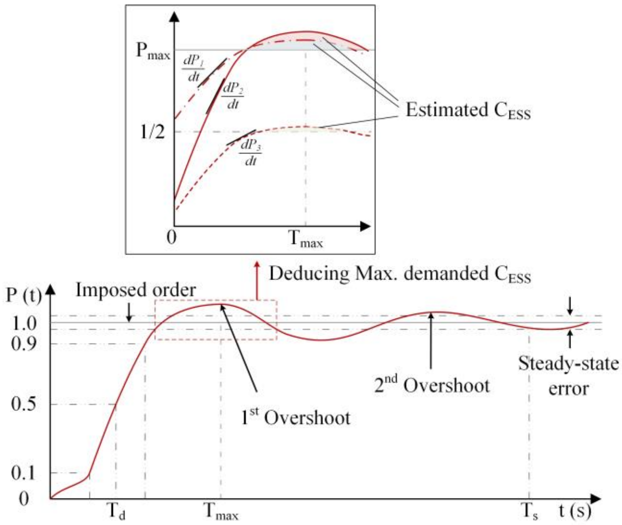

Figure 2: Mechanical response curve with curtailment option

A turbine translates wind power to electrical energy as follow:

$$P = 0.5\rho\pi R^2 v^3 C_p(\lambda,\beta) \quad (1)$$

Where ρ is the air density (kg/m3), R is the wind rotor radius (m), v is wind speed, C_p is the power coefficient that are dependent on the tip speed ratio λ and pitch angle β. The power extracting curves would be drawn according to the equation and this paper considers representative values through iterative analysis of target devices.

3. Proposed Design

3.1. Real Power Curtailment

In order to implement real power control process, full-converter based 1.75 MW permanent magnetic synchronous generator (PMSG) and super-capacitor (SC) model were considered. The composed wind system will perform power control by parallelly connected with integrated ESS which have independent power conversion system (PCS). As mentioned before, the curtailment will be carried out by based on complementary operation between mechanical movement (by blade) and electrical response (by ESS); in here, to utilize the SOC as a back-up energy, the primary response about real power response have to be progressed by wind system. Therefore, entire control algorithm should include a SOC management module. In addition, the whole controller has to be able to monitor power flows at each section.

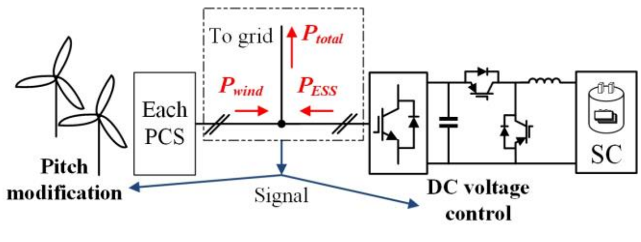

Figure 3: Flow description including control signal

Figure 3 displays basic signal and power flow drawing for main system. P_{ESS} represents power flow variations according to the charging/discharging state of ESS. In order to determine operational state, the ESS requires reference management devices (as a sub-module of main controller) that can reflect devices profile (here, wind profile P_{wind}). Additionally, to absorb a surplus power that can be caused by curtailment section promptly, an automated control scheme has to be composed. When the entire profile of combined system is represented as P_{total}, real power flow can be formulized as follow:

$$P_{total} = P_{wind} + P_{ESS},\ |P_{ESS}| \leq S_{dc-dc} \quad (2)$$

Where S_{dc-dc} is the power capacity of the DC converter for the storage system.

In smoothing process, the real power extraction from ESS will follow the imposed reference signal and represented as follows:

$$P_{ESS}(t+1) = |P_{wind}(t) - P_{ref}(t)| \quad (3)$$

Where P_{ref} is the power order for combined system.

To confirm the power consumption, the amount of transferred energy should be classified during operation. The energy is calculated as:

$$E = C_{ESS} \cdot SOC \quad (4)$$

Where C_{ESS} is capacity of storage. In operation, the energy flows occur by charging/discharging are reflected according to the PCS efficiency η.

When we estimate required energy during operation, the total transferred energy can be calculated as

$$E_T = C_{ESS} \cdot |SOC_i - SOC_f| \quad (5)$$

Where SOC_i and SOC_f are represent initial and final SOC of storage.

To continuously assist encountered curtailment signal, designated SOC state for charging process needs to be secured. Thus, the power control algorithm has to include discharging section regardless of its shape.

3.2. Supplementary Control Algorithm

A confirmation about PCSs structure that connected in combined system is required when handling power profile from each section. In general, AC/DC conversion devices for wind turbine and ESS in industrial section have similar structure. An ESS is expected to be connected to the grid thorough the PCS with a boost chopper device. A DC/DC converter measures DC voltage and directly uses the value to decide a reference signal for current controller. To construct a supervisory system that can generate a modified value for the mechanical curtailment option, further complex strategy is required. In case of pitch controller, this paper adapts an active pitch control that shed off the aerodynamic energy by turning off a blade if a curtailment signal imposed.

Figure 4 describes the power control flowchart that proposed in this paper. The TSO imposes reference signal for entire profile of combined system, and it activates single control mode in accordance with the state of wind power output, power capacity and SOC of ESS. If the extracted profile exceeds the imposed reference, the ESS preferentially performs charging control under consideration about SOC. The mechanical curtailment is imposed as a secondary option if the exceed amount is not matched with power capacity. The discharging activation depends on operator and control system design. If the storage accumulates energy high, the discharging signal may be required to prepare next surplus power. In discharging section, basically, each wind turbine follows maximum power point tracking (MPPT) curve to extract power, and pitch angle is not managed.

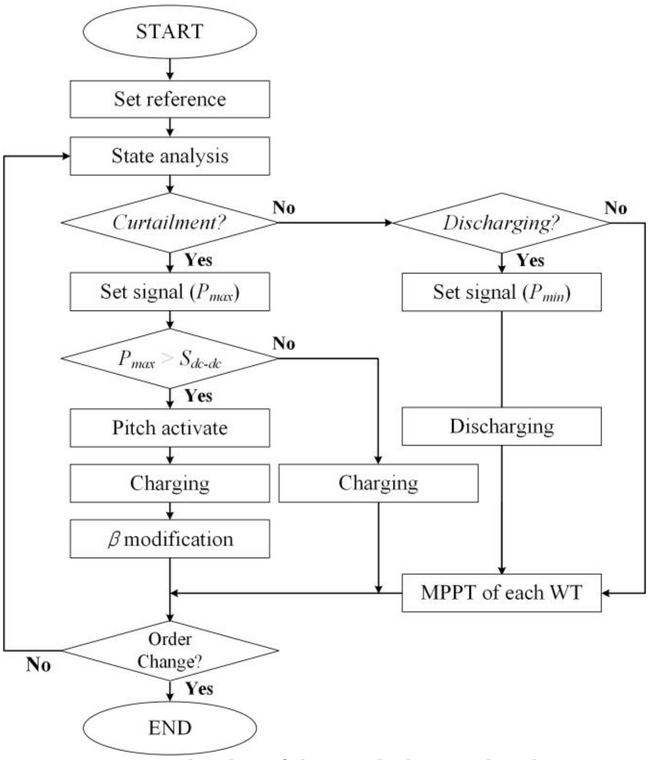

Figure 4: Flowchart of charging/discharging algorithm

3.3. Storage Capacity Estimation

The main role of the ESS is to regulate fluctuation by absorbing the exceed power promptly when the profiles of combine system reach on the designated reference. Nonetheless, the ESSs have to discharge, as mentioned above, during the non-charging period; and through this, they can achieve the repetitive absorption during the operation. The basic required energy for single wind turbine can be derived with exceed power during first overshoot section as

$$E = \int_{t_0}^{t_0+s} (P_{wt} - P_{order}) dt \quad (6)$$

Where t_0 is time(s) at start point of first overshoot, s is the interval from largest overshoot, P_{wt} is real power output by single wind turbine, and P_{order} is real power order for single wind turbine.

The largest overshoot section should be tested by using utilized wind turbine (here, this section was detected while zero start section).

In case of the number of connected wind turbines increase, the energy capacity need to be modified. The modification constant value to apply this may be imposed to estimated capacity as multiplication. Yet, since the relation coefficient of each wind turbine is different according to the target area, the value could be smaller than simple multiples. In order to consider the coefficient, the total required energy can be estimated as below by designating one wind turbine as the center.

$$E_{total} = E_1 + \alpha E_2 + \beta E_3 + \cdots + \gamma E_n \quad (7)$$

The required energy can be converted to storage capacity with applying percentage of allowance and maintenance factor. We simulated a mentioned wind turbine and measured the required energy by checking various power fluctuating condition. The found amount of energy utilized to design SC device in EMTDC case studies.

The power capacity for PCS is designated according to the overshoot scale as mentioned in Section 2.This value is affected by the size of wind system as well, and further customized analysis is required.

4. Case Study

4.1. System Configuration

Before simulating the combined system, in order to confirm the mechanical curtailment option, the single wind system and required control was simulated by selecting a commercial model [11]. 1.75 MW power capacity is considered as mentioned above; two wind turbines are composed to concern small scale distribution network. Table 1 show the numerical parameters for the utilized wind turbine. The entered state about wind and pitch angle will construct mechanical torque in simulation.

A point of common coupling (PCC) is formulated based on general short circuit parameters which is to analyze wind system connection. The basic numerical data for equivalent circuit is listed in Table 2. The transmission line for the distributed generation system have been formed with 1 km distance.

Table 1 : System parameters for wind turbine

Power rate	1.75 MW
Rotor diameter	66 m
Rated wind speed	13 m/s
Rated voltage	690 V
Number of poles	4
Damping ratio	0.58
Gear ratio	1:100

Table 2 : Based system information for case study

Grid base voltage	690 V
Transmission line length	1 km
Short circuit ratio	15
X/R ratio	15

To check the basic curtailment option based on wind turbine, pitch control mode on the basis of general condition was progressed. Figure 5 displays imposed wind speed, and the power profile when the system is operated with solely curtailment option. The wind speed was partially selected from historical data for checking repetitive curtailment condition. A 10 seconds simulation was considered including initializing section (the imposed curtailment reference is 3 MW).

Although mechanical control is applied in the basic analysis, the curve in Figure 5 (b) shows several exceed power sections. The basic simulation deduces single mechanical curtailment is hard to cover continuous variation condition. Based on this profile control, a proposed algorithm with designed ESS capacity is adapted on next case studies.

4.2. SC Utilized Case Studies

The SC will be applied along with previous mechanical control to support the curtailment option. The SC control is mainly focused on charging control mode. However, as the charging control for supporting mechanical limitations is available within the available capacity (both energy and power), discharging signal have to be generated by operator using classified SOC values.

The simulation was divided with two different capacity. Firstly, basic capacity (both power and energy capacities) was utilized without percentage of allowance and maintenance factor. In this case study, the operation was designed to maintain the initial SOC value. Next, mentioned factors were imposed in basic capacity, and improved energy was permitted to utilize at smoothing process within minimum rated SOC value. Within available SOC range, the SC was expected to support maintaining fixed power profile. Table 3 includes applied SC design and designed case studies.

Figure 6 presents the power profile curve and related SC operation in Case 1. The analysis considers not only the charging section for power curtailment but also the discharging section to confirm the operational condition of the discharging process. Compared with basic case study, effective power curtailment processes were generated with SC supporting method. The fast response of SC supports wind turbine, and reduces exceed power. To ensure the minimum SOC value, the discharging orders were not activated until the SC storing further energy by additional curtailment process.

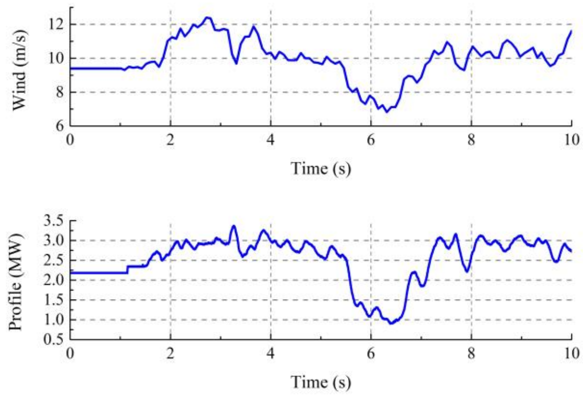

Figure 5: Simulated wind speed and power profile when imposing 3 MW curtailment signal (a) Wind velocity, (b) power profile

Table 3 : Operation conditions of Simulation

Specific Data	Case 1	Case 2
K_{pf}	1 MW/Hz	
Curtailment reference	3 MW	
Rated energy of SC	75 Wh	120 Wh
Rated power of SC	300 kVA	420 kVA
% allowance	-	1.3
Maintenance fac.	-	1.2
Initial SOC	70	70
Minimum SOC	68	20
Grid base voltage	690 V	
Transmission line length	1 km	
Short circuit ratio	15	
X/R ratio	15	

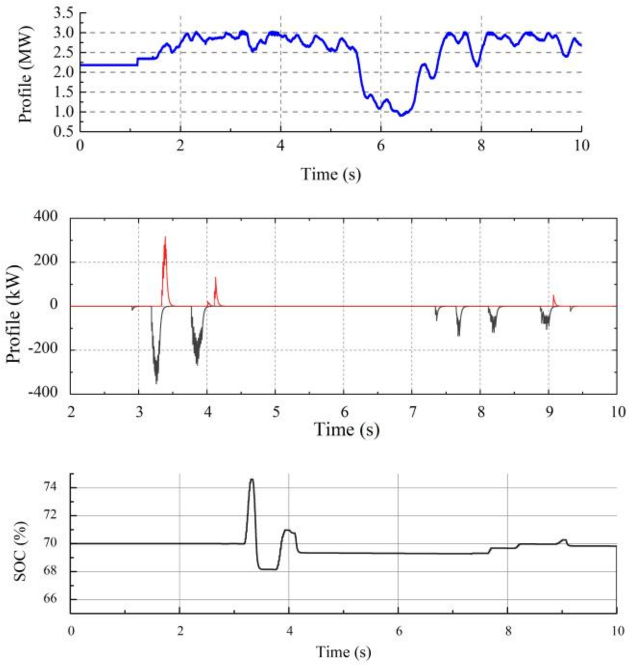

Figure 6: Simulated power profile and SC states in Case 1 (a) entire profile, (b) charging and discharging quantities of SC, and (c) SOC variation of SC

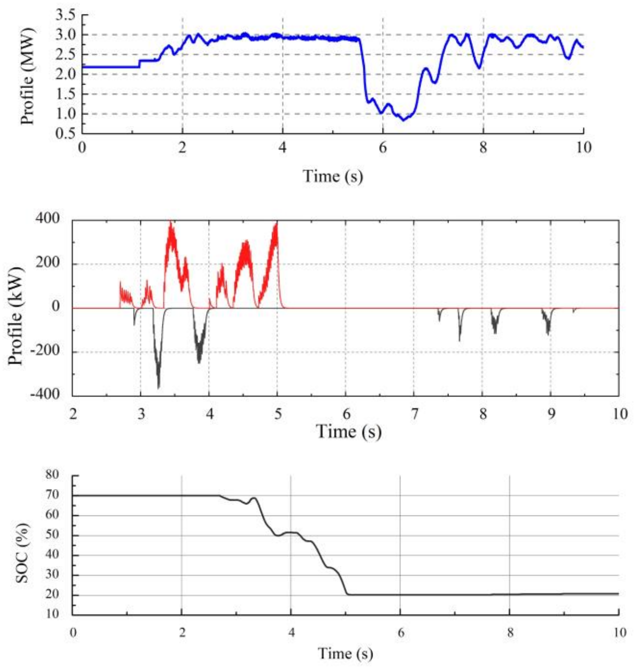

Figure 7: Simulated power profile and SC states in Case 2 (a) entire profile, (b) charging and discharging quantities of SC, and (c) SOC variation of SC

Figure 7 presents the power profile curve and related SC operation in Case 2. The analysis includes further active complement on fixed power. A short complement for fixed power was lasted until the SOC values reach to designated minimum SOC constraint. As described in the Figure 7 (c), the initial SOC has been drastically decrease due to low energy capacity. This analysis implies that continuous utilization of ESS for discharging plan can induce significant energy capacity. The required energy for supporting curtailment can be usable with compact sized storage; and securing SOC for charging process is relatively facilitate in wind system.

5. Conclusion

In this paper, a compact storage design method with utilizable power control algorithm was suggested. To cope with inefficient ESS design in small power systems, curtailment focused storage management algorithm was derived. In order to reduce mechanical load inducing on wind system, prompt charging method was formulated and adapted in the designed case studies. Through case studies, the curtailment effect improvement in terms of the real power profile that crucial to the TSO is derived. The precise response could suggest reasonable option on both wind system life cycle and grid reliance. The pitch controller cannot be neglected in proposed method; however, it is clear that combined control would match the required power balance than single control option. The exemplary design discharging plan in accordance with SOC value were also tested in case studies to check continuity of proposed control method. According to the analysis, repetitive absorption of surplus power is usable, and the securing SOC for this process can be achieved with prompt discharging algorithm such as SOC constraint.

Acknowledgment

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