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A Supercapacitor Remaining Energy Control Method for Smoothing a Fluctuating Renewable Energy Power

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Abstract – This paper proposes a control method for maintaining the energy level for a supercapacitor energy storage system coupled with a wind generator to stabilize wind power output. Although wind power is green and clean energy source, disadvantage of the renewable energy output power is fluctuation. In order to mitigate the fluctuating output power, supercapacitor energy storage system (SCESS) and wind power simulator is developed. A remaining energy supercapacitor (RESC) control is introduced and analyzed to smooth for short-term fluctuating power and maintain the supercapacitor voltage within the designed operating range in the steady as well as transient state. When the average and fluctuating component of power increases instantaneously, the RESC compensates fluctuating power and the variation of fluctuating power is reduced 100% to 30% at 5kW power. Furthermore, supercapacitor voltage is maintained within the operating voltage range and near 50% of total energy. Feasibility of SCESS with RESC control is verified through simulation and experiment.

Keywords: Fluctuating power, Supercapacitor energy storage system, Remaining energy, Smoothing, Maintaining energy level

1. Introduction

Due to an environment and energy supply security concern, electricity productions based on green/clean energy has become increasingly important. Wind power is the fastest growing renewable energy but disadvantage of the renewable energy output power is fluctuation. The problem of power quality caused by wind power output fluctuation cannot be ignored, while the level of output power penetration riches higher [1, 2]. To mitigate the fluctuating wind power, various approaches have been suggested. Some researches concern with the penetration limit posed by wind turbulence. Wind velocity fluctuation accelerates and decelerates the turbo alternators in power plants causes the system frequency to deviate from the 60 Hz standard [3, 4] and presents a method of quantifying wind penetration based on the amount of fluctuating power that can be filtered by wind turbine generator [5]. Energy storage system (ESS) into the wind power can suppress the output power fluctuation and ESS was discussed aiming for a mitigation of fluctuating power and power system stabilization [6].

The most researches proposed the control method for the ESS based on the battery or supercapacitor, they can compensate fluctuating power for long term or short term, respectively. The time scale of long term is defined as few hours from few minutes and the time scale of short term is defined as few minutes from few seconds [6]. The control is for smoothing a fluctuating power and improving for grid quality by ESS. Some paper focuses on development of a control strategy for optimal use of the battery energy storage system (BESS) for this purpose. The paper considers a conventional feedback-based control scheme with revisions to incorporate the operating constraints of the BESS. [7, 8].

ESS is mostly using BESS. A lot of researches using the BESS have been progressed until recently, but the researches using supercapacitor energy storage system (SCESS) are insufficient. The control of SCESS is different from BESS because the characteristic of supercapacitor is significantly different from battery [9]. Thus, SCESS should be approached in a different way to BESS. The pros and cons of SCESS are as follow: Advantage of SCESS is that the supercapacitor has a very rapid dynamic response and high power density. So, it is able to switch from the maximum charging current to the maximum discharging current or the vice versa, instantly. On the other hands, disadvantage of SCESS is that it cannot operate as longer than other ESS because of its low energy density. So, SCESS operates for smoothing a fluctuating wind power during short-term.

The most papers proposed the control method for the ESS. However this algorithms did not consider the state-of-charge (SOC) of the ESS, and some papers used only the flexible first-order low-pass filter (LPF) for smoothing a fluctuating power [12, 13]. The problem of the previous methods is that over-charge or over-discharge state can be occurred in ESS and then the ESS no longer compensate

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for the fluctuating power. To solve this problem, a new method considering the SOC is required, and some method change a time constant of the LPF in order to mimic the SOC compensation of the ESS for smoothing a fluctuating power [14].

Compared to the previous methods, this paper complements a control method for smoothing a fluctuating power and a new control method for maintaining the energy level for a SCESS coupled with a wind generator to stabilize wind power output. This control method is smoothing a fluctuating power, moreover, maintaining the energy level for SCESS. SCESS measures a fluctuating power and compensates it, and thus, SCESS provides a high quality and stable power to grid.

Objective of the paper is a compensation for fluctuating power on wind power and maintenance of supercapacitor voltage within the operating voltage range. This paper discusses configuration of the SCESS in section 2, compensation algorithm considering remaining energy in section 3, simulation results in section 4, experiment results and hardware composition in section 5.

2. Supercapacitor Energy Storage System

2.1 Configuration of supercapacitor energy storage system

The fluctuating output of wind power energy causes the problem of grid power quality. Through compensation by ESS the fluctuating output power is smoothed as shown in Fig. 1. Fig. 1 shows that compensated fluctuating power by SCESS.

Fig. 2 shows configuration of SCESS for smoothing fluctuating wind power. A small-scaled wind power simulator using back-to-back converter generates a

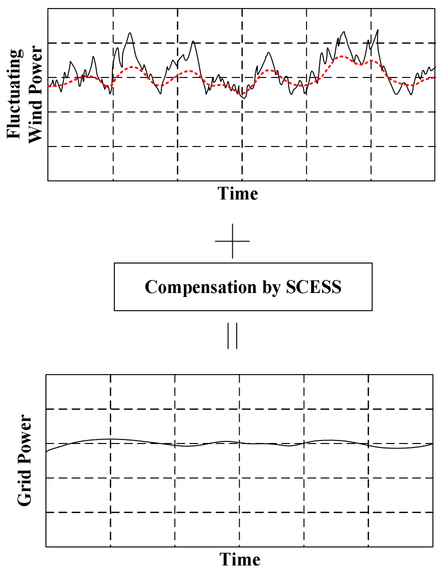


Fig. 1. Smoothing control of fluctuating output power

fluctuating power instead of real wind power generator. The small-scaled wind power simulator is implementation to fluctuating reference power via current control. SCESS consists of supercapacitor bank, three-phase dc-ac inverter, line-frequency transformer and L-filter. The fluctuating output power is generated from the wind power generator and directly flowed into the utility grid.

When the wind power simulator generates a fluctuating power, SCESS identifies output power and performs compensation for the fluctuating output power. Thus, the compensated stable power is supplied to the utility grid.

DC/AC inverter is operated by supercapacitor voltage because supercapacitor is directly connected DC link. Because the initial supercapacitor voltage is zero, DC/AC inverter needs two control modes. The control of DC/AC inverter is divided pre-charge mode and compensation mode. Fig. 3 shows block diagram of the pre-charge mode. The pre-charge mode operates to charge supercapacitor voltage by PI voltage and current. The pre-charge mode is not considered significant in SCESS because this mode is only operated at beginning of the drive. Second mode is the compensation mode as shown in Fig. 4. The compensation mode operates to compensate fluctuating wind power by PI current control. The compensation mode is main control in SCESS for mitigation to fluctuating wind power. The active power reference is computed via fluctuating wind power and used to operate SCESS.

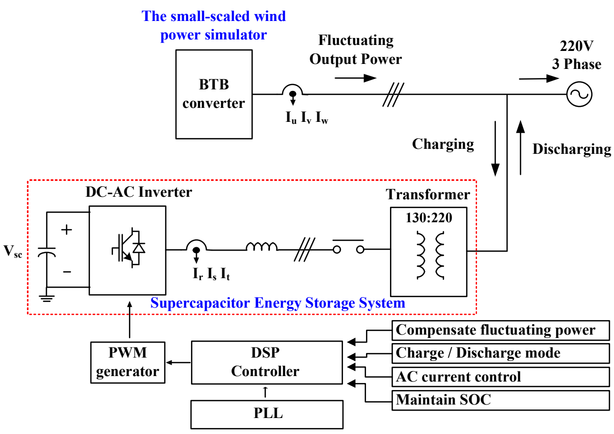


Fig. 2. Configuration of supercapacitor energy storage system

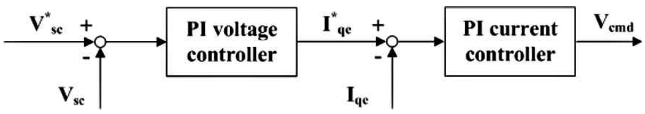


Fig. 3. Block diagram of pre-charge mode

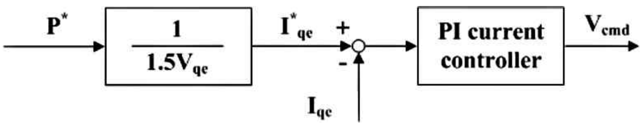


Fig. 4. Block diagram of compensated mode

Fig. 5. Unit supercapacitor and supercapacitor bank

Table 1. Specification of supercapacitor

Rated voltage	2.7V
Capacitance	360F
Internal resistance	3.2 mΩ
Max current	226A
Leakage current	0.75mA
Storage temperature range	-40℃ ~ 70℃
Cycle life(25℃)	500,000 cycle

2.2 Supercapacitor bank

The capacity of conventional capacitor is calculated by Eq. (1).

$$E = \frac{1}{2}CV^2 \tag{1}$$

The energy level of energy storage system (ESS) estimates using Eq. (1) because characteristic of super-capacitor is similar conventional capacitor. The energy level in SCESS is determined considering maximum and minimum voltage difference.

Energy can be stored in the supercapacitor by simple charging operation. Therefore, the energy stored in supercapacitor can be calculated using Eq. (2) which is used for conventional capacitors. Therefore, the energy level in SCESS varies depending on the instantaneous supercapacitor voltage [10]. The instantaneous super-capacitor voltage is measured using LPF in order to eliminate high frequency component. The compensation time of energy storage system is determined by an amount of load and capacity of supercapacitor bank. Operating voltage of the supercapacitor bank is from 240V to 400V and the supercapacitor bank is connected with 160 supercapacitors in series. Eq. (2) represents the capacity of supercapacitor bank, and energy of the supercapacitor bank is 115KJ, which means that 3kW load can be compensated for 30 seconds. Fig. 5 shows unit supercapacitor and supercapacitor bank. Table 1 shows specification of the supercapacitor.

$$E_{\max} = \frac{1}{2}C_{sc}\left(V_{\max}^2 - V_{\min}^2\right) \tag{2}$$

3. SCESS Control Considering

In design of the energy management strategy one has to consider various factors. The primary focus is to compensate the fluctuating power to a level that is acceptable to the time frame of interest. However, we need to be conscious of the upper and lower limitations of the device and any margin that one would want to maintain, perhaps for example, to fulfill some emergency operation criterion. Furthermore, the questions as to how we can combine features related to normal operation and those associated with transients need to be addressed in the management algorithm.

3.1 Basic theory of compensated fluctuating power

Supercapacitor is used to operate in 60 to 100% of rated voltage. The proposed algorithm of SCESS considering remaining energy of supercapacitor energy is discussed. Fig. 6 shows a block diagram of a simplified model for a basic smoothing control. T is the smoothing time constant, $G(s)$ is fluctuating power, $O_o(s)$ is smoothing power, $H_o(s)$ is SCESS reference power without remaining energy supercapacitor (RESC) control and $E_o(s)$ is instantaneous energy of supercapacitor without RESC control. $O_o(s)$ is similar to the LPF result of fluctuating power. The transfer functions are expressed Eqs. (3) and (4).

$$O_o(s) = \frac{1}{1+sT}G(s) \tag{3}$$

$$H_o(s) = \frac{1}{1+sT}G(s) - G(s) = \frac{-sT}{1+sT}G(s) \tag{4}$$

Relation of Eqs. (3) and (4) shows SCESS power is similar to the result of applying to the high-pass filter (HPF) on fluctuating power. If time constant is increased, LPF output becomes more flat. Otherwise, if time constant is decreased, LPF output is similar to the simulator power.

The time constant must be greater than or equal to the response time of the supercapacitor. Its value, the energy is handled by the SCESS. In case of $T<(E/P_{rate})$, the variation of the SOC remains within the rated capacity of a sueprcapacitor. In case of $T=(E/P_{rate})$, the variation of the SOC is equivalent to the rate capacity of a supercapacitor. In case of $T>(E/P_{rate})$, the variation of the SOC exceeds the rated capacity of a supercapacitor. Thus, T must be satisfied less than (E/P_{rate}) or equal to (E/P_{rate}) [2].

The basic compensation of fluctuation output is determined the output of HPF, $H_o(s)$. The basic smoothing control isn't considered to SOC of SCESS because the

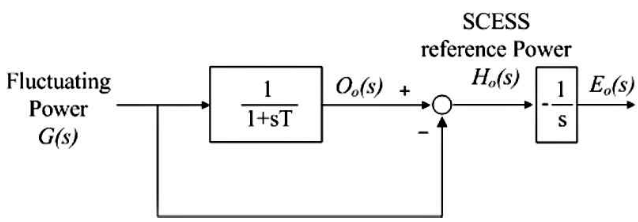


Fig. 6. Block diagram of a simplified model for a basic smoothing control

purpose of using SCESS is mitigated fluctuating power. Therefore, the problem is occurred at basic smoothing control. When the compensation algorithm isn't considered to SOC of SCESS, supercapacitor is occurred to overcharge or over discharge. Then, SCESS cannot compensate to the fluctuating power. The other problem is occurred a conversion loss in DC-AC Inverter and supercapacitor own losses (an internal resistance loss and a self-discharge loss). Thus, to solve the problem, the algorithm considered SOC is required.

Also, several researches proposed to change time constant of the LPF in order to consider SOC of energy storage system for smoothing a fluctuating power in basic algorithm. However, when time constant is changed from the initial value, ESS cannot compensate a fluctuating power. For this reason, SCESS needs new algorithm for compensating a fluctuating power in all conditions.

3.2 Analysis of RESC Control

A new algorithm of SCESS considering RESC control is discussed. Fig. 7 shows proposed algorithm in this paper. This algorithm is combined two techniques that are compensated fluctuating power and maintain SOC by RESC control.

Where, $H(s)$ is SCESS reference power with RESC control, $E_{ref}(s)$ is reference energy of supercapacitor, $E(s)$ is instantaneous energy of supercapacitor, SOC_{cmp} is energy feed-forward by RESC control, K_1 is gain of RESC control and $O(s)$ is compensated grid power with RESC.

SCESS controller operates smoothing power and maintaining SOC level, simultaneously. It means that two input values, $G(s)$ and $E_{ref}(s)$, extract one output value, $O(s)$, via controller. The interactional two control loops are existed in block diagram as shown in Fig. 7. When $H(s)$ is positive value, SCESS operates discharge mode for compensating enough power. On the other hand, when $H(s)$ is negative value, SCESS operates charge mode for compensating deficient power.

The proposed algorithm should be considered relationship for basic theory of compensated fluctuating power, RESC control and combined techniques. First, the basic theory of compensated fluctuating power is simplified control using LPF. The transfer function of basic theory is expressed

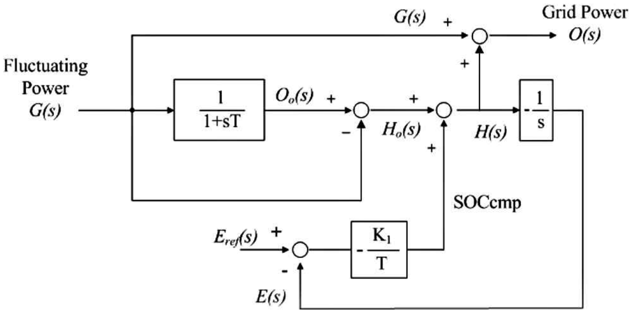


Fig. 7. Block diagram of the proposed algorithm control

Eq. (5).

$$\frac{H_o(s)}{G(s)} = \frac{-sT}{1+sT} \tag{5}$$

Second, RESC control is considered SOC of supercapacitor and tracking energy reference value. The relation between $E_{ref}(s)$ and $E(s)$ can be verified to performance by compensated SOC operation that is defined SOC feedback loop. The transfer function of SOC feedback loop is expressed Eq. (6). The fluctuating power is ignored in Eq. (6). How to select K_1 gain is mentioned in next part.

$$\frac{E(s)}{E_{ref}(s)} = \frac{K_1}{K_1 + sT} \tag{6}$$

RESC control is considered that the proposed algorithm is controller method for considering SOC of supercapacitor and tracking reference energy level of supercapacitor. Output of RESC control is reacted variable wind power via $-K_1/T$. RESC control is compensated and calculated to DC component which is reference SOC of supercapacitor.

RESC control is operated charge and discharge mode. When $E(s)$ is less than $E_{ref}(s)$, output of $E_f(s)$ is negative value. It means that RESC operates to charging mode for tracking reference energy level. On the other hands, when $E(s)$ is larger than $E_{ref}(s)$, output of $E_f(s)$ is positive value. It means that RESC operates to discharging mode for tracking reference energy level. The difference between $E(s)$ and $E_{ref}(s)$ is gradually decreased. Fig. 8 shows the operating mode of RESC control. $E_{ref}(s)$ is determined 50% of maximum energy level, in this paper.

Last, New algorithm that combined basic theory and RESC control is mentioned in this part. The smoothing power, $O(s)$, is determined by combined controller when the fluctuating power, $G(s)$, is entered. The transfer function between the input power and output power is expressed Eq. (7). The reference energy value is ignored in Eq. (7).

$$\frac{O(s)}{G(s)} = \frac{K_1 + s(T + K_1 T)}{K_1 + s(T + K_1 T) + s^2 T^2} \tag{7}$$

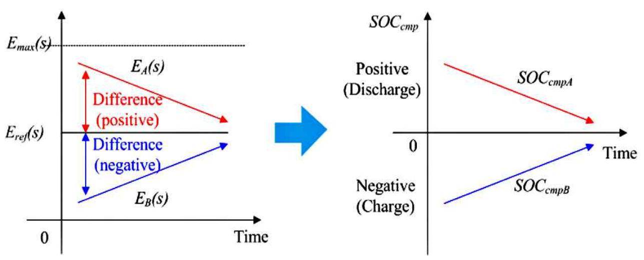


Fig. 8. Operating mode of RESC control

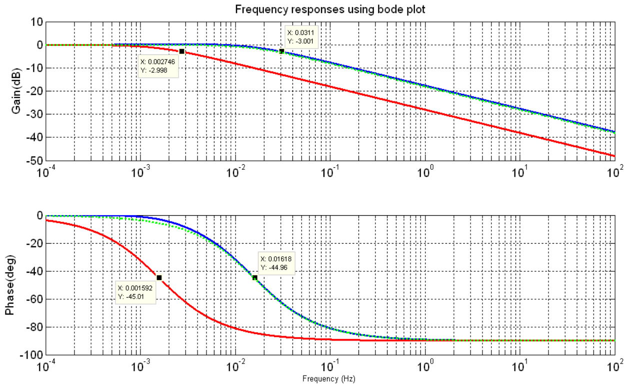


Fig. 9. Compare to bode-plot of three transfer functions by gain of 0.1

3.3 Verification the validity of proposed algorithm

To prove the validity of proposed algorithm, the transfer function is analyzed by MATLAB. Though SCESS simultaneously operates smoothing power and maintaining SOC level, the main control and sub control is divided in SCESS control. The main control is smoothing power. So, controller is considered the system response of relationship smoothing power and maintaining SOC level. The transfer function of Eqs. (5), (6) and (7) is compared using bode-plot.

Design method of K_1 is explained as follow:

First, cutoff frequency of proposed algorithm must be lower than cutoff frequency of general HPF at identical time constant in order to mitigate more fluctuating power. Second, -3dB frequency of proposed algorithm has to be higher -3dB frequency of RESC control because main control is compensating fluctuating power.

Fig. 9 shows that the transfer function of Eqs. (5), and (7) is compared by bode-plot at gain of 0.1. The transfer function of general HPF is green line, the transfer function of RESC control is red line and the transfer function of proposed algorithm is blue line. The time constant is 10sec. The graph of proposed algorithm coincide the graph of HPF. The -3dB frequency of proposed algorithm is 0.03 Hz, on the other hand the -3dB frequency of RESC is 0.0028Hz. This means that the proposed algorithm is faster operation than RESC control. Also, the proposed algorithm is appropriated on the performance in compensating fluctuating power because cutoff frequency of proposed algorithm is identical to general HPF. Thus, 0.1 is suitable gain by K_1.

4. Simulation Results

The simulation is performed using PSIM. The simulation parameters are shown in Table 2. The capacity of supercapacitor is reduced in simulation than real capacity because PSIM is difficult to perform over 10 seconds. Fig. 10 shows fluctuating power of simulator. Simulation is performed in the other conditions as the initial super-capacitor voltage. The variation of fluctuating power is 100% at 5kW power.

Table 2. System parameters

Rated voltage	Three-phase 220V
Rated frequency	60Hz
Rated of wind simulator power	5kW
Supercapacitor	0.225F (10%)
Energy of supercapacitor	11.5kJ
Line frequency transformer	10kVA 220V:130V
Switching frequency	10kHz

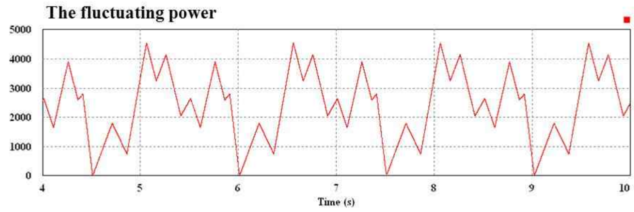


Fig. 10. The output of wind power simulator

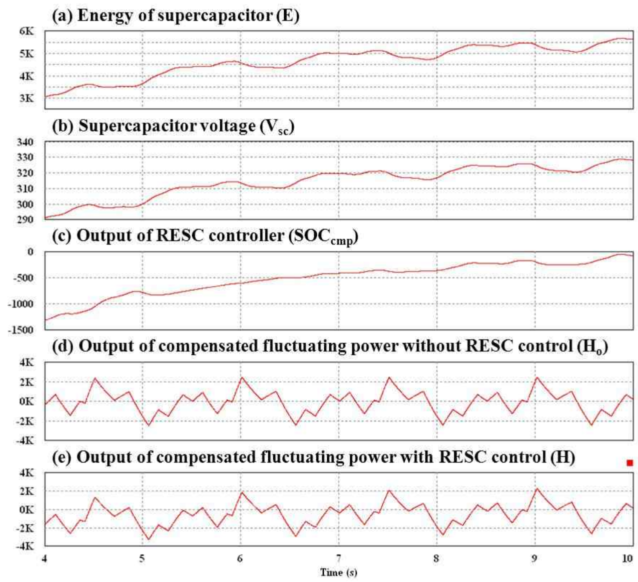


Fig. 11. Result of simulation when initial V_{sc} is 260V

Fig. 11 shows the results of simulation with RESC control when initial supercapacitor voltage is 260V. (a) shows energy of supercapacitor, (b) shows supercapacitor voltage, (c) shows output of RESC controller, (d) shows output of compensate fluctuating power without RESC control and (e) shows output of compensate fluctuating power with RESC control as shown in Fig. 11.

The output of RESC controller (SOC_{cmp}) is determined DC component by RESC controller. The $E_f(s)$ is negative value because the energy of supercapacitor is less than $E_{ref}(s)$.

In other words, RESC operates charge mode for tracking to $E_{ref}(s)$ and the negative value of SOC_{cmp} is converged to

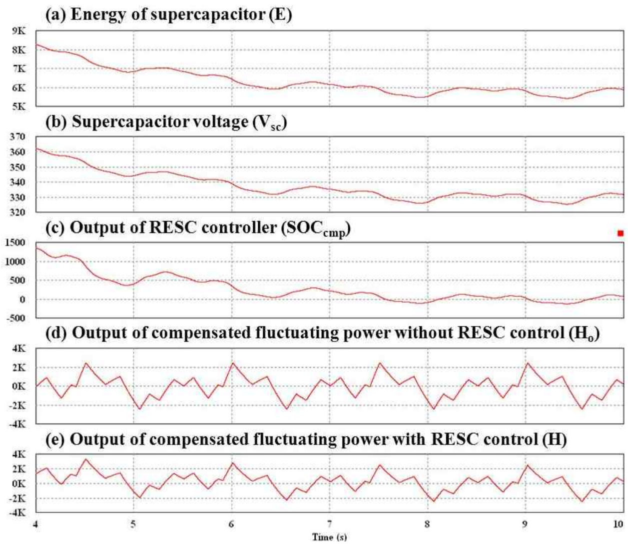


Fig. 12. Result of simulation when initial V_{sc} is 380V

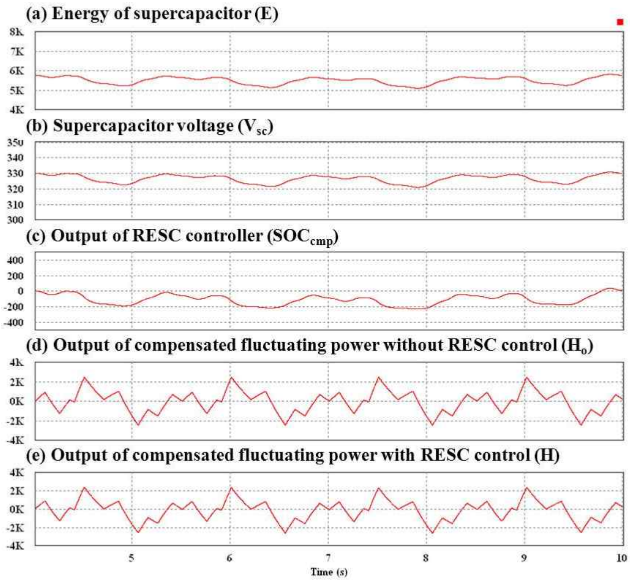


Fig. 13. Result of simulation when initial V_{sc} is 330V

zero when energy of supercapacitor increases to $E_{ref}(s)$. At this time, ESS compensates to fluctuating power properly, regardless of the operating RESC control as shown Figs. 11-(d) and (e).

Fig. 12 shows the results of simulation with RESC control when initial supercapacitor voltage is 380V. The output of RESC controller is determined DC component by RESC controller. The SOC_{cmp} is positive value because the energy of supercapacitor is more than $E_{ref}(s)$. In other word, RESC operates discharge mode for tracking to $E_{ref}(s)$ and the positive value of SOC_{cmp} is converged to zero when energy of supercapacitor decreases to $E_{ref}(s)$. At this time, SCESS compensates to fluctuating power properly, regardless of the operating RESC as shown Figs. 12-(d) and (e).

Fig. 13 shows the results of simulation with RESC control when initial supercapacitor voltage is 330V. 330V

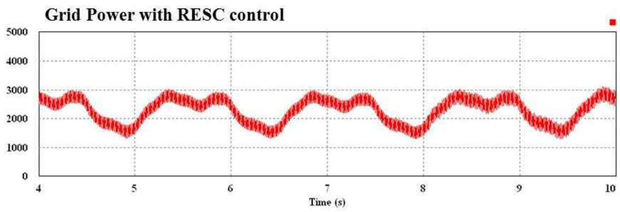


Fig. 14. Grid Power with RESC control

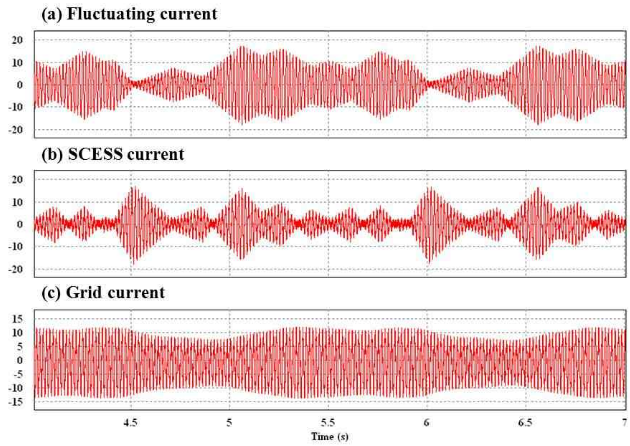


Fig. 15. Current waveforms

means almost 50% SOC. In order to converge to zero, the SOC_{cmp} is determined negative value and positive value repeatedly as shown Fig. 13-(c). Furthermore energy of supercapacitor is reached almost $E_{ref}(s)$, 5760J and SOC_{cmp} is almost zero.

Fig. 14 shows the grid power with RESC control. The variation of fluctuating power is reduced 100% to 30% at 5kW power. Fig. 12 shows the current waveforms. The magnitude of current at fluctuating power is variable. The difference of fluctuating current between the minimum and maximum value is 12.6A_{rms}. Using SCESS, grid current is mitigated as shown Fig. 15-(c).

5. Experiment Results

Fig. 16 shows assembled a small-scaled wind power simulator using back-to-back converter and SCESS. Back-to-back converter is composed of DSP28335 controller, L-filter and 5kW back-to-back power stack. SCESS is composed supercapacitor bank (360F, 160series connection), DSP28335 controller and 3kW DC-AC inverter. The experimental parameter shows in Table 3.

Fig. 17 shows fluctuating power of the small-scaled wind power simulator (a), the output of LPF (b) and compensating reference of SCESS (c). The fluctuating power is moved zero to 5kW as shown in Fig. 17. Fig. 17-(c) is determined by difference between (a) and (b).

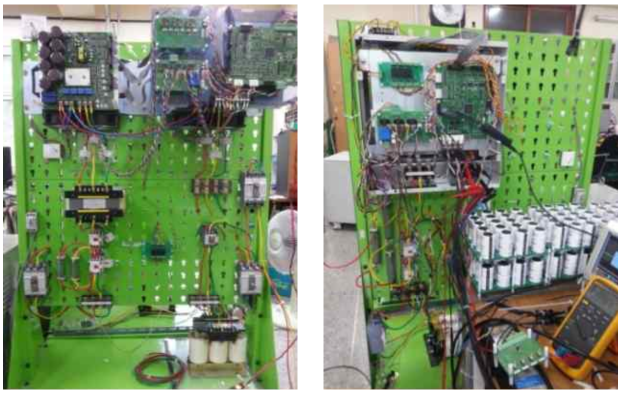
Fig. 18 shows the results of experiment with RESC control. (a) shows grid current, (b) shows wind power simulator current, (c) shows SCESS current and (d) shows supercapacitor voltage. The simulator current is fluctuating between $0A_{rms}$ to $13A_{rms}$. The grid current is fluctuating $4.5A_{rms}$ to $8.5A_{rms}$ due to compensated SCESS current. The maximum value of fluctuating current ripple is 37A and the minimum value is zero. Otherwise, the maximum value of grid current ripple is 25A and the minimum value is 10A. The grid power is fluctuating between 1.3kW and 3kW, and the wind power simulator output is fluctuating between zero and 5kW. Thus, fluctuating power in grid is reduced 1.3kW from 5kW by SCESS. According to perform RESC control, V_{sc}(green) is maintained 305V to 340V, near by the 50% of full energy.

Figs. 19 and 20 show detailed results of experiment with RESC control. SCESS is performed charge or discharge mode instantaneously by difference of LPF and simulator power. The grid current is lacked when the wind power simulator current is almost zero as shown in Fig. 19. Thus, SCESS operates discharge mode and supplies power to grid. The wind power simulator current (b) is $0.5A_{rms}$, the SCESS current (c) is $3.26A_{rms}$ and the grid current (a) is $3.35A_{rms}$. Otherwise, SCESS operate charge mode to absorb to simulator when the wind power simulator current is exceeded the limit as shown Fig. 17. The wind power simulator current (b) is $11A_{rms}$, the SCESS current (c) is $2.14A_{rms}$ and the grid current (a) is $8.7A_{rms}$. At the results, SCESS operates discharge mode to compensate for lacking power and charge mode to compensate for over power.

Fig. 21 shows the results of experiment with RESC

Table 3. Experimental parameters

Rated power of wind power simulator	5kW
Rated power of SCESS	3kW
Capacity of supercapacitor	2.25F
Energy of supercapacitor	115kJ
Operation time of SCESS	30sec
Switching frequency	10kHz
LPF Time constant	10sec



(a) (b)

Fig. 16. (a) Small-scaled wind power simulator using back-to-back converter; (b) Supercapacitor energy storage system

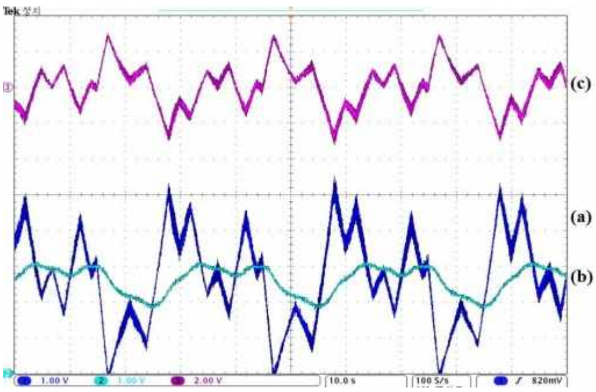


Fig. 17. The experiment reference value

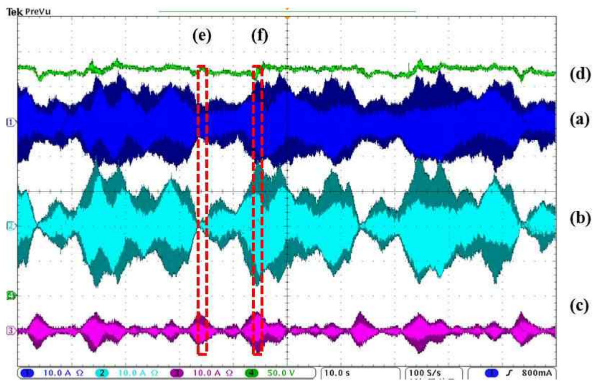


Fig. 18. The results of experiment with RESC

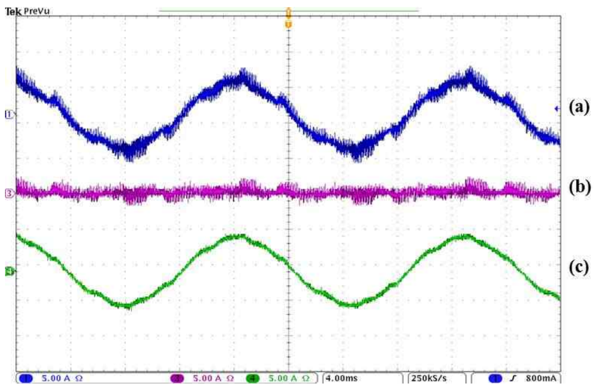


Fig. 19. The result of each current in discharge mode

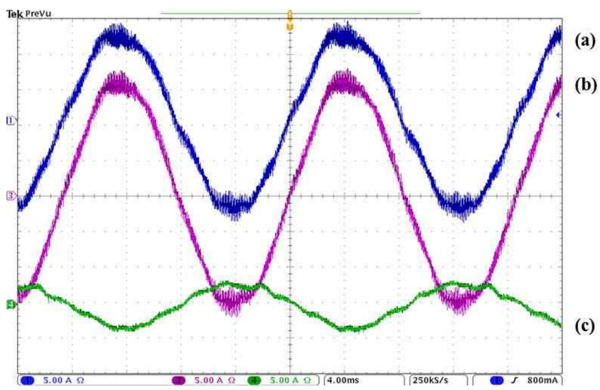


Fig. 20. The result of each current in charge mode

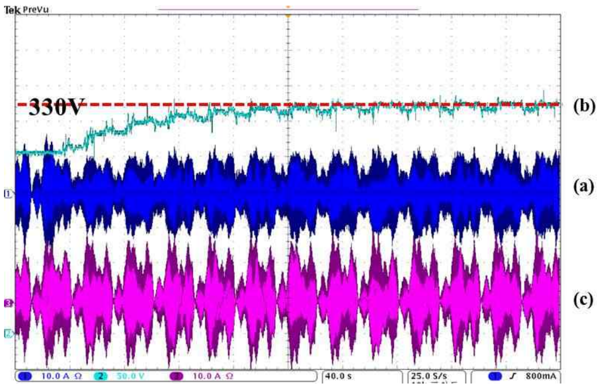


Fig. 21. Result of experiment when initial V_{sc} is 260V

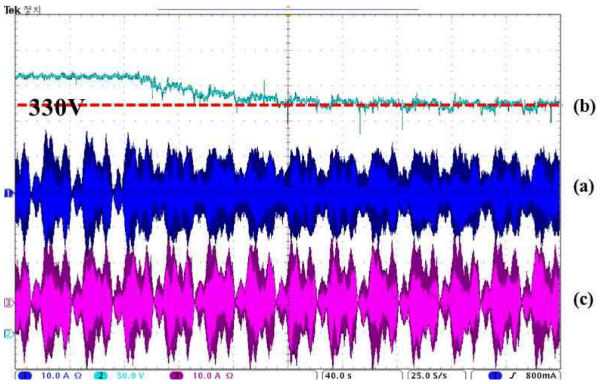


Fig. 22. Result of experiment when initial V_{sc} is 360V

control when initial supercapacitor voltage is 260V. Otherwise, Fig. 22 shows the results of experiment with RESC control when initial supercapacitor voltage is 360V. (a) shows grid current, (b) shows supercapacitor voltage and (c) shows simulator current as shown in Figs. 21 and 22. Supercapacitor voltage is increased to 330V because initial energy of supercapacitor is less than $E_{50}(s)$. And Supercapacitor voltage is decreased to 330V because initial energy of supercapacitor is more than $E_{50}(s)$. Thus, supercapacitor voltage is tracking and maintaining near 330V as shown in Figs. 21 and 22.

6. Conclusion

This paper has proposed a control method for maintaining the energy level for a SCESS coupled with a wind generator to stabilize wind power output. In order to mitigate the fluctuating output power, SCESS and wind power simulator has been developed. SCESS has been applied to smooth for short-term fluctuating power and provided a high quality power to grid system. When the average or fluctuating component power has been increased instantaneously, the proposed RESC control has been stably compensated the fluctuating power in the steady as well as transient state. The fluctuating power has been reduced 100% to 30% at 5kW when SCESS is compensated fluctuating power. Also energy of SCESS has been maintained 50% of total energy. Feasibility of SCESS with RESC control method has been verified through simulation and experiment.

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