Doctoral thesis

Novel Management of BESS in Voltage and Unbalance Factor Control of PV Connected Distribution System

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Abstract

This Ph.D. thesis documents the research work for obtaining the Ph.D. degree from the Nagoya Institute of Technology.

With environment protection and threat of limited traditional resources, power generation via renewable energy joins in conventional power system. The distributed feature of renewable generation in power system makes its flexible location. And the variation construction of renewable generation releases conventional power system from the demand pressure of consumers. Renewable generation is also the backup of conventional power generation to provide stable power to load side. And with PV and energy storage devices' development in power system, the power retail business promotes the liberalization of power market.

Besides of the highlight of renewable generation, the problem is also significant. The feature of renewable energy like Photovoltaic leads to unstable power generation. The capacity, location and management of renewable generation is also a problem. In Japan, PV is widely distributed in power system, and the poor power quality is more severe and directly reflects to consumers. Because PV relies on insolation and can't be accurate predicted, voltage in PV connected distribution system becomes complex and hard to control. The traditional devices without the PV control version is incapable to perfectly solve the voltage problem caused by PV. Therefore, novel method and novel devices is needed in voltage improvement.

In this thesis, novel management of energy storage devices cooperated with conventional devices in voltage management of PV connected distribution system is proposed.

Chapter 1

Introduction

1.1 Background

Power system mainly contains three parts, power generation, transmission and distribution as shown in Fig. 1. 1. Power generated from fossil, hydro, nuclear, etc. provides the consumption of loads in power system via transmission and distribution system. The aggregated stable power generation support the power system in the past few decades. With the population growth, need of electricity continues increasing. The increasing power generation leads to environment issues like global warming, and the limited power generation resource is threat to power system. With consideration on these problems of power system, renewable energy like Photovoltaic (PV) and Wind Farm (WF) is applied as a clean power generation resource. In Japan, PV is under well development, and the schedule capacity of PV in power system is 53GW in 2030. In [1], one objective of PV development is aiming to reduce the power generation cost to 14 yen/kWh in 2020 and 7 yen/kWh in 2030. With the cost reduction of PV, the growth speed of its introduction amount in power system is faster.

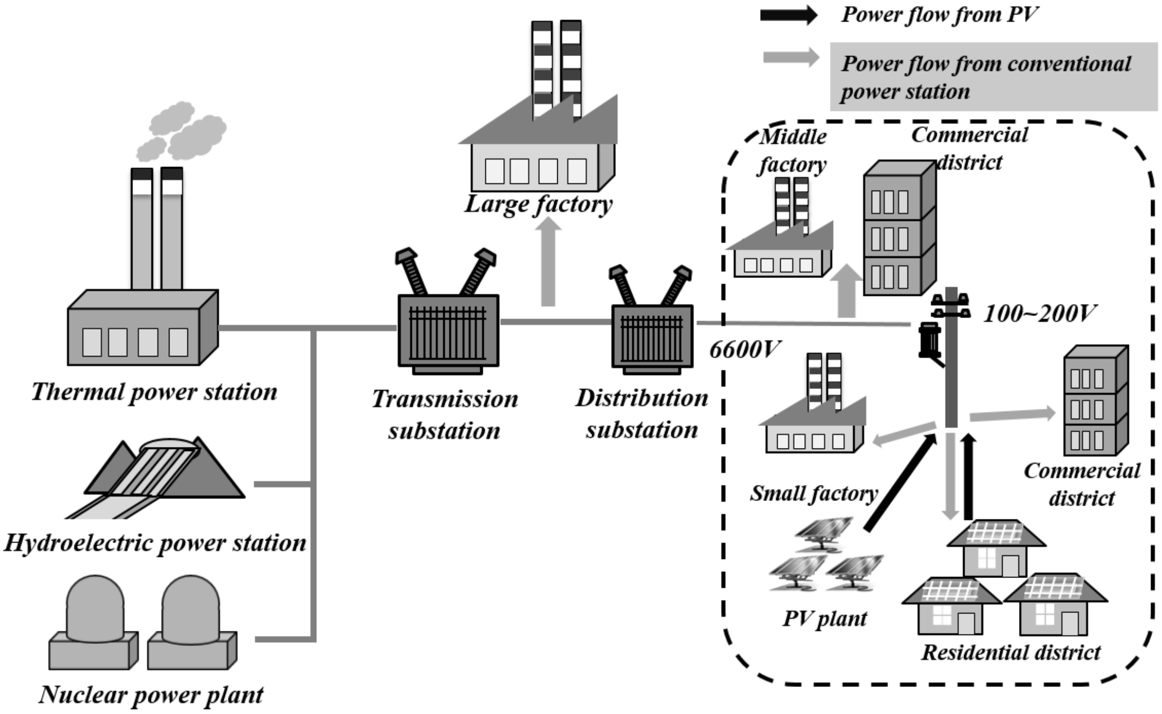

Fig. 1. 1 Image of power system

The growth of PV in power system is noticeable because there is not a limit of its location and scale. Especially the power generation reduction after the Great East Japan Earthquake which leads to deficit of power. With the spread of PV, the role of consumer converses to provider, and bring the evolution of power market. Also, power generated by PV can relatively cover the shortcoming of electricity caused by the flood in 2017 summer at Kyushu which leads to blackout. However, the large amount of power generation by renewable energy can't be effectively used by consumers. Because power generation with PV has a significant feature, unstable. And it is distributed in power system with small power generation capacity compared to traditional amount. All the feature makes the application of PV become a complex problem. A kind of central generation of renewable energy transmitted via ultra-high-voltage is under development to realize effective utilization. While in Japan, more attention pays to distribution side. Because large amount of PV is connected in distribution system as roof-top solar, the problem caused by PV directly reflects to consumers and the job of providing stable power quality to consumers is emergency.

The demerit of PV in distribution system mainly reflects on two parts, voltage and frequency. The introduction of voltage deterioration caused by PV is presented here. Because PV totally relies on insolation, the inaccurate prediction of PV output leads to uncontrollable voltage in distribution system.

The first part of the problem caused by PV in distribution system is voltage violation. The inverse power flow caused by PV leads to the unexpected voltage rise in distribution system especially in midday of summer, and the sudden change of voltage by variable PV output brings complex voltage profile to manage. The second part of PV's demerit in voltage is unbalance factor degradation. In distribution system, unbalance factor increases with the growth of unbalanced single-phase load, and PV in distribution system is normally connected with single-phase load. The location of PV in distribution system also has bad effect on voltage balance. This paper discusses the voltage problem mentioned above in PV connected distribution system, and novel method of Battery Energy Storage System (BESS) and established tap-change devices is proposed to improve the voltage magnitude and unbalance factor.

1.2 Existed voltage management in distribution system

In Fig. 1. 2, a simple model of distribution system is illustrated. Based on the existed devices, two parts in voltage management are introduced here.

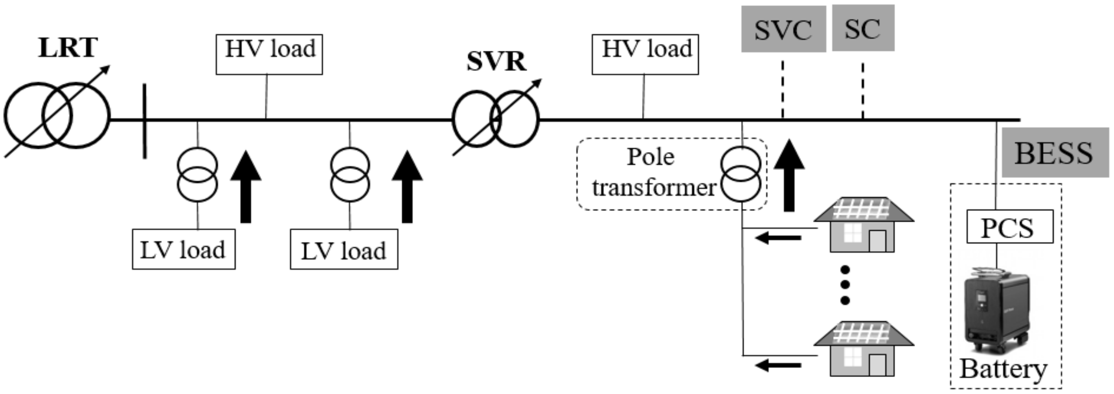

Fig. 1. 2 Model of distribution system

[Part 1: voltage magnitude regulation]

The conventional devices mainly control the voltage magnitude with tap-change like Load Ratio Control Transformer (LRT), Step Voltage Regulator (SVR) and pole transformer. They locate at the root, middle and terminal of distribution line, respectively. For LRT, the biggest inconvenient of its control is multiple distribution system controlled by one LRT. It means every tap-change of LRT has the same regulation result for several different distribution systems. And this leads to unexpected voltage change for uncertain distribution system. Therefore, the operation of LRT for voltage regulation of certain distribution system is imperfect. For SVR, it locates in the middle of distribution line. The simple tap-change control with different ratio realizes step-change of voltage. However, the long settle is always a problem in voltage suppression. Especially with the growth of PV in distribution system, the voltage profile becomes variable and short period violation of voltage has increased. SVR operates based on only one measured phase voltage, and the fixed regulation amount of voltage by tap-change of SVR leads to voltage violation with the extra regulation amount. And increasing tap-change time is another issue in dealing with frequent voltage violation caused by PV. Pole transformer is set with a fixed ratio, it’s helpless in voltage regulation of PV connected distribution system.

Besides the traditional tap-change devices, new devices are introduced to distribution system to realize more effective voltage control. Reactive power compensation is the major method, and devices like Static Capacitor (SC) and Static Var Compensator (SVC) are suggested to deal with the voltage violation. The end of distribution line is the normal location of these devices because relatively small output is needed in dealing with the severe voltage violation appearing at the end of distribution line. SC provides distribution system with reactive power, and changes its output with its number of connected banks. Comparing with other new devices, the low cost is the highlight of SC. For SVC,_the coupled thyristor makes it capable to give an immediate and flexible output. The excellent control ability in dealing with the complex voltage profile caused by PV draws the public’s attention.

[Part 2: voltage unbalance factor improvement]

$$unbalance\ factor = \frac{negative\ phase\ voltage}{positive\ phase\ voltage} * 100\%$$

In distribution system, the increasing of roof-top solar leads to the deterioration of Voltage Unbalance Factor (VUF). Because VUF has the relation with negative phase voltage as the equation above shown, location of PV as roof-solar leads to the increasing of negative phase voltage and makes VUF become worse. One way to realize the improvement of VUF is the reduction of inverse phase voltage as illustrated in [2] and [3]. And other inverter attached devices is also has the same objective in unbalance factor improvement with negative phase voltage suppression.

The other method is to reduce the maximal line voltage difference $DVline$ as the equation below shown. In [4], SC is used in suppressing unbalance factor with connection number changing of SC banks.

$$DVline = \max[Vline] - \min[Vline]$$

1.3 Topic of issues in voltage management of PV connected distribution system and previous study

In distribution system, the quality of voltage is directly reflected to consumers, and it makes voltage management in distribution system be more emergency. With the growth PV, the construction of distribution system is changed little by little, and effective control by established and new devices is important. The issue of voltage management in distribution system with the expanding of PV mainly focuses on three aspects.

(1) Application of established devices

The increasing of PV in distribution system leads to the variable voltage, and established devices with tap-change control has operation delay in voltage management. Furthermore, the fixed regulation amount by tap-change is incapable in dealing with the speedy and tiny violation of voltage, and results in unexpected voltage violation with the over-regulated amount by one tap-change. For effective utilization of established devices, novel method is proposed in [5] and [6]. The data of PV is introduced in SVR and LRT operation in these two papers, respectively. And in this way, proper control is operated via these tap-change devices to suppress the voltage violation. However, PV relies on insolation that is hard to obtain the accurate output, and the error processing for accurate PV output is an important issue to deal with. The cooperation of PV and LRT is also introduced in [7], it has the same problem in PV control, and the suppression amount of PV output also needs to be discussed. In [8]-[10], the voltage control with tap-change devices is improved with voltage estimated calculation, and more effective utilization is realized. However, the speedy variation of PV in distribution system leads to the error in voltage calculation that causes unsuitable operation of tap-change devices.

For VUF improvement, established tap-change devices realize the operation with simultaneously control of three phase voltages with the same amount. Therefore, no effect appears on balancing three phase voltages and improvement of VUF.

(2) Introduction of novel method with new devices

The application of voltage control devices like BESS and SVC. PV distributes in power system with unstable output, and devices with PCS is capable to provide immediate and accurate control to voltage violation problem caused by PV. The biggest obstacle in promotion of PCS attached new devices is the cost. Therefore, effective utilization for essential control objective needs to be discussed. In [11]-[13], voltage management with SVC and STATCOM is mentioned. In these proposed method, voltage control results go well. And SVC is popular devices with reactive power supply to distribution system._These reactive power compensator devices have an excellent control ability. However, there is two parts needed to be discussed. The first is the control effectiveness when value of resistance is larger than reactance. The other is the increasing of storage devices in distribution system like BESS, Home Energy Management System (HEMS) and Electric Vehicle (EV). There are coupled with Power Conditioning System (PCS) which can supply both active and reactive power, and realizes more effective control. With the liberalization in future power market and power retail business of these energy storage devices, the profitable use of SVC need to be discussed.

Among all the proposed methods in voltage management, more attention is payed to BESS in PV connected distribution system. Besides the excellent control ability, BESS has unique feature in absorbing inverse power from PV and reuse it for electricity power cost reduction. BESS application is illustrated in [14]-[16]. The capacity of BESS is always the biggest issue for cost reduction in BESS application. To realize effective control with small-scale BESS application, the cooperation of BESS with established devices in voltage control is discussed a lot. The study on proper utilization is proposed in [17]-[19], respectively. In the cooperation, established devices deal with long period voltage violation and BESS solves the dramatically short period violation caused by PV, and the definition of the proper time for operation change between BESS and established devices is the issue. And the study of BESS in VUF suppression is wanted more for effective utilization.

Besides the development of BESS, HEMS and EV with speedy development are protentional backup of BESS in distribution system [20]. From the view of future smart grid, the cooperation method between these devices for maximizing profit is also a topic to discuss.

In VUF suppression, besides the high cost devices, SC with relatively low cost has the same problem with the mentioned tap-change devices above. The over compensation of SC leads to leading power factor which is the demerit of its application. Furthermore, the reduction of switch-change times of SC is the issue of SC for the proposed method illustrated in [4].

(3) Increasing of anticipators in distribution system

The increasing PV, HEMS and EV in distribution system is another challenge for distribution system[21],

[22]. The energy storage devices owned by consumers stores and reuses the power from PV, and sells the rest of the power to power company. This promotes the power retail business and the evaluation of power market. The construction of power trading of Grid to Vehicle (G2V) [23] and Grid to HEMS (G2H)[24] changes to V2G and H2G little by little. And the profit of consumers and power company with the consideration of stable voltage supply is the issue needed to be balance. Therefore, the definition of proper price and amount of power trading on voltage management is urgent to be discussed especially in smart grid and remote areas.

1.4 Overview

This thesis focuses on voltage and VUF suppression with BESS. The outline of this thesis is shown in Fig. 1.3. With PV penetration in distribution system as roof-top solar, the voltage violation and deterioration caused by inverse power flow and connection type of PV is noticeable. To realize excellent control in voltage management, BESS draws author's attention. In application of BESS, capacity directly connects with cost, therefore, capacity reduction is important issue. And the other essential constraint in BESS application is State of Charge (SOC). The adequate range of SOC keeps BESS from over change/discharge to prolong the cycle life of BESS. To make effective application of BESS, the proper SOC management is indispensable. Therefore, each chapter discusses the application of BESS with variation of its capacity and SOC management.

In chapter 2, with the flexible control ability of BESS, a novel method for accurate voltage unbalance factor suppression is proposed. Because BESS is high cost device, SC with relatively low cost assists BESS in voltage unbalance factor suppression via provide reactive power to distribution system. With the consideration of BESS development, chapter 2 assumes multiple BESSs averagely locate along distribution line with distributed control. SOC management hasn't been discussed. In chapter 3, cooperation of multiple BESS with novel SOC management is proposed. Based on chapter 2, chapter 3 targets the full use of available capacity in multiple BESSs with proper SOC management. The cooperation of BESS group composed by multiple BESSs is proposed, and in this way, reduction of the peak value of BESS output for small capacity of each BESS is realized. And novel SOC management is proposed to make more available capacity in the operation and realize a further reduction of BESS capacity. Chapter 4 targets the application of small-scale BESS in voltage and VUF suppression with SVR's assistance. Different from previous chapters, with the assume of the large scale utilization of small scale BESS owned by consumer in future power retail business, chapter 4 proposes the cooperation of small scale BESS in distribution system. And SVR cooperates with small scale BESS in its operation without extra cost for other assistance facilities. From the view of BESS development in future smart grid, HEMS and EV as backup of BESS is possible with their high penetration, and cooperation of these energy storage devices is necessary for liberalization of power market. In chapter 5, the cooperation of BESS, EV and HEMS is proposed in voltage fluctuation suppression.

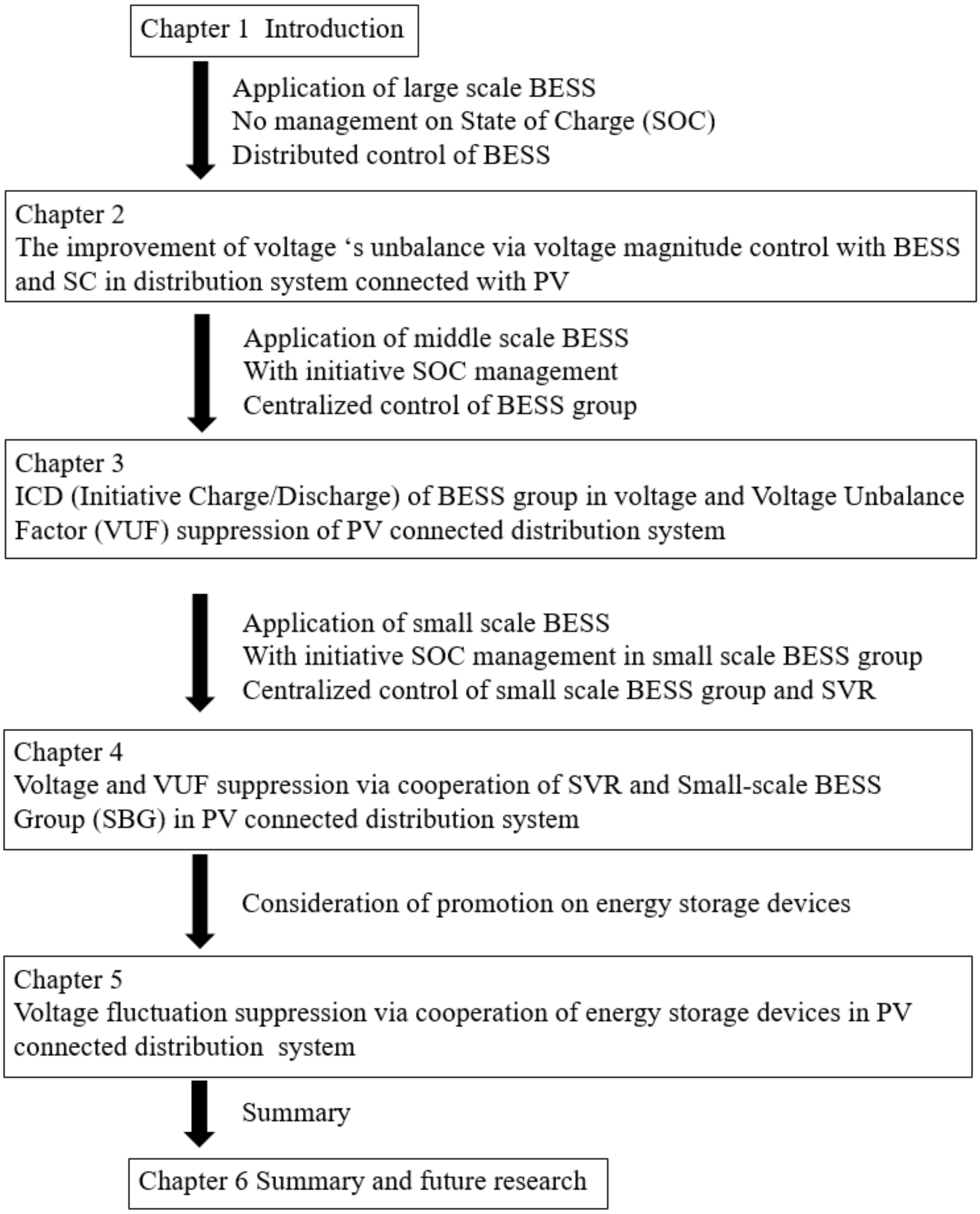

Fig. 1. 3 Model of distribution system

[1] Chapter 2

Cooperation of BESS and SVR is proposed for VUF suppression in PV connected distribution system. In distribution system, VUF control is normally operated via decreasing of negative phase voltage. However, it difficult to suppress VUF to a fixed reference value. With the liberalization of power market, the constraint of VUF for different consumers won't always be same. Hence, this chapter proposes a flexible VUF control method via regulation of phase voltage. The proposed method realizes accurate regulation amount in VUF. SC assists BESS in VUF suppression for BESS's capacity reduction. Multiple BESSs averagely locate in distribution system to provide accurate control to verify the proposed method.

[2] Chapter 3

Because PV output varies with time and location, voltage in distribution system varies with PV. This leads to the output and available capacity of BESS differ with different location, capacity in distribution system. With the development of BESS, BESS group composed by multiple BESS is applied in distribution system, the different state of BESS in BESS group makes the management be inconvenient. Cooperation of BESS is proposed to solve the problem and achieve full use of BESS available capacity with the different state of each BESS in BESS group. For SOC management, different from existed passive charge/discharge of BESS, a novel initiative charge/discharge is proposed to prolong the operation period and reduce BESS capacity.

[4] Chapter 4

Novel control method of Small-scale BESS Group (SBG) composed by Small-scale BESS (S-BESS) in voltage and VUF management is proposed. In the development of smart grid, the increasing of BESS application is inevitable. And the increasing energy storage devices like Home Energy Storage System (HEMS) is also notable. The study of large-scale in voltage management is done a lot, while the method in S-BESS application can't just take the existed method for large-scale BESS. Because of the different capacity and location of S-BESS, novel method in the cooperation of S-BESS is needed for their effective utilization. SVR works as an assistance.

[5] Chapter 5

Voltage fluctuation suppression is done in this chapter with the utilization of energy storage devices. In remote area, the established devices are incapable to provide the regulation of voltage to meet consumers' require. In emergency like earthquake and flood that destroy devices in transmission and distribution system, the recovering of power supply needs long period and it's unacceptable to consumers. To promote the stable power supply in distribution system, author pays attention to energy storage devices which have unique feature in storing and reusing power. Under the growth of BESS, HEMS and EV in distribution system, choice of devices in voltage management is increased. Because the different owner of these devices, the justice control method is wanted. With the consideration of future smart grid and power retail system, cooperation between BESS, HEMS and EV is proposed in voltage fluctuation suppression.

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Chapter 2

The Improvement of Voltage’s Unbalance via Voltage Magnitude Control with BESS and SC in Distribution System Connected PV

2.1 Introduction

In recent years, in considering the reduction of the air pollution emission from power generation with fossil fuels for environment protection, PV is widely applied in power system as a type of clean and renewable energy in Japan. However, large amount of PV causes the problem in distribution line. The output of PV relying on the solar radiation which varies a lot in a short period leads to the severe voltage change which is unacceptable. In distribution system, the increasing of roof top type PV leads to the deterioration of voltage unbalance [1] [2]. To solve the problem caused by PV, the established devices are applied such as SVR, SC, LRT, etc. SVR and SC are taken into regulating voltage, however, with the quick-change feature of voltage caused by PV, SVR and SC which are with a fixed regulating amount and long setting time seem insufficient to manage voltage fluctuation. The setting time of Load Ratio control Transformer (LRT) is also too long to manage the voltage problem caused by PV. SVC is capable with its quick and flexible management. However, it is an expensive device [3]-[6].

BESS is used to control the voltage in distribution system because it can give a fast, accurate, and flexible output to regulate voltage properly, and absorb the reverse power flow caused by PV. The stored energy in BESS can be reused to support the demand of consumers during emergency period. However, with the highlight of BESS in voltage management, high cost obstructs the wide application of BESS. To propel the application of BESS, a lot of study has done around it. In [7], BESS is set with each PV to regulate the voltage into proper range, and local control algorithm of BESS is proposed to stabilize the voltage. In [8], centralized BESS in microgrid is used in balancing the power to mitigate the intermittency of PV, and both grid-connected and island cases are discussed to manage the power quality. In a high PV penetration distribution system, BESS takes an important part in peak shaving, load leveling, and reverse power flow absorbing with centralized and decentralized control in [9]. In [10], [11], both mentioned a DC bus, which can be used to promote the efficiency of BESS utilization along with the penetration of renewable energy, and it seems like a possible trend of the development of BESS. And from the view of cost, it mainly focuses on the reduction of battery’s capacity to reduce the cost on BESS, and the management of SOC protects the battery from overcharge/discharge. In [12], the SOC optimal control method is proposed to take full use of the capacity of battery as well as manage SOC in adequate range to prolong the lifetime of BESS. And the optimal sizing and placement of BESS in PV connected distribution system is discussed during the regulation of voltage in

[13] and [14]. The study of BESS is trying to propose a method to apply it in a low consumption with high quality control way.

In this paper, BESS focuses on the management of Voltage Unbalance Factor (VUF) caused by PV and single-phase load that hasn't been discussed a lot. Different from SC and SVC that just give reactive power with the traditional calculation [15] and complicated control method [16], BESS that provides distribution system with both active power and reactive power is more applicable with the development of PV in distribution system.

Generally, as VUF is calculated from a positive phase sequence component and negative phase sequence component, it causes the increasing burden of controller. The authors propose a simple method for VUF improvement by reducing the maximal difference of line voltage. The relation of the magnitude of phase voltage and the line voltage is discussed, and the output current of each phase by BESS is determined. To reduce the cost of BESS, this paper proposes a method with minimal regulation amount of phase voltage in distribution line into its adequate range. SC supports BESS to provide reactive power to reduce the capacity of inverter used in BESS. The placement is also discussed with the case that one BESS at the end of distribution line and the case that several BESSs distribute in the distribution line. With the change of placement, BESS is verified to regulate VUF with proper output.

In section 2.2, the management method of BESS and SC in voltage and VUF are described; the simulation is all done on MATLAB and the result is shown in section 2.3; and finally, in section 2.4, the conclusion is presented.

2.2 Voltage and VUF Control

2.2.1 VUF control with SC

The voltage of distribution system is largely influenced by the output of PV. To suppress the voltage deviation and the unbalanced voltage, BESS is a better device than the other voltage control device because of fast operation and flexible output. However, BESS has the problem of cost.

In this section, the author proposes the cooperative control of SC and BESS to improve VUF. As SC is relatively cheap compared with BESS, it is expected that the total cost of VUF improvement decreases. Multiple single-phase SCs are connected in parallel with BESS. By switching SCs, the unbalanced voltage is improved. As suppressing the unbalanced voltage, the negative sequence current in distribution line is decreased. Hence the power loss of distribution line is decreased. However, in the case of over compensation of VUF, excessive reactive power of SC causes the unnecessary power loss of the line. Therefore, the relation of VUF and the power loss due to changing of SCs becomes a parabolic curve as shown in Fig. 2. 1 [17]. From this relationship, the number of SC to on/off is determined as equation (2.1). V_P is defined as the phase voltage of the distribution line at the point that SC is connected. V_{MAX} and V_{MIN} are the upper limit and lower limit of the proper voltage range of the distribution line respectively. When V_P is larger than V_{MAX}, the connected SC is opened, and when V_P is smaller than V_{MIN}, SC is closed. In the case that V_P is in the proper range, the capacity of the single-phase SCs is determined by minimizing the power loss (P_{loss}) of distribution line for VUF improvement. N is the connection number of SC.

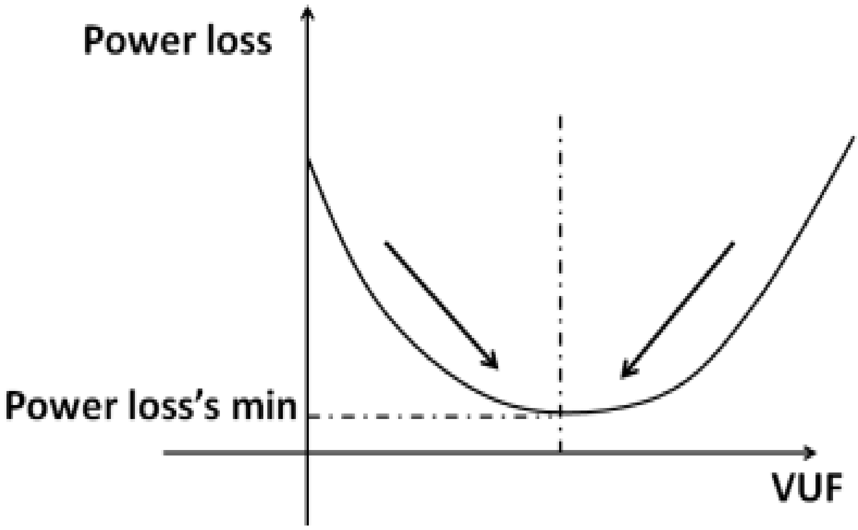


Fig. 2. 1 Image of relation of power loss and VUF.

$$\begin{cases} \text{if } V_p > V_{MAX}\ , N * Q_{SC} \to (N-1) * Q_{SC} \\ \text{if } V_p < V_{MIN}\ , N * Q_{SC} \to (N+1) * Q_{SC} \\ \qquad \text{if } V_{MIN} < V_p < V_{MAX} \\ \quad N * Q_{SC} \ \text{ to minimize } P_{loss} \end{cases} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots(2.1)$$

2.2.2 Voltage control with BESS

In this section, the objective of the operation of BESS is that voltage deviation and unbalanced voltage are suppressed with minimizing the output of BESS as much as possible.

Based on section 2.1, the control method of BESS to regulate the unbalanced voltage is divided into two parts. Firstly, the line voltage at the connected point of BESS is regulated into the proper range. In the next step, the unbalanced voltage is suppressed. The simple model of distribution line is illustrated in Fig. 2. 2. BESS is connected at node i. $\dot{I}_B$ is the output of BESS. P_i and Q_i is the active power and reactive power of the load at node i respectively. Z_k is the impedance of section k in the distribution line.

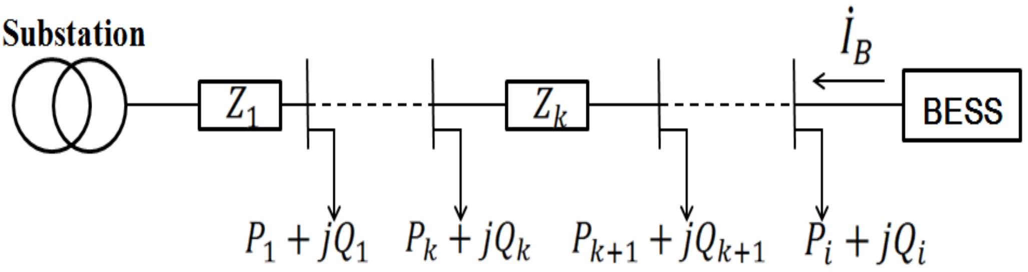


Fig. 2. 2 Simple model of distribution system

$\Delta\dot{V}_B$ is the voltage variation by BESS in equation (2.2), and it is calculated with the multiplication of $\dot{I}_B$ and the total line impedance Z_k that is the summation from the distribution substation to the node i.

$$\Delta\dot{V}_B = \dot{I}_B * \sum_1^i Z_k \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.2)}$$

The regulated voltage $\dot{V}_{BP}$ is shown in equation (2.3), and the apparent power of BESS is shown in equation (2.4).

$$\dot{V}_{Bp} = \dot{V}_p + \Delta\dot{V}_B \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.3)}$$

$$\dot{S}_B = \dot{V}_{Bp} * \dot{I}_B^{\;*} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2.4)}$$

By substituting $\dot{V}_{BP}$ to equation (2.4), $\dot{S}_B$ is arranged in equation (2.5).

$$S_B = \Delta\dot{V}_B^{\;2} + \Delta\dot{V}_B * \left(\dot{V}_P / \sum_1^i Z_k\right)^* \ldots\ldots\ldots\ldots\ldots\ldots \text{(2.5)}$$

From equation (2.5), in order to decrease the output of BESS for the reduction of BESS's capacity, $\Delta\dot{V}_B$ should be minimized. Fig. 2. 3 shows a vector diagram on the complex coordinate of the phase voltage. Dotted curve is the upper limit of the proper range of the phase voltage in the distribution line. $\dot{V}_P$ is the phase voltage of node i before BESS is operated. When the voltage change $\Delta\dot{V}_B'$ with BESS has a different phase angle with $\dot{V}_P$, the phase voltage becomes $\dot{V}_{BP}'$. When the voltage change $\Delta\dot{V}_B$ with BESS has a same phase angle with $\dot{V}_P$, the phase voltage is regulated to $\dot{V}_{BP}$. It can be seen that magnitude of $\Delta\dot{V}_B$ which has a same angle with $\dot{V}_P$ is the smallest. Therefore, the voltage is regulated by BESS with a same phase angle to the phase voltage of the line.

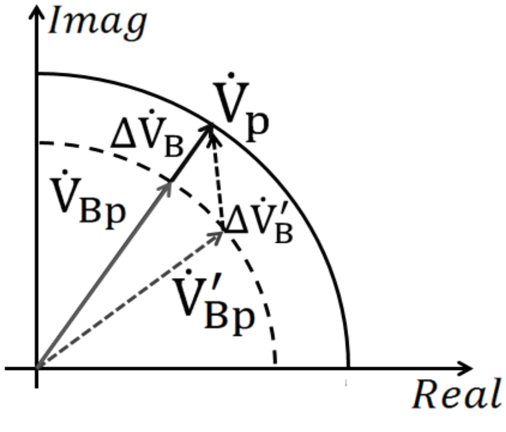


Fig. 2. 3 Image of voltage control with BESS

2.3 VUF control with BESS

Basically, PV in the distribution system is a roof top type, and they cause the sudden change of a certain phase voltage. Hence, a specific management with certain changes is required for an accurate control. In this section, based on the relation of VUF and the difference of line voltage, the accurate and simple control of phase voltage to improve VUF is proposed.

2.3.1 Mathematical Relation of Line Voltage's Difference and VUF

The maximal difference of line voltage and VUF has a proportional relation which is proved in [5].

$\mathrm{V_i\_diff}$ is the maximal difference of line voltage which is the difference between the largest line voltage and the smallest one. $\mathrm{V\_ki}$ is an unbalance factor at node i. Vi_diff is expressed with the proportionality coefficient $\mathrm{K_i}$ of node i in equation (2.6). During the whole sampling period, the coefficient at each sampling time $\mathrm{K_i(t)}$ is ranged according to the magnitude of the middle line voltage. The average value $\mathrm{\overline{K}_i}$ of the discrete data can be calculated in equation (2.7). N is the number of sampling data. The mean squared error $\mathrm{K_{MSE}}$ is calculated in equation (2.8). The construction of the distribution system is generally kept in the same state, and the discrete coefficient is used to get a mathematical relation of line voltage difference and VUF. The limit error is applied to calculate the range of coefficient. The maximal coefficient $\mathrm{K_{iMAX}}$ and minimal coefficient $\mathrm{K_{iMIN}}$ are calculated in equation (2.9).

$$\mathrm{V_i\_diff(t) = K_i(t) * V\_ki(t)} \quad (2.6)$$

$$\mathrm{\overline{K}_i = \frac{\sum_1^N K_i(t)}{N}} \quad (2.7)$$

$$\mathrm{K_{MSE} = \sum_1^N (K_i(t) - \overline{K}_i)^2 / N} \quad (2.8)$$

$$\begin{cases} \mathrm{K_{iMAX} = \overline{K}_i + 3 * K_{MSE}} \\ \mathrm{K_{iMIN} = \overline{K}_i - 3 * K_{MSE}} \end{cases} \quad (2.9)$$

The coefficient $\mathrm{K_i(t)}$ distributes in the range composed by $\mathrm{K_{iMAX}}$ and $\mathrm{K_{iMIN}}$ randomly. The reference of the line voltage difference Vi_diff is determined as shown in Fig. 2. 4.

Here, a target value of VUF is set as $\mathrm{V_{Kmin}}$, $\mathrm{K_i(t)}$ randomly falls in its range, to make sure that VUF at node i can always be regulated, the line voltage difference needs to be regulated into the grey region in Fig. 2. 4, therefore, the minimal coefficient $\mathrm{K_{iMIN}}$ is applied. From equation (2.10), the target value of line voltage difference is $\mathrm{Vi\_diff_{MIN}}$ for VUF improvement.

$$\mathrm{V_i\_diff_{MIN} = K_{iMIN} * V_{Kmin}} \quad (2.10)$$

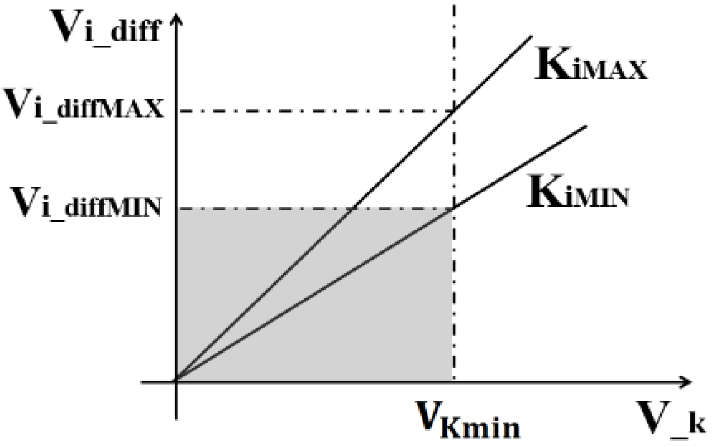


Fig. 2. 4 Image of the relation Vi_diff of and V_k

2.3.2 The trigonometric relation of phase voltage and line voltage

From Fig. 2. 4, the value of line voltage difference which should be decreased is determined. In this section, in order to determine the voltage for VUF improvement, the relationship between the order of line voltage and the order of phase voltage is discussed.

The suppression of unbalance factor is realized through the regulation of line voltage by the current output from BESS, the relation of line voltage is shown in equation (2.11).

$$\dot{V}_{ab} + \dot{V}_{bc} + \dot{V}_{ca} = 0 \quad \text{……….………………………} \quad (2.11)$$

The relation of phase voltage ($\dot{V}_a$, $\dot{V}_b$, $\dot{V}_c$) and line voltage ($\dot{V}_{ab}$, $\dot{V}_{bc}$, $\dot{V}_{ca}$) is shown in equation (2.12).

$$\begin{cases} \dot{V}_{ab} = \dot{V}_a - \dot{V}_b \\ \dot{V}_{bc} = \dot{V}_b - \dot{V}_c \\ \dot{V}_{ca} = \dot{V}_c - \dot{V}_a \end{cases} \quad \text{……………………….…………………} \quad (2.12)$$

The trigonometric relation between phase voltage and line voltage is shown in Fig. 2. 5. In the triangle composed by line voltage, the phase voltage just locates at the median of the triangle. A, B and C stand for the vertex of the triangle. O, P, and Q stand for the midpoint of each vertex's opposite side. G is the gravity center of the triangle.

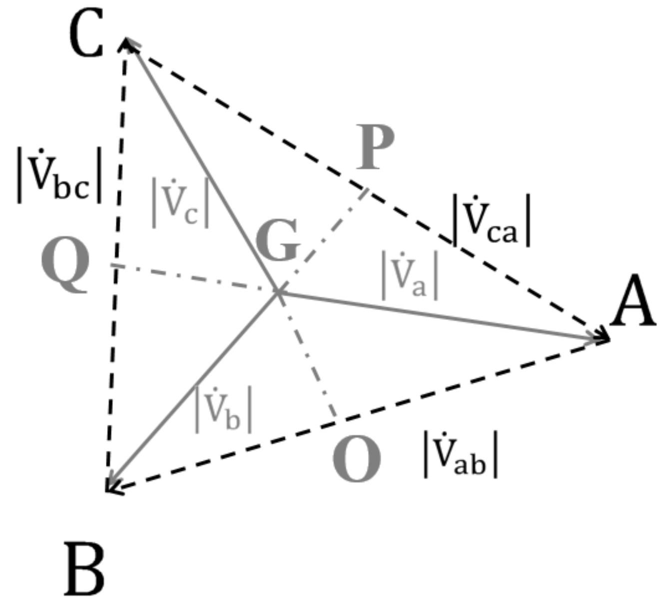


Fig. 2. 5 Image of the relation of phase and line voltage

From Apollonius theorem, the relation of triangle's sides and medians is shown in equation (2.13)

$$\begin{cases} AB^2 + CA^2 = \frac{1}{2} * BC^2 + 2 * AQ^2 \\ AB^2 + BC^2 = \frac{1}{2} * CA^2 + 2 * BP^2 \\ BC^2 + CA^2 = \frac{1}{2} * AB^2 + 2 * CO^2 \end{cases} \quad \text{…………………... (2.13)}$$

And in the triangle composed by line voltage and phase voltage, it can be seen that AB, BC, and CA stand for $|\dot{V}_{ab}|$, $|\dot{V}_{bc}|$, and $|\dot{V}_{ca}|$. And GA, GB, and GC stand for $|\dot{V}_{a}|$, $|\dot{V}_{b}|$ and $|\dot{V}_{c}|$. The relation between phase voltage and median is shown in equation (2.14).

$$\begin{cases} AQ = \frac{3}{2} * |\dot{V}_{a}| \\ BP = \frac{3}{2} * |\dot{V}_{b}| \\ CO = \frac{3}{2} * |\dot{V}_{c}| \end{cases} \quad \text{……………………………..…………... (2.14)}$$

By replacing the side and median with phase voltage and line voltage in equation (2.13), the magnitude relation of phase voltage and line voltage are shown in equation (2.15).

$$\begin{cases} |\dot{V}_{a}|^2 = \left(2 * |\dot{V}_{ab}|^2 + 2 * |\dot{V}_{ca}|^2 - |\dot{V}_{bc}|^2\right)/9 \\ |\dot{V}_{b}|^2 = \left(2 * |\dot{V}_{ab}|^2 + 2 * |\dot{V}_{bc}|^2 - |\dot{V}_{ca}|^2\right)/9 \\ |\dot{V}_{c}|^2 = \left(2 * |\dot{V}_{bc}|^2 + 2 * |\dot{V}_{ca}|^2 - |\dot{V}_{ab}|^2\right)/9 \end{cases} \quad \text{………... (2.15)}$$

Through the subtraction of phase voltage's magnitude $|\dot{V}_{a}|$, $|\dot{V}_{b}|$, and $|\dot{V}_{c}|$, the squared difference relation of phase voltage and line voltage is shown in equation (2.16)

$$\begin{cases} |\dot{V}_a|^2 - |\dot{V}_b|^2 = \left(|\dot{V}_{ca}|^2 - |\dot{V}_{bc}|^2\right)/3 \\ |\dot{V}_b|^2 - |\dot{V}_c|^2 = \left(|\dot{V}_{ab}|^2 - |\dot{V}_{ca}|^2\right)/3 \\ |\dot{V}_c|^2 - |\dot{V}_a|^2 = \left(|\dot{V}_{bc}|^2 - |\dot{V}_{ab}|^2\right)/3 \end{cases} \quad \text{(2.16)}$$

In equation (2.16), it can be seen that the order of line voltage's magnitude is got from the order of phase voltage's magnitude. Here, $|\dot{V}_a|$ is set as the maximal phase voltage as an example. In equation (2.16), the squared difference of $|\dot{V}_a|$ and $|\dot{V}_b|$ is positive and then the squared difference of $|\dot{V}_{ca}|$ and $|\dot{V}_{bc}|$ is also positive. It means that $|\dot{V}_{ca}|$ is larger than $|\dot{V}_{bc}|$. And the squared difference of $|\dot{V}_a|$ and $|\dot{V}_c|$ is negative and then the squared difference of $|\dot{V}_{bc}|$ and $|\dot{V}_{ab}|$ is also negative. It means that $|\dot{V}_{ab}|$ is larger than $|\dot{V}_{bc}|$. Therefore, the maximal phase voltage $|\dot{V}_a|$ combines with the minimal line voltage $|\dot{V}_{bc}|$. The same relation of other phases is also derived from equation (16), and the results are shown in equation (2.17) and equation (2.18).

$$\begin{cases} \text{If } \mathrm{MAX}(|\dot{V}_p|) = |\dot{V}_a| \text{ then } \mathrm{MIN}(|\dot{V}_l|) = |\dot{V}_{bc}| \\ \text{If } \mathrm{MAX}(|\dot{V}_p|) = |\dot{V}_b| \text{ then } \mathrm{MIN}(|\dot{V}_l|) = |\dot{V}_{ca}| \\ \text{If } \mathrm{MAX}(|\dot{V}_p|) = |\dot{V}_c| \text{ then } \mathrm{MIN}(|\dot{V}_l|) = |\dot{V}_{ab}| \end{cases} \quad \text{(2.17)}$$

$$\begin{cases} \text{If } \mathrm{MIN}(|\dot{V}_p|) = |\dot{V}_a| \text{ then } \mathrm{MAX}(|\dot{V}_l|) = |\dot{V}_{bc}| \\ \text{If } \mathrm{MIN}(|\dot{V}_p|) = |\dot{V}_b| \text{ then } \mathrm{MAX}(|\dot{V}_l|) = |\dot{V}_{ca}| \\ \text{If } \mathrm{MIN}(|\dot{V}_p|) = |\dot{V}_c| \text{ then } \mathrm{MAX}(|\dot{V}_l|) = |\dot{V}_{ab}| \end{cases} \quad \text{(2.18)}$$

From equation (2.17), (2.18), it can be seen that the magnitude order of line voltage is expressed as the order of phase voltage. With applying the order, the line voltage which should be regulated by BESS to realize the improvement of VUF is determined.

In the operation of BESS, the phase voltage is required. Hence, it has to decide the exact phase voltage to achieve the line voltage regulation for VUF suppression. Therefore, the relation of phase voltage, line voltage and line voltage difference is required.

In Fig. 2.5, from triangles △COB and △COA, with cosine theorem, equation (2.19) is illustrated.

$$\begin{cases} BC^2 = CO^2 + OB^2 - 2 * CO * OB * \cos\angle COB \\ CA^2 = CO^2 + OA^2 - 2 * CO * OA * \cos\angle COA \end{cases} \quad \text{(2.19)}$$

And in △ABG, with cosine theorem, equation (2.20) is illustrated.

$$AB^2 = GB^2 + GA^2 - 2 * GB * GA * \cos\angle AGB \quad \text{(2.20)}$$

Here, in the triangle, CO is 1.5 times of CG, OB is 0.5 times of AB, OA equals to OB. Substituting AB, BC, CA, GA, GB, CO, OB, and OA with its corresponding line voltage and phase voltage, equation (2.21) is derived from equation (2.19) and equation (2.22) is derived from equation (2.20).

$$\begin{cases} |\dot{V}_{bc}|^2 = \left(\frac{1}{4}\right) * (|\dot{V}_{ab}|^2 + 9 * |\dot{V}_c|^2 - 6 * |\dot{V}_{ab}| * |\dot{V}_c| * \cos\angle COB) \\ |\dot{V}_{ca}|^2 = \left(\frac{1}{4}\right) * (|\dot{V}_{ab}|^2 + 9 * |\dot{V}_c|^2 - 6 * |\dot{V}_{ab}| * |\dot{V}_c| * \cos\angle COA) \end{cases} \quad \text{(2.21)}$$

$$|\dot{V}_{ab}|^2 = |\dot{V}_a|^2 + |\dot{V}_b|^2 - 2 * |\dot{V}_a| * |\dot{V}_b| * \cos\angle AGB \quad \text{(2.22)}$$

And with the subtraction of the two equations in equation (2.21), the relation of squared difference of line voltage and phase voltage is shown in equation (2.23).

$$\left|\dot{V}_{ca}\right|^2 - \left|\dot{V}_{bc}\right|^2 = 3 * \left|\dot{V}_{ab}\right| * \left|\dot{V}_{c}\right| * \cos\angle COB \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.23)$$

In equation (2.23), the angle $\angle COB$ is fixed value, and from equation (2.22), $\left|\dot{V}_{ab}\right|$ is not changed during the variation of $\left|\dot{V}_{c}\right|$. It can be seen that the squared difference of $\left|\dot{V}_{ca}\right|$ and $\left|\dot{V}_{bc}\right|$ has a proportional relation with $\left|\dot{V}_{c}\right|$. In $\triangle$APB and $\triangle$CPB, and $\triangle$CQA and $\triangle$BQA, the same relation is shown in equation (2.24) and (2.25).

$$\begin{cases} \left|\dot{V}_{bc}\right|^2 = \left(\frac{1}{4}\right) * (\left|\dot{V}_{ca}\right|^2 + 9 * \left|\dot{V}_{b}\right|^2 - 6 * \left|\dot{V}_{ca}\right| * \left|\dot{V}_{b}\right| * \cos\angle CPB) \\ \left|\dot{V}_{ab}\right|^2 = \left(\frac{1}{4}\right) * (\left|\dot{V}_{ca}\right|^2 + 9 * \left|\dot{V}_{b}\right|^2 - 6 * \left|\dot{V}_{ca}\right| * \left|\dot{V}_{b}\right| * \cos\angle APB) \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.24)$$

$$\begin{cases} \left|\dot{V}_{ca}\right|^2 = \left(\frac{1}{4}\right) * (\left|\dot{V}_{bc}\right|^2 + 9 * \left|\dot{V}_{a}\right|^2 - 6 * \left|\dot{V}_{bc}\right| * \left|\dot{V}_{a}\right| * \cos\angle CQA) \\ \left|\dot{V}_{ab}\right|^2 = \left(\frac{1}{4}\right) * (\left|\dot{V}_{bc}\right|^2 + 9 * \left|\dot{V}_{a}\right|^2 - 6 * \left|\dot{V}_{bc}\right| * \left|\dot{V}_{a}\right| * \cos\angle BQA) \end{cases} \ldots\ldots (2.25)$$

Where $\angle COB + \angle COA = \pi, \angle CQA + \angle AQB = \pi,$

$\angle CPB + \angle APB = \pi.$

And in $\triangle$BCG and $\triangle$CAG, equation (2.26) and (2.27) is got.

$$\left|\dot{V}_{bc}\right|^2 = \left|\dot{V}_{b}\right|^2 + \left|\dot{V}_{c}\right|^2 - 2 * \left|\dot{V}_{b}\right| * \left|\dot{V}_{c}\right| * \cos\angle BGC \ldots\ldots\ldots\ldots (2.26)$$

$$\left|\dot{V}_{ca}\right|^2 = \left|\dot{V}_{c}\right|^2 + \left|\dot{V}_{a}\right|^2 - 2 * \left|\dot{V}_{c}\right| * \left|\dot{V}_{a}\right| * \cos\angle CGA \ldots\ldots\ldots\ldots (2.27)$$

According to equation (2.21), (2.24) and (2.25), the squared difference of line voltage is calculated shown in equation (2.28).

$$\begin{cases} \left|\dot{V}_{ca}\right|^2 - \left|\dot{V}_{bc}\right|^2 = 3 * \left|\dot{V}_{ab}\right| * \left|\dot{V}_{c}\right| * \cos\angle COB \\ \left|\dot{V}_{ab}\right|^2 - \left|\dot{V}_{bc}\right|^2 = 3 * \left|\dot{V}_{ca}\right| * \left|\dot{V}_{b}\right| * \cos\angle CPB \\ \left|\dot{V}_{ab}\right|^2 - \left|\dot{V}_{ca}\right|^2 = 3 * \left|\dot{V}_{bc}\right| * \left|\dot{V}_{a}\right| * \cos\angle CQA \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots (2.28)$$

In equation (2.28), $\angle COB$, $\angle CQA$ and $\angle CPB$ are set as accurate angle.

2.3.3 VUF improvement by phase voltage

From the measured phase voltage at the point of BESS, the order of phase voltage is got. And in equation (2.17) and (2.18), the order of line voltage is derived from the order of phase voltage. Fig. 2.6 shows the image of the relation between phase voltage and line voltage. Because phase voltage at the connection point of BESS is always measured, taking $\left|\dot{V}_{a}\right| > \left|\dot{V}_{b}\right| > \left|\dot{V}_{c}\right|$ in the left of Fig. 2.6 as an example, then the order of line voltage is got as the right of Fig. 2.6 shows. And in this way, the line voltage with maximal difference needed be regulated for VUF suppression is decided.

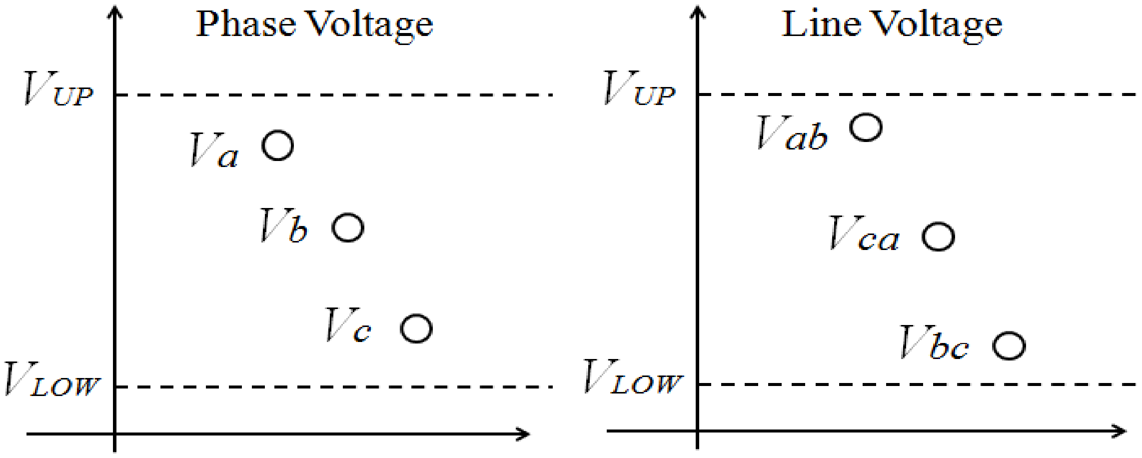


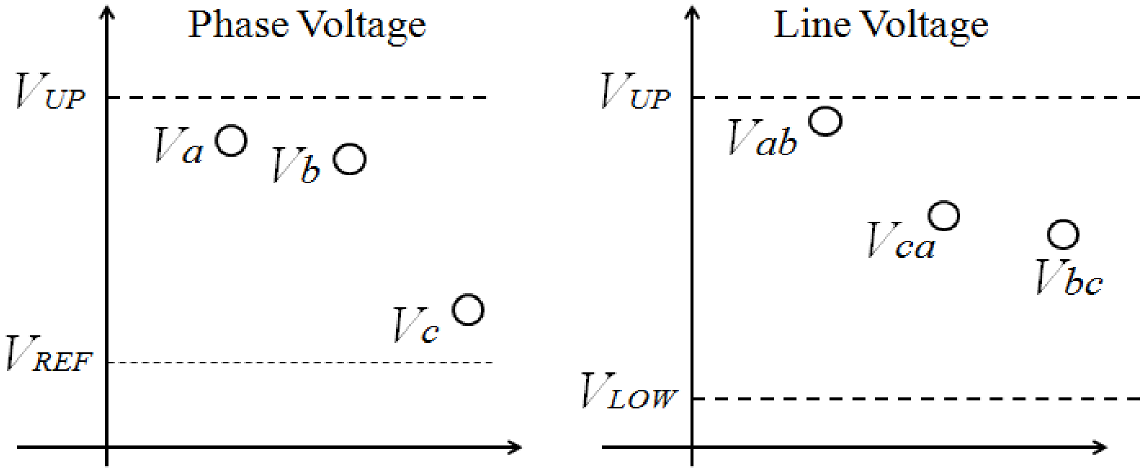
Fig. 2.6 Image of the order relation between phase voltage and line voltage

In VUF suppression, the main objective is that all phase voltages are moved closer to the reference voltage. And in the management, there are three cases as shown in Table 2.1. $|\dot{V}_P|$ is the magnitude of phase voltage, and V_R is the reference voltage of phase voltage.

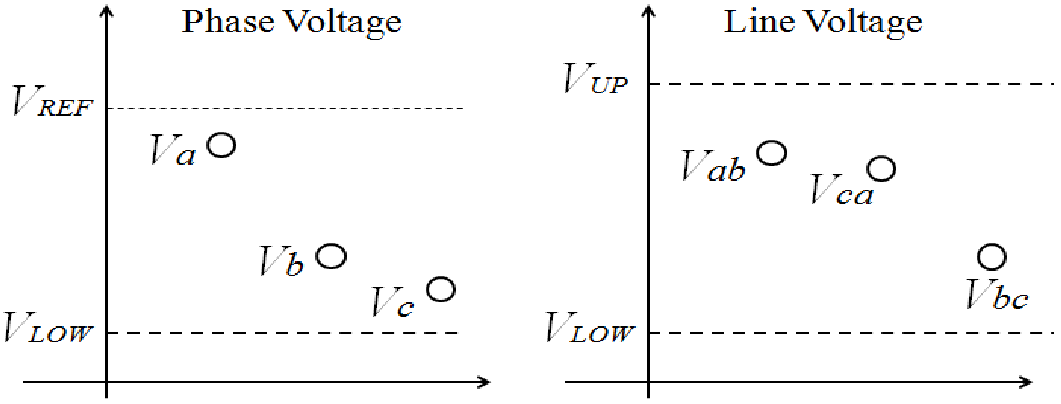
Table 2.1 phase voltage's distribution case

Case 1	$\mathrm{MIN}(\lvert\dot{V}_P\rvert) > V_R$
Case 2	$\mathrm{MAX}(\lvert\dot{V}_P\rvert) < V_R$
Case 3	$\mathrm{MAX}(\lvert\dot{V}_P\rvert) > V_R$; $\mathrm{MIN}(\lvert\dot{V}_P\rvert) < V_R$

Case 1 is that all of the phase voltage are larger than the rated voltage. Case 2 is that all of the phase voltage are smaller than the rated voltage. Case 3 is that the maximal phase voltage is larger than the rated voltage, and the minimal voltage is smaller than the rated voltage.



(a) Case 1



(b) Case 2

Fig. 2.7 Image of VUF control of Case 1 and Case 2

[Case 1]

In Fig. 2.7 (a), the image of case 1 is illustrated. According to equation (2.10), the target difference of line voltage Vi_diff is calculated. In case of Fig. 2.7 (a), the difference of $|\dot{V}_{ab}|$ and $|\dot{V}_{bc}|$ should be decreased to realize VUF improvement. In equation (2.22) and (2.26), the decreasing $|\dot{V}_b|$ causes the decreasing of $|\dot{V}_{ab}|$ and $|\dot{V}_{bc}|$, and also the decreasing of line voltage difference in equation (2.28). However, $|\dot{V}_{bc}|$is the minimal line voltage, to avoid over decreasing, instead of $|\dot{V}_b|$, $|\dot{V}_a|$ is decreased to achieve the reduction of line voltage difference. The decreasing of $|\dot{V}_a|$ causes the decreasing of $|\dot{V}_{ab}|$ and the line voltage difference. And also the reduction speed of line voltage difference is faster with the regulation of $|\dot{V}_a|$.

The updated line voltage of $|\dot{V}_{ab}|'$is calculated in equation (2.29) and, and the updated phase voltage is calculated in equation (2.30). The updated $|\dot{V}_{ca}|'$ is calculated in equation. (2.31).

$$|\dot{V}_{ab}|' = |\dot{V}_{bc}| + \text{Vi\_diff} \ldots\ldots \tag{2.29}$$

$$|\dot{V}_{ab}|' = |\dot{V}_a{}' - \dot{V}_b| \ldots\ldots \tag{2.30}$$

$$|\dot{V}_{ca}|' = |\dot{V}_c - \dot{V}_a{}'| \ldots\ldots \tag{2.31}$$

After the regulation of $|\dot{V}_a|$, if VUF is still larger than its target value, it means the difference of $|\dot{V}_{ab}|$ and $|\dot{V}_{ca}|$ is larger than its target value V_i_diff as Fig. 2.8 shows. Therefore, a further regulation is needed.

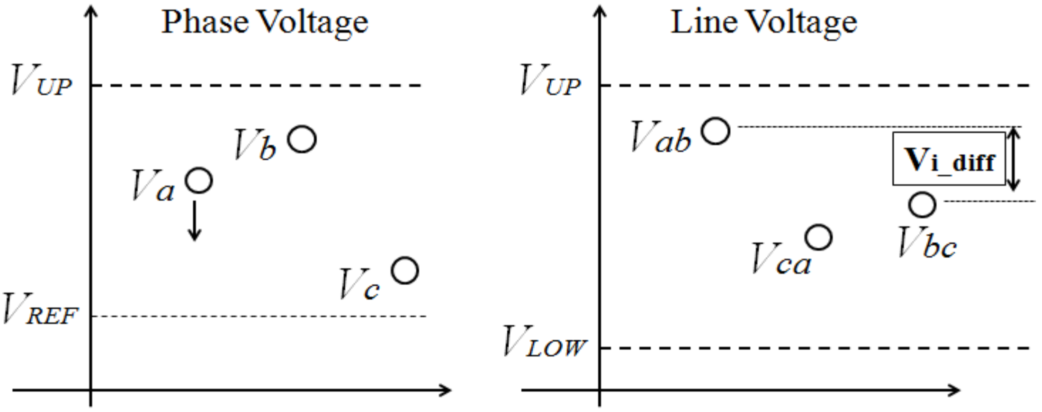


Fig. 2.8. Regulation in case 1

The same with the first step of regulation, $|\dot{V}_b|$ is here for the further regulated and line voltage $|\dot{V}_{ab}|''$ and updated phase voltage are calculated in equation (2.32) and (2.33). In this way, the VUF is improved with the output of BESS.

$$|\dot{V}_{ab}|'' = |\dot{V}_{ca}|' + \mathrm{Vi\_diff} \tag{2.32}$$

$$|\dot{V}_{ab}|'' = |\dot{V}_a{}' - \dot{V}_b{}'| \tag{2.33}$$

[Case 2]

In Fig. 2.7 (b), the example of case 2 is given. In Case 2, all of the phase voltage are smaller than reference voltage. To decrease the difference of $|\dot{V}_{ab}|$ and $|\dot{V}_{bc}|$, $|\dot{V}_c|$ is chosen for fast regulation speed and getting close to reference voltage, the updated voltage is calculated in equation (2.34) and (2.35).

$$|\dot{V}_{bc}|' = |\dot{V}_{ab}| - \mathrm{Vi\_diff} \tag{2.34}$$

$$|\dot{V}_{bc}|' = |\dot{V}_b - \dot{V}_c{}'| \tag{2.35}$$

And also the updated $|\dot{V}_{ca}|'$ is got.

However, in equation (2.28), the increasing of $|\dot{V}_c|$ leads to the increasing of the difference between $|\dot{V}_{ca}|$ and $|\dot{V}_{bc}|$ as Fig. 2.9 shows.

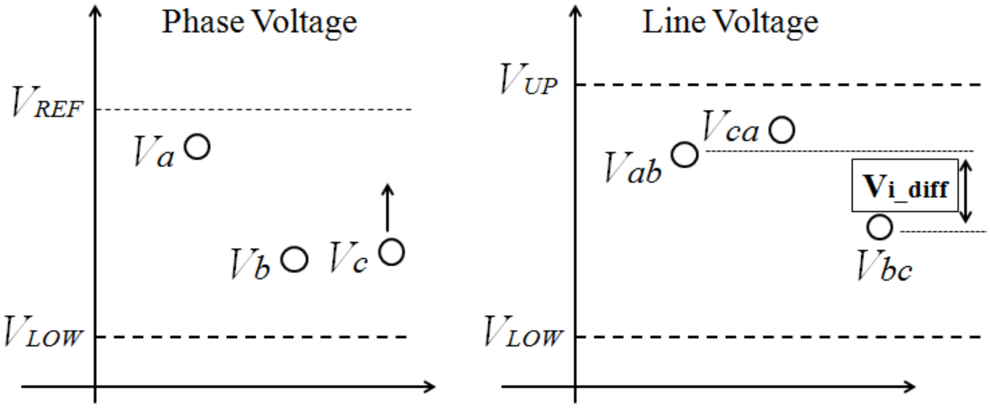


Fig. 2.9 Regulation in case 2

If the situation in Fig. 2.9 happens, during the suppression of the difference of $|\dot{V}_{ab}|$ and $|\dot{V}_{bc}|$ to Vi_diff, to avoid unnecessary increasing and decreasing of phase voltage, a constraint is set in equation (2.36). In equation (2.36), the updated $|\dot{V}_c|$ is calculated under the constraint. Then, to reach target value Vi_diff to achieve VUF improvement, $|\dot{V}_a|$ is decreased and calculated in equation (2.37) and (2.38).

$$\text{if } |\dot{V}_{ca}|' > |\dot{V}_{ab}| \text{ then } |\dot{V}_{ca}|' = |\dot{V}_{ab}| \tag{2.36}$$

$$|\dot{V}_{ab}|' = |\dot{V}_{bc}|' + \mathrm{Vi\_diff} \tag{2.37}$$

$$|\dot{V}_{ab}|' = |\dot{V}_a{}' - \dot{V}_b| \tag{2.38}$$

[Case 3]

Case 3 is that phase voltage distributes on both sides of reference voltage. There are two modes in Case 3, that is, the middle phase voltage is over the reference voltage V_R and the middle phase voltage is below V_{REF} as Fig. 2.10 shows. To realize the line voltage difference decreasing for VUF improvement, the maximal and the minimal phase voltage are moved to be close to V_{REF}.

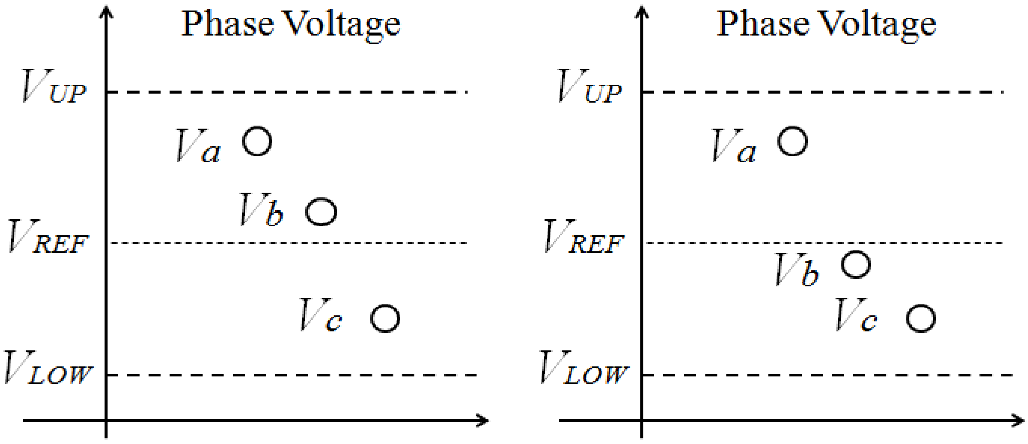


Fig. 2.10 Image of Case 3's VUF control

The management of phase voltage's magnitude obeys the proportion of distance between reference voltage and each phase voltage. For example, during the regulation of $|\dot{V}_a|$ and $|\dot{V}_c|$ to decrease the difference between $|\dot{V}_{ab}|$ and $|\dot{V}_{bc}|$, $|\dot{V}_{ab}|$ is decreased and $|\dot{V}_{bc}|$ is increased, and the difference ΔV between $|\dot{V}_{ab}|$ and $|\dot{V}_{bc}|$ is decreased. The change of line voltage's difference ΔV_diff is shown in equation (2.39).

$$\Delta V\_diff = \Delta V - Vi\_diff \quad (2.39)$$

The regulated value of $|\dot{V}_a|$ and $|\dot{V}_c|$ is according to equation (2.40) with application of weight coefficient m. The phase voltage which has further distance to the reference voltage is with a larger change.

$$\begin{cases} m = (MAX(|\dot{V}_P|) - V_{REF})/(V_{REF} - MIN(|\dot{V}_P|)) \\ \Delta|\dot{V}_{bc}| = \frac{m}{m+1} * \Delta V \\ \Delta|\dot{V}_{ab}| = \frac{1}{m+1} * \Delta V \end{cases} \quad (2.40)$$

The updated line voltages are shown in equation (2.41) and (2.42).

$$|\dot{V}_{ab}|' = |\dot{V}_{ab}| - \Delta|\dot{V}_{ab}| \quad (2.41)$$

$$|\dot{V}_{bc}|' = |\dot{V}_{bc}| - \Delta|\dot{V}_{bc}| \quad (2.42)$$

The left side in Fig. 2.10 of case 3 is similar with Case1, and the right side is similar with Case 2.

During the decreasing of line voltage difference to achieve VUF improvement, the updated phase voltage $\dot{V}_a{}'$, $\dot{V}_b{}'$, and $\dot{V}_c{}'$ are determined. Therefore, the output current of BESS $\dot{I}_{Ba}$, $\dot{I}_{Bb}$, and $\dot{I}_{Bc}$ are calculated by equation (2.43).

$$\begin{cases} \dot{I}_{Ba} = (\dot{V}_a{}' - \dot{V}_a)/\sum_1^i Z_k \\ \dot{I}_{Bb} = (\dot{V}_b{}' - \dot{V}_b)/\sum_1^i Z_k \\ \dot{I}_{Bc} = (\dot{V}_c{}' - \dot{V}_c)/\sum_1^i Z_k \end{cases} \quad (2.43)$$

Fig. 2.11 shows the control flow chart of VUF control with SC and BESS. $V_{\_kMAX}$ is the constraint of VUF. After the regulation of SC, BESS gives an immediate output to regulate the difference of the line voltage.

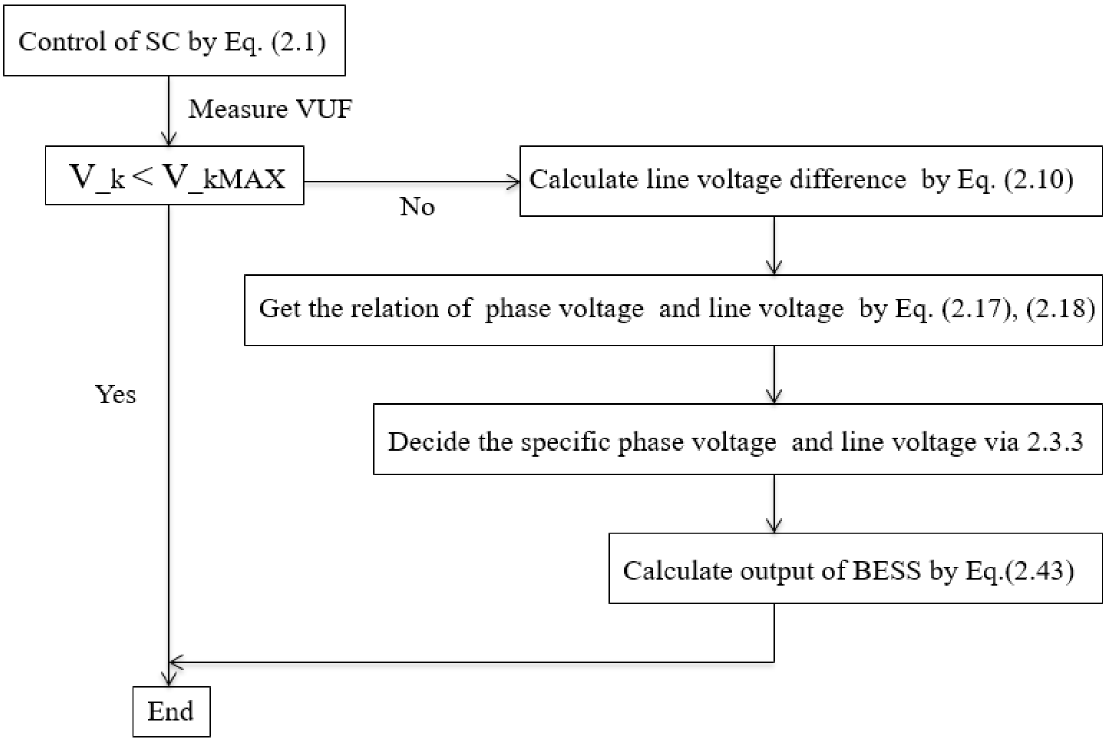


Fig. 2.11. Control flow chart

2.4 Case study

2.4.1 Distribution system model

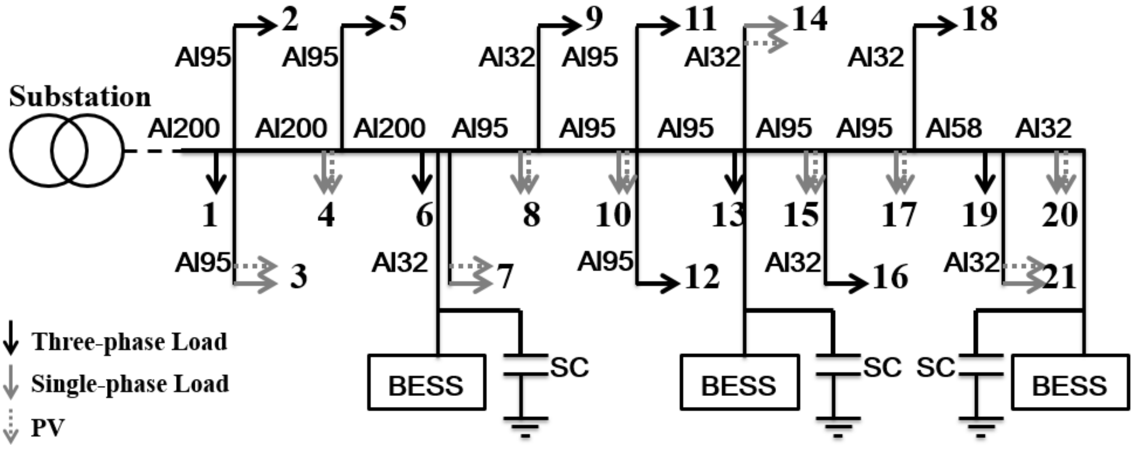


Fig. 2.12. Model of distribution system with PV connected

Fig. 2.12 shows a detailed model of distribution system which has 21 loads with PV. The black arrows stand for three-phase loads that are office, store and school. The green arrows stand for single-phase loads that are residential load. PVs are connected at the same placement of single-phase loads.

With this model, two cases of BESS's placement are studied. One is connecting one BESS at the end of distribution line where has the most severe unbalanced voltage and voltage deviation, and another case is that BESSs distribute in distribution line. In considering of the load consumption and PV's output, three of BESS are connected at node 6, 13 and 21. The parameters of the simulation model are shown in Table 2.2. Table 2.3 gives the connection of single-phase load.

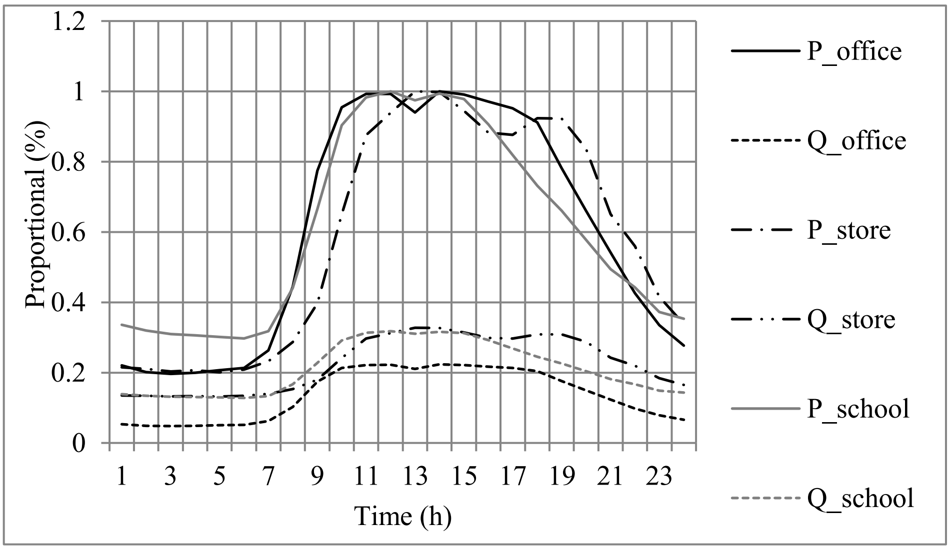
Table 2.2. Distribution line's data.

Impedance of distribution line	$\text{Al32}: 0.899 + j0.389\Omega/\text{km}$ $\text{Al58}: 0.497 + j0.331\Omega/\text{km}$ $\text{Al95}: 0.301 + j0.315\Omega/\text{km}$ $\text{Al200}: 0.182 + j0.288\Omega/\text{km}$
Total length of the line	3.09km

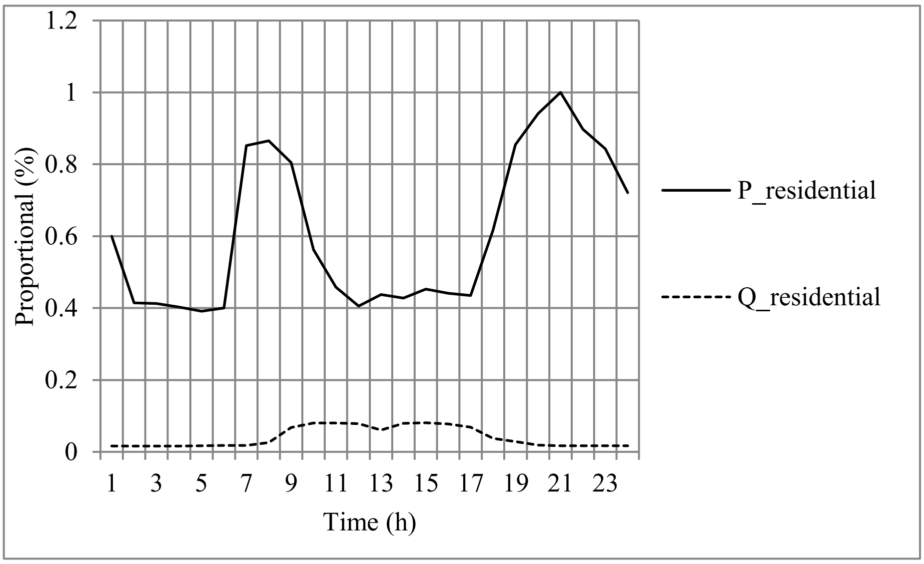
Table 2.3 Connection of single-phase load.

Connection phase	Load No.
a-b	3, 8, 15, 21
b-c	4, 10, 17, 20
c-a	7, 14

The pattern of loads is illustrated in Fig. 2.13. Fig. 2.13 (a) shows the load pattern of three-phase load which consumption is 104kW of each one, and it gives the proportional consumption of the load compared to the maximum consumption through a conversion, and load operation rate is set to be 60%. Fig. 2.13 (b) shows the single-phase load with the consumption ranges from 90kW to 504 kW, and load operation rate is set to be 70%.



(a) Three-phase load



(b) Single-phase load

Fig. 2.13. Load pattern

Fig. 2.14 shows PV output at sunny day, and the output range is from 81kW to 453.6kW which is 90% of the maximum single-phase load consumption.

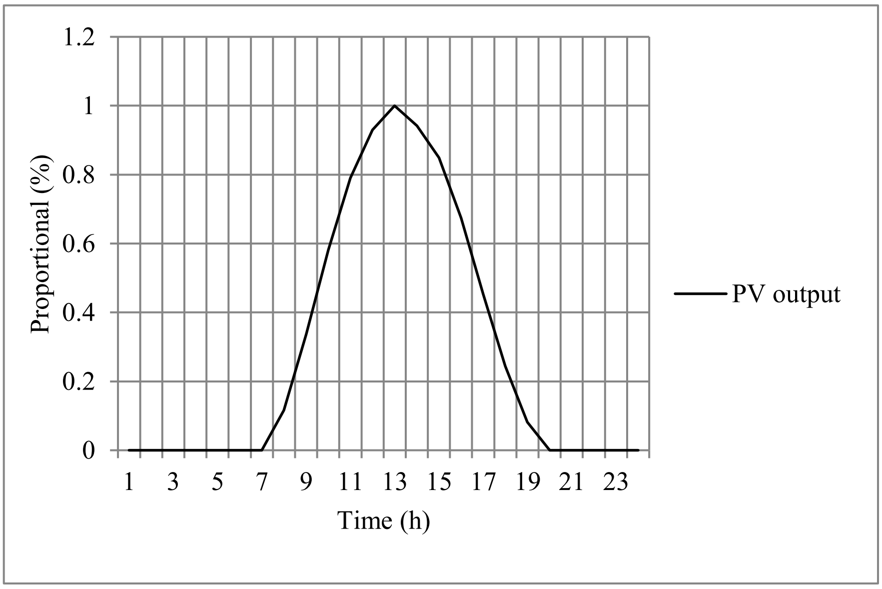


Fig. 2.14. PV pattern

The time step of the simulation is 1 min. The adequate range of voltage is from 101 to 107 with a conversion to low voltage side using voltage ratio (= 6600/105). The upper limit of VUF is set to 1%. In Table 2.4, the simulation conditions are illustrated. And the simulation cases are shown in Table 2.5.

Table 2.4. Simulation conditions.

Simulation time	24hours
Simulation interval	1.0min
Adequate range's V_{MAX}	107V (up voltage)
Adequate range's V_{MIN}	101V (low voltage)
Constraint of VUF	1%
Ratio of voltage	6600/105
Sending voltage of substation	6600V

Case 1 is the original distribution system without BESS and SC, it is taken as a reference of control with BESS and SC. Case 2 set one BESS at the end of distribution line. Case 3 is set one BESS at the end of the distribution line without the connection of SC. Case 4 discusses the control of BESS with proposed placement.

Table 2.5 Simulation cases.

Case 1	No BESS and SC
Case 2	One BESS at the end of distribution line (node 21) with/without SC set at proposed placement
Case 3	One BESS at the end of distribution and no SC
Case 4	Proposed placement with BESS and SC (node 6, 13 and 21)

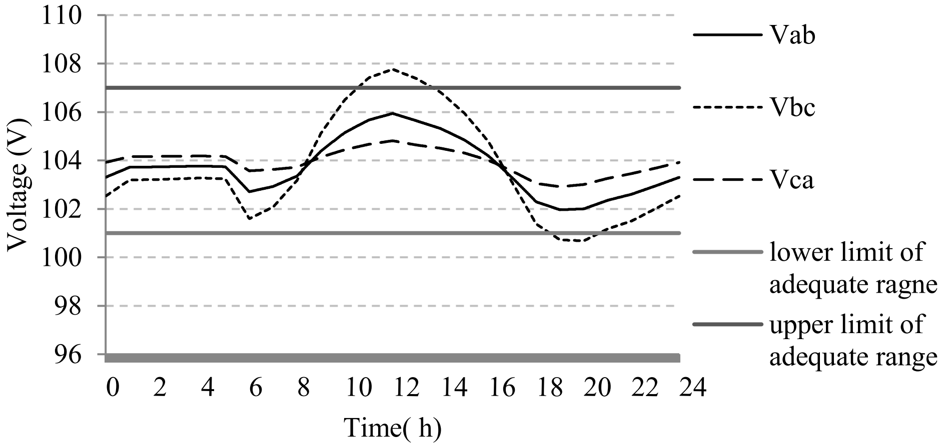
In case 2 and 4, the constraint of VUF for different node in the distribution line is set with a ratio method. The VUF's constraint of the node connected with BESS and SC is shown in Table 2.6.

Table 2.6. Constraint of VUF

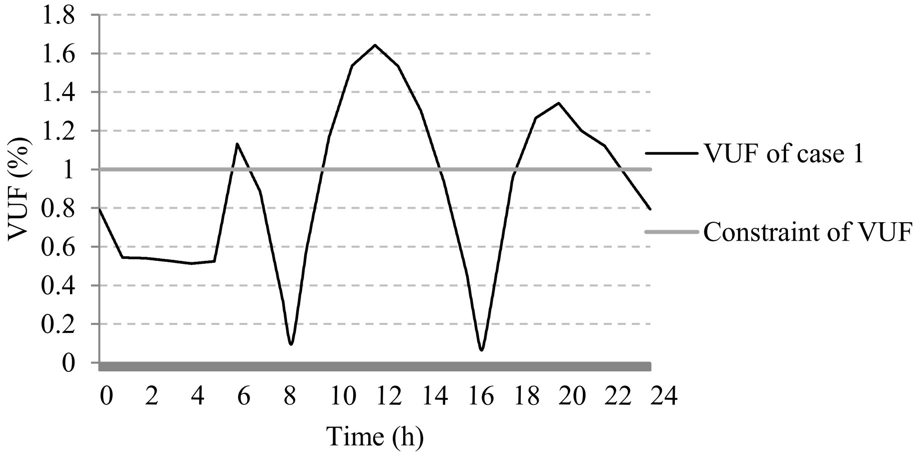
	Node 6	Node 13	Node 21
Maximal VUF	0.897%	1.280%	1.643%
Constraint of VUF	0.546%	0.779%	1.000%

2.4.2 Simulation results

The line voltage and VUF at the end of the distribution line in Case 1 is shown in Fig. 2.15. In this case, it takes the severe node (node 21) of system as a reference of the control of BESS and SC. From Fig. 2.15, it can be seen that the maximal VUF in one day is over 1.6%, and the voltage of phase bc deviates from the adequate range.



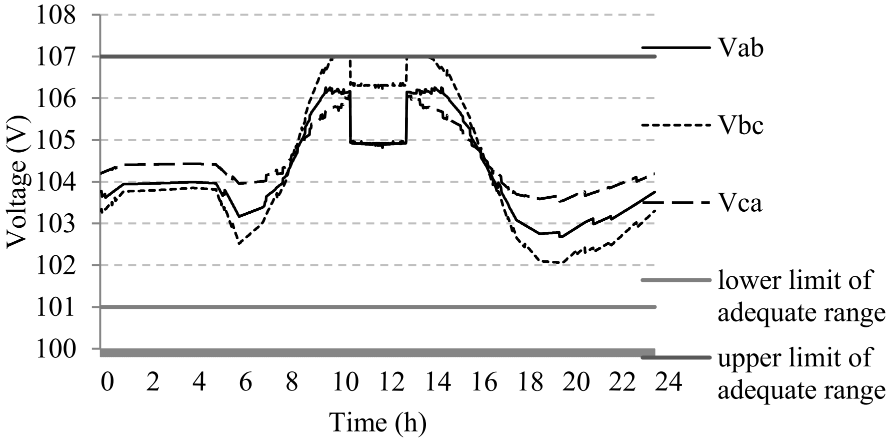
(a) Line voltage at node 21.



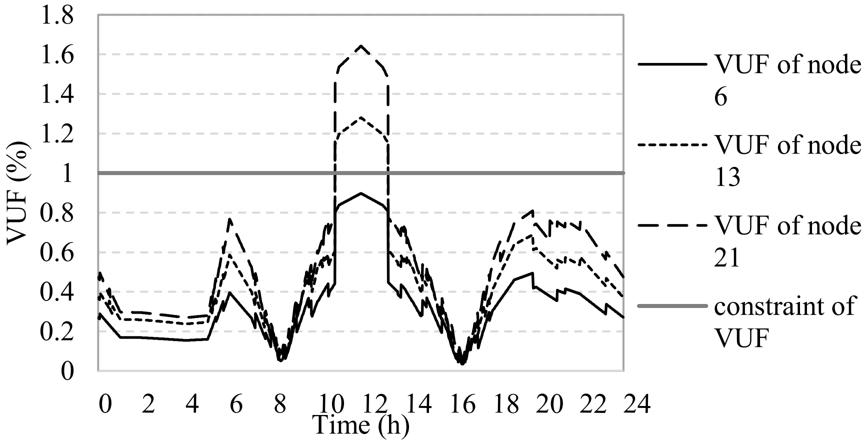
(b) VUF at node 21

Fig. 2.15. Line voltage and VUF of case 1

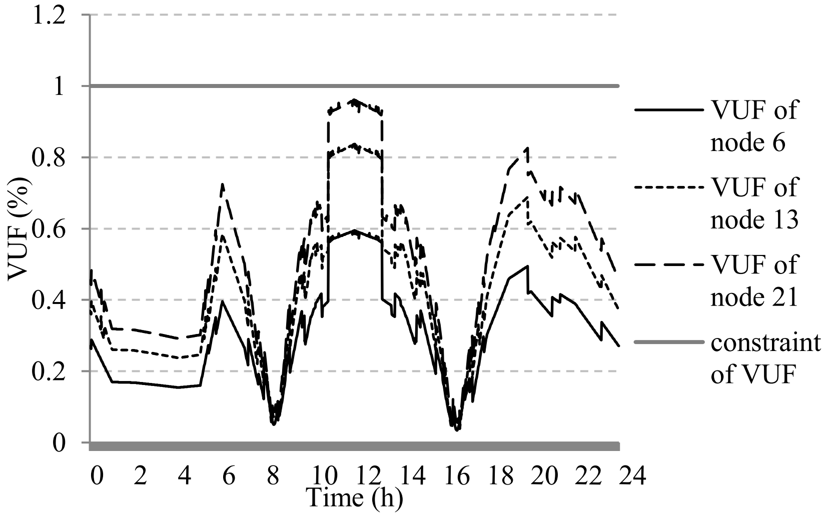
Fig. 2.16 shows the voltage and VUF in case of Case 2. SC at the proposed placement gives a voltage rising to reduce the VUF, and when the voltage deviates from the adequate range, SC stops to give a reactive power support to avoid voltage's over raise during the peak period. And a further regulation based on the support of SC is given by BESS. With the output of BESS, the voltage is controlled in adequate band. The improvement of VUF with proposed method is shown in Fig. 2.16 (b). in Fig. 2.16 (b1), VUF is regulated only with SC, the over suppression of VUF by SC appears in the morning and evening. Because SC operates with the feature of step change in its output variation. Accurate control by SC is impossible. And in mid-day, with the output of PV, the suppression of VUF by SC fails because SC can only provide leading reactive power. VUF is successfully control under the constraint with the cooperation of BESS and SC in Fig. 2.16 (b2). The largest VUF value is about 0.9% that is a little smaller than 1% because to make sure that all the day's VUF is manageable; the minimal weight coefficient of VUF is selected.



(a) Line voltage at node 21



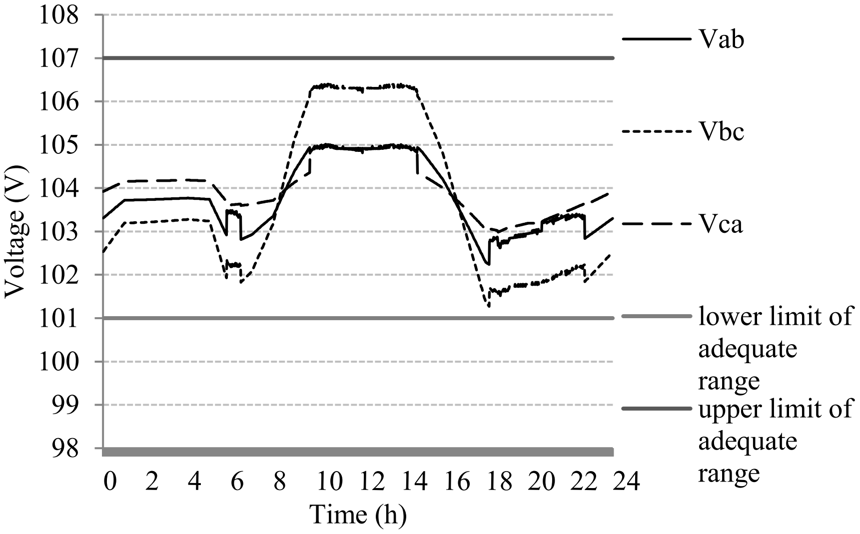
(b1) VUF of case 2 only with SC



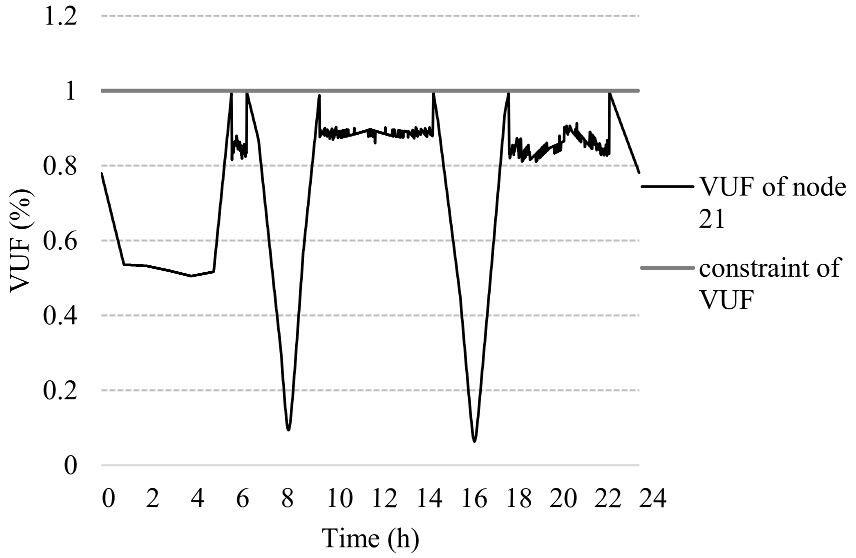
(b2) VUF of case 2

Fig. 2.16. Line voltage and VUF of case 2

In case 3, just one BESS is set at the distribution line to manage the voltage and VUF. The result is shown in Fig. 2.17. In Fig. 2.17 (a), the line voltage is well controlled, and the voltage is converted into low voltage side with voltage ratio 6600/105. And in Fig. 2.17 (b), the VUF is well suppressed under the constraint of it.



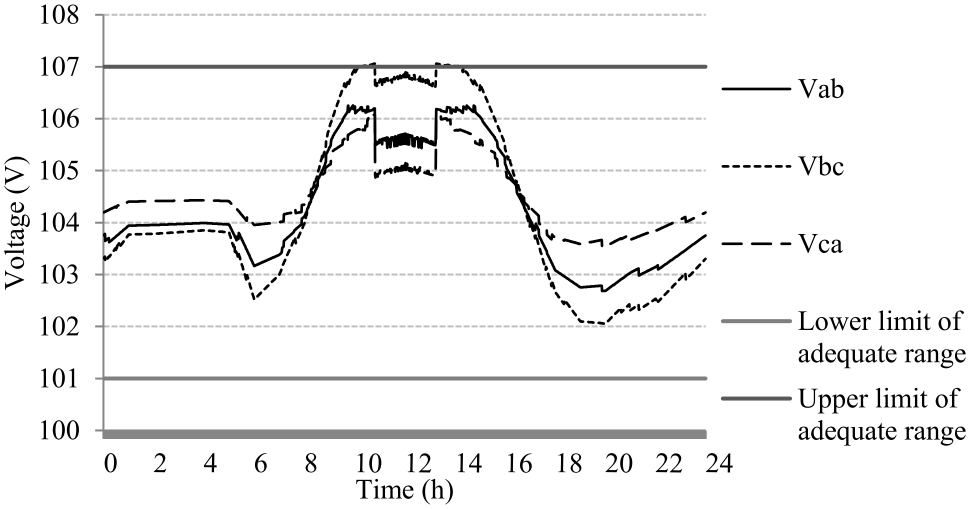
(a) Line voltage at node 21



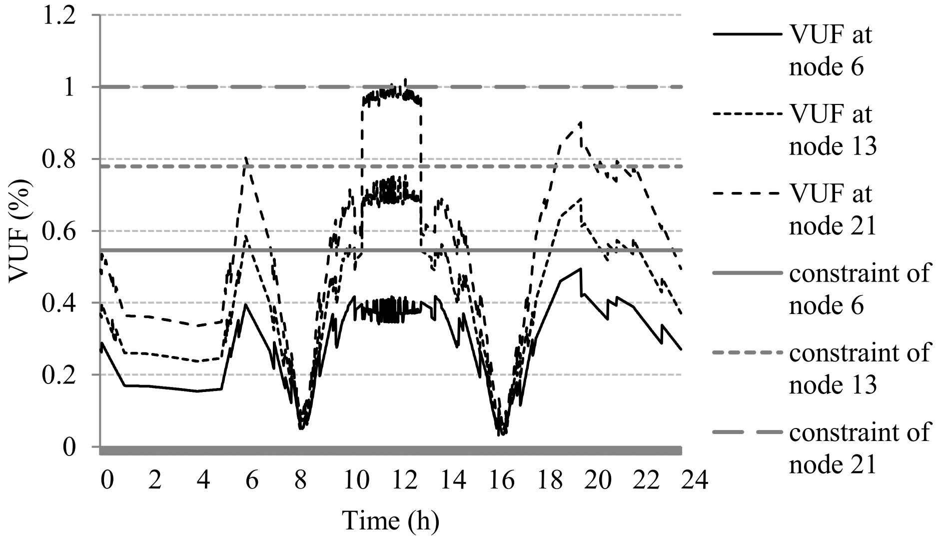
(b) VUF at node 21

Fig. 2.17. Line voltage and VUF of case 3

In case 4, BESS and SC are both applied in the voltage and VUF control, and from the result in Fig. 2.18(a), the phase voltage is suppressed, and in Fig. 2.18 (b), the VUF is well controlled according to its constraint of VUF in Table 2.6. Constraint of VUF.



(a) Line voltage at node and 21



(b) VUF at node 6, 13 and 21

Fig. 2.18 Line voltage and VUF of case 4

Above all the four cases, the proposed method of BESS has a better control of VUF that is shown in Fig. 2.16(b), Fig. 2.17 (b) and Fig. 2.18 (b). The VUF control with discussed placement in case 4 has more accurate VUF suppression along the distribution line than case 2. In case 4, the voltage rising via SC is shown in Fig. 2.18 (a) compared with Fig. 2.17 (a) in case 3, and both two cases has a well control of voltage. The capacity of BESS taking SOC from 20% to 80% is illustrated in Table 2.7.

Table 2.7 Capacity of BESS

Case No.	Capacity (kWh)
1	NO
2	432.719
3	579.355
4	257.812

In Table 2.7, from the capacity of four cases, it can be seen that, with the support of SC, the capacity of BESS is largely reduced in case 2 comparing with case 3. And comparing case 2 and case 4, the capacity of case 4 with 3 BESS is smaller than that of case 2 with just one BESS. Both two cases have a well control of voltage. Case 4 has a highlight that is realize the management with a smaller capacity and VUF improvement has a more specific, accurate and well control than case 2.

All over the simulation, the control with proposed method considering the placement of BESS and SC has a more accurate, fast regulation, and the most important is the small capacity of BESS comparing with the load consumption.

2.5 Discussion and summary

In this section, to promote the application of BESS, SC is used to give a reactive output to support BESS for its cheap cost, and the trend of VUF and power loss with its output; in voltage and VUF control, the method of VUF improvement through voltage control with BESS is proposed to realize a relatively specific and simple regulation of certain phase voltage's magnitude in distribution system. And the method is verified by MATLAB.

While in this paper, the construction of distribution system is set to keep in stable mode, in real system, changes of distribution system always exist. Therefore, a more accurate control method is needed to be discussed. With the discussion of the placement of BESS, the owner of BESS may change to the consumer with the widely application of BESS. The SOC management is also important in BESS's application that is needed to be managed. VUF and voltage control are discussed in this paper, with improvement of voltage quality, the reduction of power loss in distribution line is also needed to be discussed in future study.

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Chapter 3

ICD (Initiative Charge/Discharge) of BESS group in voltage and VUF suppression of PV connected distribution system

3.1 Introduction

In prior study, with the growth of PV in distribution system, established devices like SVR and LRT is insufficient in dealing with complex voltage profile. Though a lot of novel method is proposed to achieve the effective utilization of these tap-change devices, the mechanical feature limits their presentation in voltage management. BESS is used in distribution system to give the excellent control of variable voltage caused by PV. Comparing with other PCS attached devices, BESS has the unique feature to store the energy and reuse it. It increases the utilization of power and gives the chance for power trading in promoting the power retail business in future smart-grid. From this view, the study on BESS application is very meaningful. With the development of BESS, the number of BESS connected in distribution system is changing from single one to multiple BESS that compose BESS group (BG). The control method for each BESS in BG is directly related with the control ability, and proper control method for effective utilization of BG is the issue to solve.

The inevitable constraint in BESS application is capacity and State of Charge (SOC). Because they directly connected with the cost. In previous study of BESS, the control of single BESS in distribution system is discussed a lot. However, little of them discuss the management of SOC variation of BESS. And the capacity is set to meet their control objective without discussion of capacity reduction. In [1], the application of BESS deals with the PV prediction error to average the load consumption. However, comparing to load consumption, the capacity of BESS is relatively large to achieve the constraint of SOC and it leads to the increasing of cost. [2] discusses the effect of location of BESS in voltage control. The verification of separate output of reactive and active power of BESS is limited by the parameter in the simulation model. Comparing to single BESS control, the previous study of BG hasn't been done a lot considering the high cost of widespread application of BESS. Therefore, mainly two control method are used. One is distributed control, and the other is centralized control. [3] discussed the distributed control of BESS group in voltage stabilization. [4] proposed centralized control of small scale BESS with simultaneous control of BG. [5] does propose the average output strategy of BG, however, SOC hasn't been mentioned. Besides BG, energy storage devices like HEMS and EV in distribution system is also a choice to compose BG in voltage management in future smart-grid, therefore, the proper method of BG is urgent to be discussed. This chapter focuses on the management of BG.

The proposed control strategy realizes the reduction of BESS capacity and effective utilization of available capacity.

3.2 Issue in BG application

In this chapter, the management of BG in voltage control is proposed. From the aspect of cost, the capacity of BESS is wanted to be as small as possible. For the proper application of each BESS, the constraint of capacity and SOC is essential elements. And from the view of BG, the cooperation in BG is the issue to achieve effective utilization. This section introduces the issue of BG from three points. The simple model of BG in distribution system is shown in Fig. 3. 1. For simplicity, two BESSs compose the BG as Fig. 3. 1 shows.

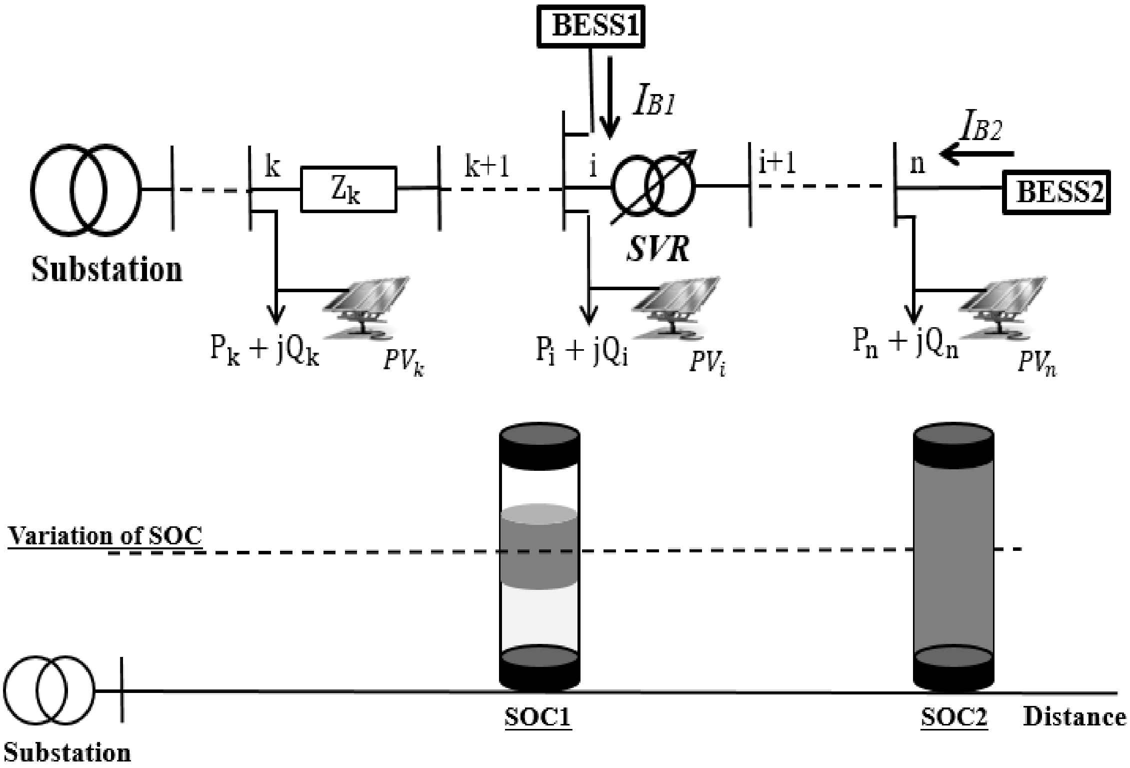

Fig. 3. 1 Simple model of BESS in distribution system

[Issue 1: Location]

During the application of BESS, a significant feature is BESS output variation along with the distribution line. In Fig. 3. 1, because in radial distribution system, the severe voltage violation appears at the end of distribution line, BESS output amount increases along with the increasing of the distance from substation side. On consideration of dispersal BESS in BG, for the same regulation amount of voltage, minimal output of BESS is wanted. The effect of location on BESS output is discussed in section 3.3.1.

[Issue 2: Capacity]

In radial distribution system, normally, the longer the distance from substation side is, the larger the capacity of BESS is. With the different capacity and output, the variation amount of SOC is different as the grey part in Fig. 3. 1 shows. The exist centralized control of BG is with simultaneous control and average output control as [5] illustrated. It can't balance the SOC of BESS in BG. The unbalanced SOC leads to overcharge/discharge of certain BESS as SOC2 shows and ineffective utilization of BESS with the unused available capacity as shown in SOC1. In section 3.3.2, cooperation in BG is proposed to balance SOC and make full use of available capacity of BESS in BG.

[Issue 3: SOC]

In BESS, battery is the important element. To prolong the cycle life of battery, SOC is the index with proper limit to prevent battery from overcharge/discharge. Fig. 3. 2 gives the image of SOC variation of BESS in voltage control. There are three states of BESS: charge, discharge and non-operation. When voltage surpasses its upper bond, BESS starts charging and SOC is increasing. When voltage surpasses its lower bond, BESS starts discharging and SOC is decreasing. Non-operation period appears when SOC reaches its limit or no voltage violation happens. On consideration of BESS capacity, charge or discharge period compared with non-operation period is very short because charge/discharge of BESS is always passive. To reduce the non-operation period for high utilization as well as low consumption of BESS, Initiative Charge/ Discharge (ICD) of BESS is proposed in section 3.3.3.

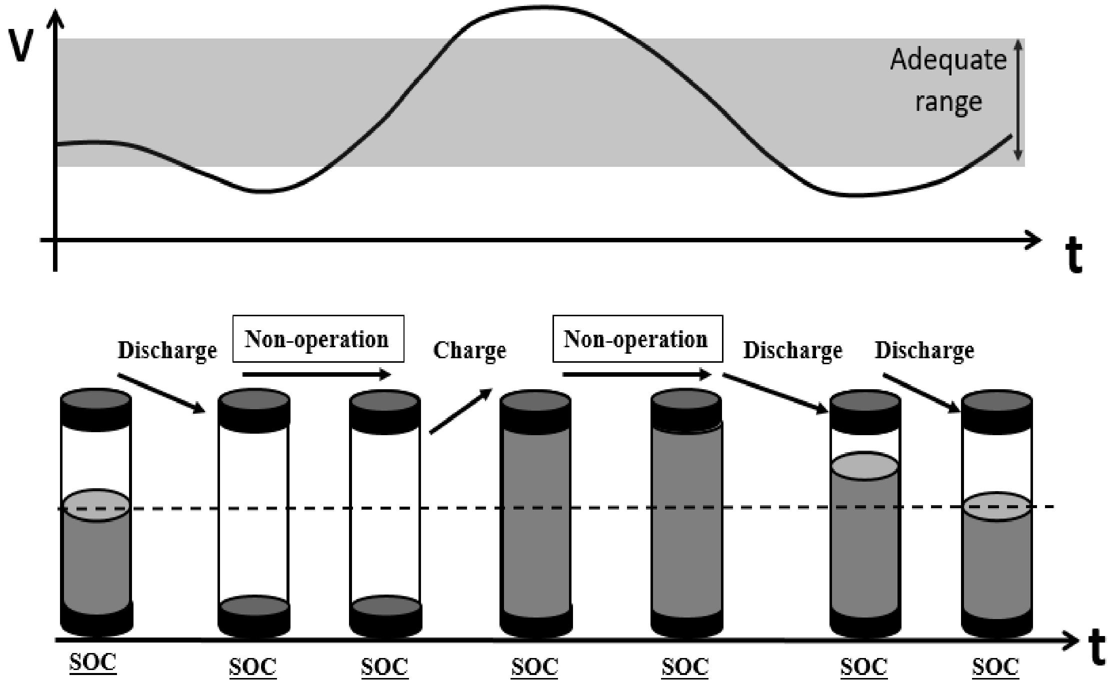

Fig. 3. 2 Image of SOC variation in voltage control

3.3 Novel management of BG

3.3.1 BESS output in voltage suppression on consideration of its location

Firstly, the cooperation of BESS in voltage control is expressed. As Fig. 3. 1 shown, two BESS are connected in distribution system. Normally, voltage at the end of distribution line has the severe variation. Therefore, the regulation of node n’s voltage is taken as an example. With respect to capacity curtailment of BESS, the output decreasing of BESS in voltage regulation need to be discussed, thereby an economic management of BESS’ output is proposed. BESS regulates voltage phase by phase and provide an immediate output when voltage excesses its bound. The voltage regulation amount is shown in equation (3.1). And BESSs are taken as current resources. The regulation amount for BESS1 and BESS2 are calculated in equation (3.2) and (3.3), respectively.

$$\Delta\dot{V}_n = \begin{cases} \dot{V}_{upperlimit} - \dot{V}_n & if\ \left|\dot{V}_n\right| > \left|\dot{V}_{upperlimit}\right| \\ \dot{V}_n - \dot{V}_{lowerlimit} & if\ \left|\dot{V}_n\right| < \left|\dot{V}_{lowerlimit}\right| \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

$$\Delta\dot{V}_{BG1} = \dot{I}_{BG1} * \textstyle\sum_1^i Z_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

$$\Delta\dot{V}_{BG2} = \dot{I}_{BG2} * \textstyle\sum_1^n Z_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

For the regulation of node n’s voltage, equation (3.4) is derived from equation (3.1) - (3.3).

$$\Delta\dot{V}_n = \Delta\dot{V}_{BG1} + \Delta\dot{V}_{BG2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

In equation (3.4), the output of BESS1 and BESS2 realizes voltage management of node n. The regulated voltage $\dot{V}_i'$ and $\dot{V}_n'$ are shown in equation (3.5) and (3.6), respectively. And apparent power output $\dot{S}_{BG1}$ and $\dot{S}_{BG3}$ are shown in equation (3.7) and (3.8), respectively.

$$\dot{V}_i' = \dot{V}_i + \Delta\dot{V}_{BG1} + \Delta\dot{V}_{BG2} * \frac{\sum_1^i Z_j}{\sum_1^n Z_j} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

$$\dot{V}_n' = \dot{V}_n + \Delta\dot{V}_{BG1} + \Delta\dot{V}_{BG2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

$$\dot{S}_{BG1} = \dot{V}_i' * \dot{I}_{BG1}^{\ *} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

$$\dot{S}_{BG2} = \dot{V}_n' * \dot{I}_{BG2}^{\ *} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

By substituting equation (3.2)-(3.6) to equation (3.7), (3.8), the apparent power output are arranged in equation (3.9) and equation (3.10).

$$\dot{S}_{BG1} = (\dot{V}_i + \Delta\dot{V}_{BG1} + \Delta\dot{V}_{BG2} * \frac{\sum_1^i Z_j}{\sum_1^n Z_j}) * (\frac{\Delta\dot{V}_{BG1}}{\sum_1^i Z_j})^* \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.9)$$

$$\dot{S}_{BG2} = (\dot{V}_n + \Delta\dot{V}_{BG1} + \Delta\dot{V}_{BG2}) * (\frac{\Delta\dot{V}_{BG2}}{\sum_1^n Z_j})^* \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.10)$$

Cartesian coordinates is changed to Polar coordinates. For simplicity, with the postulation that the voltage violation of node n is totally suppressed by BESS1, equation (3.9) is arranged in equation (3.11).

$$\dot{S}_{BG1} = \frac{|\Delta\dot{V}_{BG1}|^2}{|\sum_1^i Z_j|}\angle\theta_{Zi} + \frac{|\dot{V}_i| * |\Delta\dot{V}_{BG1}|}{|\sum_1^i Z_j|}\angle(\theta_{Vi} + \theta_{Zi} - \theta_{BG1}) \quad \ldots\ldots\ldots\ldots\ldots (3.11)$$

The image of voltage management by BESS is illustrated in Fig. 3. 3. The grey zone comprised by $\left|\dot{V}_i\right|$,

$|\dot{V}_i'|$ and $|\Delta\dot{V}_{BG1}|$ is shown in Fig. 3. 3. φ is angle of $|\dot{V}_i|$ and $|\Delta\dot{V}_{BG1}|$. The equivalent triangle is ΔABC. As voltage violation of node n is taken as an example. $|\dot{V}_n|$ is always measured, and $|\dot{V}_n'|$ equals to voltage limit value. Therefore, in equation (3.11), two variables, $|\Delta\dot{V}_{BG1}|$ and θ_{BG1} decide $\dot{S}_{BG1}$. In triangle ΔABC, with cosine theorem, equation (3.12) is derived. The angle φ is calculated in equation (3.13).

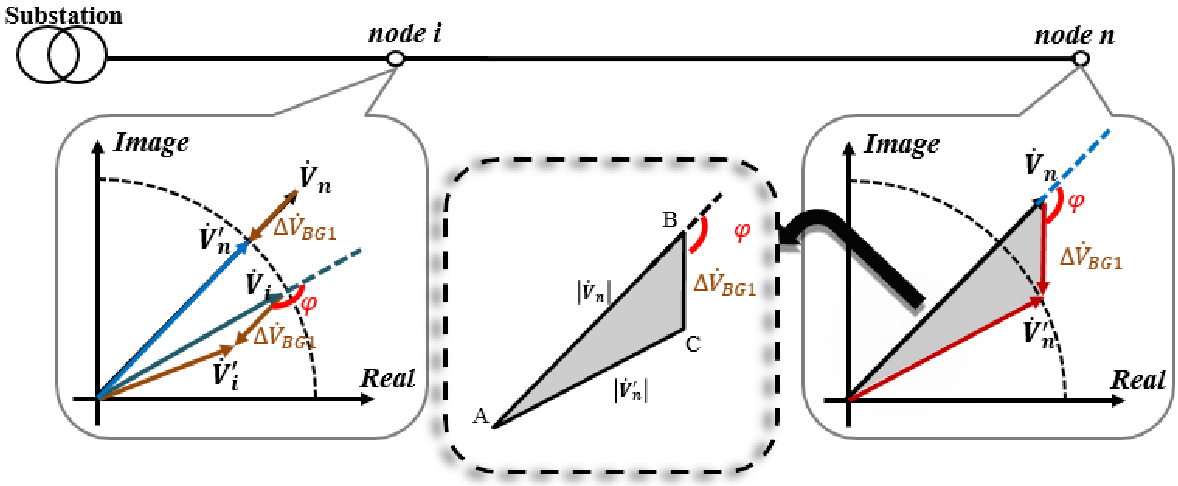

Fig. 3. 3 Image of voltage regulation by BESS

$$\cos(\pi-\varphi)=\frac{|\dot{V}_n|^2+|\Delta\dot{V}_{BG1}|^2-|\dot{V}_n'|^2}{2*|\dot{V}_n|*|\Delta\dot{V}_{BG1}|} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.12)$$

$$\theta_{Vn}-\theta_{BG1}=\varphi=\pi-\mathrm{arcos}\left(\frac{|\dot{V}_n|^2+|\Delta\dot{V}_{BG1}|^2-|\dot{V}_n'|^2}{2*|\dot{V}_n|*|\Delta\dot{V}_{BG1}|}\right) \quad \ldots\ldots\ldots\ldots (3.13)$$

$$\theta_{V\mathrm{n-i}}=\theta_{V\mathrm{n}}-\theta_{V\mathrm{i}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.14)$$

Substituting equation (3.13) to (3.11), the apparent power output is decided by $|\Delta\dot{V}_{BG1}|$ as equation (3.15) shown.

$$\dot{S}_{BG1}=\frac{|\Delta\dot{V}_{BG1}|^2}{|\sum_1^i Z_j|}\angle\theta_{Zi}+\frac{|\dot{V}_i|*|\Delta\dot{V}_{BG1}|}{|\sum_1^i Z_j|}\angle(\theta_{Zi}-\theta_{V\mathrm{n-i}}+\pi-\mathrm{arcos}((\frac{|\dot{V}_n|^2+|\Delta\dot{V}_{BG1}|^2-|\dot{V}_n'|^2}{2*|\dot{V}_n|*|\Delta\dot{V}_{BG1}|})) \quad \ldots..(3.15)$$

The value of $\dot{S}_{BG1}$ is shown in equation (3.16) and arranged in equation (3.17).

$$F(|\Delta\dot{V}_{BG1}|)=\left|\frac{|\Delta\dot{V}_{BG1}|^2}{|\sum_1^i Z_j|}\angle\theta_{Zi}+\frac{|\dot{V}_i|*|\Delta\dot{V}_{BG1}|}{|\sum_1^i Z_j|}\angle(\theta_{Zi}-\theta_{V\mathrm{n-i}}+\pi-\mathrm{arcos}((\frac{|\dot{V}_n|^2+|\Delta\dot{V}_{BG1}|^2-|\dot{V}_n'|^2}{2*|\dot{V}_n|*|\Delta\dot{V}_{BG1}|}))\right|$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.16)$$

$$F(|\Delta\dot{V}_{BG1}|)^2=\frac{|\Delta\dot{V}_{BG1}|^4}{|\sum_1^i Z_j|^2}+\frac{|\Delta\dot{V}_{BG1}|^2}{|\sum_1^i Z_j|^2}*|\dot{V}_i|^2$$

$$-2*\frac{|\Delta\dot{V}_{BG1}|^3}{|\sum_1^i Z_j|^2}*|\dot{V}_i|*\cos(\theta_{V\mathrm{n-i}}+\mathrm{arcos}(\frac{|\dot{V}_n|^2+|\Delta\dot{V}_{BG1}|^2-|\dot{V}_n'|^2}{2*|\dot{V}_n|*|\Delta\dot{V}_{BG1}|})) \quad \ldots\ldots\ldots..(3.17)$$

In equation (3.17), to calculate the derivative, the range of variable needs firstly be defined. According to the voltage control objective, the variable $|\Delta\dot{V}_{BG1}|$ is positive and always larger than the subtraction of $|\dot{V}_n|$

and $|\dot{V}_n'|$. And based on equation (3.16)-(3.17), the verification is done on Matlab. $F(|\Delta\dot{V}_{BG1}|)$ and $F(|\Delta\dot{V}_{BG1}|)'$ with $|\Delta\dot{V}_{BG1}|$ as variable are shown in Fig. 3. 4 and Fig. 3. 5. The peak time with largest violation of voltage is choose to verify the monotonic of $F(|\Delta\dot{V}_{BG1}|)$. The horizon axis is $|\Delta\dot{V}_{BG2}|$, and vector axis is $F(|\Delta\dot{V}_{BG1}|)$ and $F(|\Delta\dot{V}_{BG1}|)'$, respectively. From Fig. 3. 5, it can be seen that $F'(|\Delta\dot{V}_{BG1}|)$ is always a positive number, therefore, $F(|\Delta\dot{V}_{BG1}|)$ is monotonic increasing function. As Fig. 3. 4 shows, the apparent power output of BESS1 obtains the minimal value when $|\Delta\dot{V}_{BG1}|$ is regulated along the yellow arrow. Also, this optimization method is capable for BESS2.

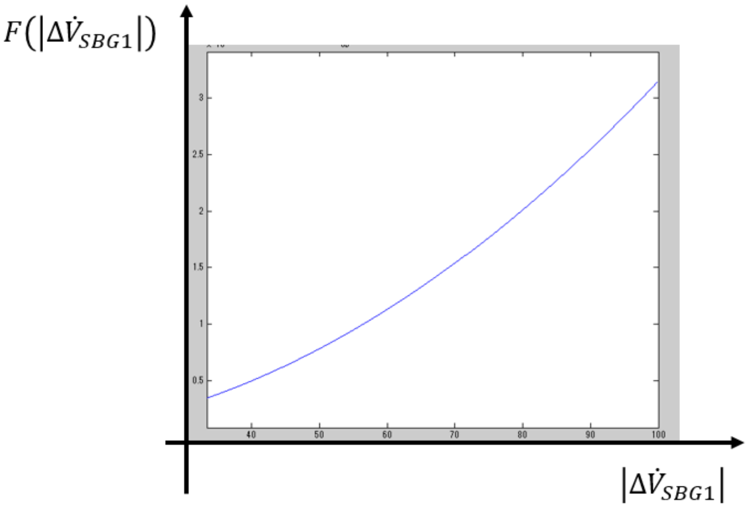

Fig. 3. 4 Image of relation between $F(|\Delta\dot{V}_{SBG1}|)$ and $|\Delta\dot{V}_{SBG1}|$

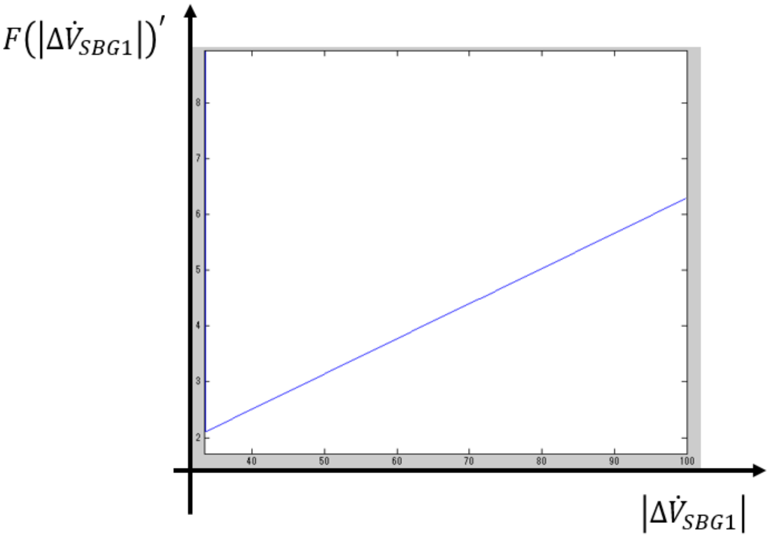

Fig. 3. 5 Image of relation between $F(|\Delta\dot{V}_{SBG1}|)'$ and $|\Delta\dot{V}_{SBG1}|$

BESS1 and BESS2 work together on voltage suppression, and equation (3.4) is rearranged in equation (3.18). And the apparent power output in equation (3.9) and (3.10) are rearranged in equation (3.19).

$$\left|\Delta\dot{V}_n\right| = \left|\Delta\dot{V}_{BG1}\right| + \left|\Delta\dot{V}_{BG2}\right| \quad \dots\dots\dots\dots\dots\dots\dots\dots (3.18)$$

$$\begin{cases} \dot{\mathrm{S}}_{\mathrm{BG1}} = \frac{|\Delta\dot{V}_{BG1}|^2}{|\sum_1^i Z_j|}\angle\theta_{Zi} + \frac{|\dot{V}_i|*|\Delta\dot{V}_{BG1}|}{|\sum_1^i Z_j|}\angle(\theta_{Vi} + \theta_{Zi} - \theta_{BG1}) + \frac{|\Delta\dot{V}_{BG2}|*|\Delta\dot{V}_{BG1}|}{|\sum_1^n Z_j|}\angle(2 * \theta_{Zi} - \theta_{Zn}) \\ \dot{\mathrm{S}}_{\mathrm{BG2}} = \frac{|\Delta\dot{V}_{BG2}|^2}{|\sum_1^n Z_j|}\angle\theta_{Zn} + \frac{|\dot{V}_n|*|\Delta\dot{V}_{BG2}|}{|\sum_1^n Z_j|}\angle(\theta_{Vn} + \theta_{Zn} - \theta_{BG2}) + \frac{|\Delta\dot{V}_{BG2}|*|\Delta\dot{V}_{BG1}|}{|\sum_1^n Z_j|}\angle\theta_{Zn} \end{cases}$$

$$\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.19)$$

$$\begin{cases} \theta_{BG1} = \theta_{Vn} + \pi, \ \ \theta_{BG2} = \theta_{Vn} + \pi \quad if \left|\dot{V}_{upperlimit}\right| < \left|\dot{V}_n\right| \\ \theta_{BG1} = \theta_{Vn}, \ \ \theta_{BG2} = \theta_{Vn} \quad if \left|\dot{V}_{lowerlimit}\right| > \left|\dot{V}_n\right| \end{cases}$$

In conclusion, the minimization of BESS's apparent power appears when the regulation amount of voltage obtains minimal value. Therefore, BESS regulates voltage along its objective voltage's angle and the placement of BESS has no effect on apparent power optimization.

3.3.2 Cooperation in BG for voltage suppression

In previous study of BESS's cooperation in [4], BESS provides output to distribution system just taking SOC as the constraint to decide the its operation/nonoperation. And the random SOC of BESSs lead to their variation operation period that difficult to management. Also, the synchronous control of SOC is illustrated in [6], EV is management in the order based on the value of SOC. And this control method does have time delay in the operation and relatively small total output at each sampling time. Meanwhile, the synchronous control aiming to balance SOC has bad effect on voltage suppression with unexpected charge/discharge.

In this section, for simplicity, image of BESS in Fig. 3. 6 is taken as an example. The problem in cooperation of BESS is the output division between BESSs. BESS's output based on its own state of capacity and SOC is proposed here. BESS with more available capacity provides more output in voltage control. The proposed cooperation's objective is to balance SOC of distributed BESS, and at the same time, reduce the peak value of BESS's output via synchronous operation in voltage management of distribution system.

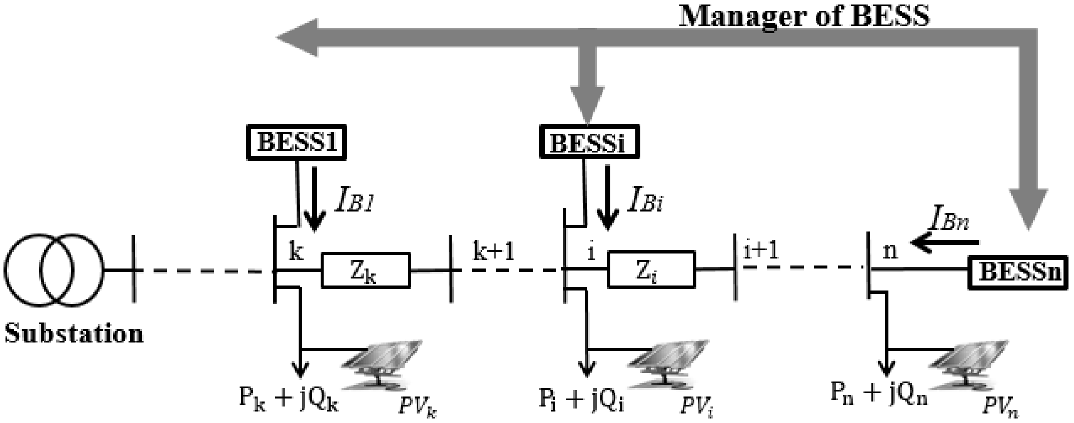

Fig. 3. 6 Image of BESS in distribution system

For the same regulation of voltage $\dot{V_n}$ in previous section, with the regulation amount $\Delta\dot{V_n}$, the output of each BESS needs to be decided. Therefore, based on the proposed method, the available capacity of BESS is shown in equation (3.20). And the weight coefficient in deciding each BESS's output is shown in equation (3.21).

$$\begin{cases} AC_{BGk}(\mathrm{t}) = \left(\mathrm{SOC}_{upperlimit} - SOC_{BGk}(\mathrm{t})\right) * C_{BGk} \\ AC_{BGk}(\mathrm{t}) = (SOC_{BGk}(\mathrm{t}) - \mathrm{SOC}_{lowerlimit}) * C_{BGk} \end{cases} \quad \text{............................} \quad (3.20)$$

$$w_{BGk}(\mathrm{t}) = \frac{AC_{BGk}(\mathrm{t})}{\sum_1^n AC_{BGk}(\mathrm{t})} \quad \text{.......................................} \quad (3.21)$$

Where, $SOC_{BGk}(\mathrm{t})$ is SOC BESS at time t. C_{BGk} is capacity of each BESS, k and n are the number of BESS.

For suppression of voltage in node n, the equality constraint is shown in equation (3.22). With the equality constraints, the output division of each BESS is obtained.

$$\left|\Delta\dot{V_n}\right| = w_{BGk}(\mathrm{t}).* \left|\Delta\dot{V_n}\right| + w_{BGj\neq k}(\mathrm{t}).* \left|\Delta\dot{V_n}\right| \quad \text{.......................} \quad (3.22)$$

3.3.3 Initiative charge/discharge (ICD) in SOC management of BESS

BESS regulates voltage phase by phase, and it makes the proper management of different phase be possible. In this section, ICD in SOC management is proposed to increase the efficiency of BESS's utilization. As shown in Fig. 3. 2, the non-operation period is wanted to be reduced. The proposed method mainly deals with two cases for SOC regulation with SOCref as reference value. The first is to reduce SOC when it excesses SOCref; and the other is to increase SOC when it's smaller than SOCref. In this way, more available capacity of BESS is ensured. The regulation of SOC is realized via suppression of voltage and improvement of VUF. The definition of SOCref is with the consideration of PV output and battery cycle time. In [7], the depth of discharge has a significant relation with cycle time reduction. The value of SOC during BESS operation is wanted to relatively large. However, during daytime BESS absorbs inverse power flow from PV, the available capacity of BESS for charge is wanted to be as large as possible and SOC is small. With all the consideration above, in this section, SOCref is set as Table 3.1 shows. In study of BESS, 50% of SOC is taken as a proper value of BESS. Peak time of PV output is Tp. When voltage surpasses its upper limit, BESS normally in charge status, and the change of mode 1 to mode 2 suppress SOC with ICD. The upper limit of mode 1 ensures the regulation period for SOC suppression in mode 2. Voltage below its lower limit has the same process in SOC regulation. When voltage in its proper range, its reference value changes with PV. In this way, more available capacity is prepared for charge of BESS in daytime and discharge of BESS in nighttime.

Table 3.1 Definition of SOCref

SOCref	$V > V_{upperlimit}$		$V < V_{lowerlimit}$		$V_{upperlimit} > V > V_{lowerlimit}$		
	Mode 1	Mode 2	Mode 1	Mode 2	PV>0		PV=0
					t<Tp	t>Tp	
Upper limit	70%	90%	70%	50%	50%	70%	50%
Lower limit	20%	70%	50%	20%			

The severe voltage violation and unbalance factor normally appears at the end of the distribution line in radial distribution system, node n in Fig. 3. 6 is taken as an example. ICD is divided into two modes, the first is in voltage suppression, and the other is VUF improvement. The two modes of ICD are discussed in two cases below.

[Case 1: $\mathrm{SOC} > SOCref_{upperlimit}$]

Mode 1: VUF improvement mode

In [8], the relation of line voltage difference and unbalance factor is proved. When SOC is larger than SOCref, ICD in SOC management makes the initiative discharge (IC) of BESS to reduce SOC as well as VUF suppression. To improve VUF, the maximal line voltage difference is reduced. As Fig. 3. 7 shows, phase ab, bc and ca are taken as an example with the descending order of their magnitude. And the descending order of phase voltage is b, a and c. When VUF excesses its limit, to suppress VUF, phase ca is increased to reduce the line difference between ca and ab via IC with the reduction of SOC. And instead of phase a whose increasing leads to the enlarging of line voltage difference, phase c is increased for the regulation of phase ca.

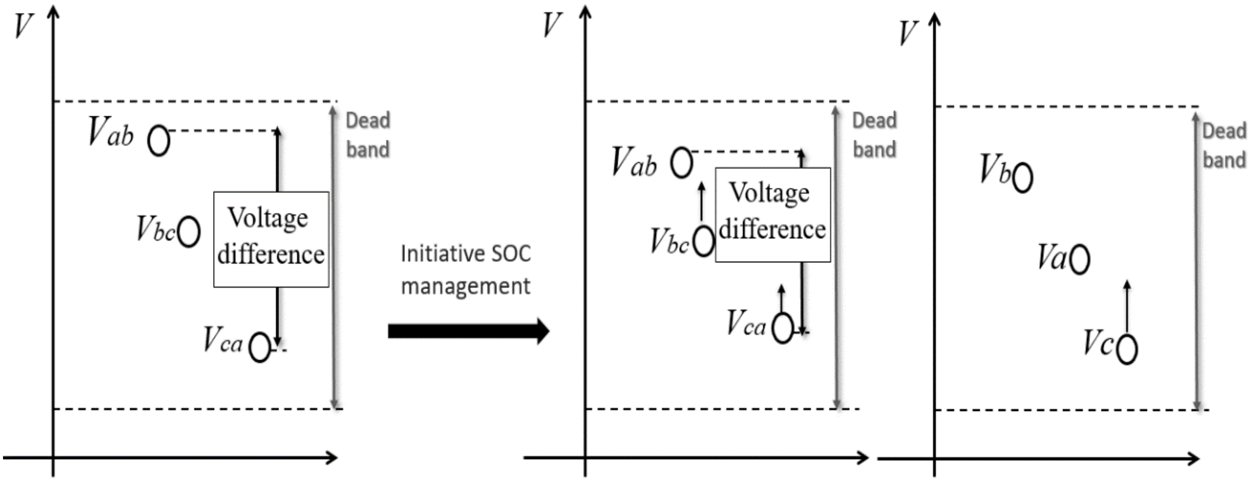

Fig. 3. 7 Image of initiative SOC management in VUF suppression

Mode 2: Voltage suppression mode

When voltage violation occurs as Fig. 3. 8 shows, voltage suppression is superior in BESS operation. Though SOC is larger than SOCref, and IC is needed. To reduce phase ab, phase a and b decrease simultaneously for speedy suppression which leads to speedy increase of SOC. Phase c is increases to mitigate the increasing of SOC.

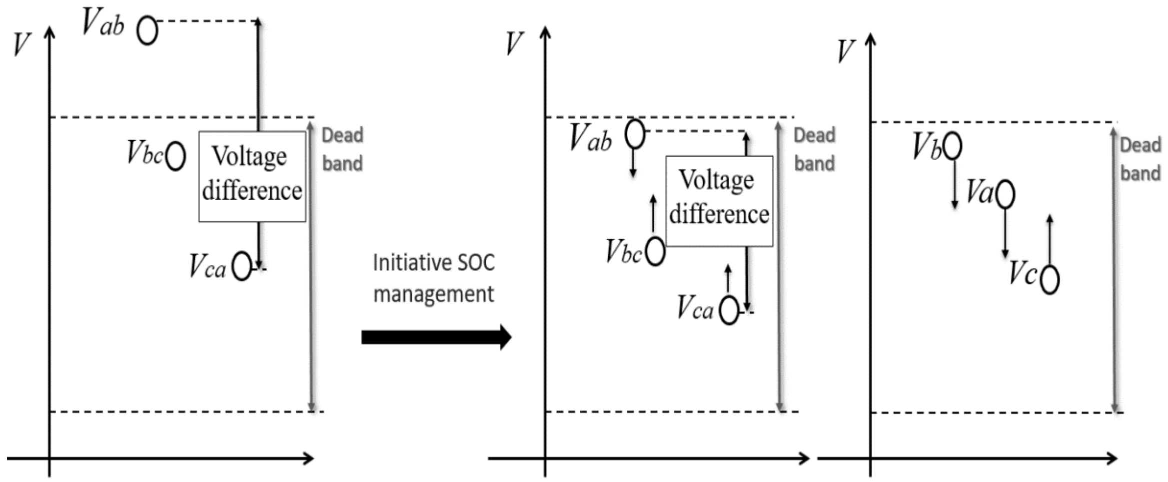

Fig. 3. 8 Image of initiative SOC management in voltage suppression

The constraint of BESS is shown in equation (3.24)-(3.27). Based on the calculation of BESS output in section 3.3.1, The active power output P_{Bp} of each phase in ICD is calculated. The variation of SOC caused by P_{Bp} is $\Delta\mathrm{SOC}_{ini}$ in equation (3.23), and p stands for different phase. With the regulation, unbalance factor V_k, line voltage V_l and SOC always meets the inequality constraints shown in below.

$$\Delta\mathrm{SOC}_{ini} = \int_{t}^{\mathrm{t}+T_{ini}} \sum \mathrm{P}_{Bp}(t)\, dt \qquad \text{……} (3.23)$$

Constraint to:

$$V_k < 1.0\% \qquad \text{……} (3.24)$$

$$\mathrm{V}_{upperlimit} > \mathrm{V\_l} > \mathrm{V}_{lowerlimit} \qquad \text{……} (3.25)$$

$$\mathrm{V}_{ab} > \mathrm{V}_{bc} > \mathrm{V}_{ca} \qquad \text{……} (3.26)$$

$$\mathrm{SOC}_{upperlimit} > \mathrm{SOC(t)} + \Delta\mathrm{SOC}_{ini} > \mathrm{SOC}_{lowerlimit} \qquad \text{……} (3.27)$$

[Case 2: SOC<SOCref]

Fig. 3. 9 shows the voltage variation by the initiative discharge (ID) of BESS. When SOC is smaller than SOCref, in VUF improvement mode, phase b is decreased for line voltage difference reduction as well as SOC increasing. In voltage suppression mode in Fig. 3. 10, both phase a and c is increased for effective control of voltage. Phase b is reduced for SOC increase. The equality and inequality constraints of initiative management is same with case 1. With the proposed initiative SOC management, SOC is always regulated around SOCref. And in this way, BESS is prevented from overcharge/discharge and obtained more available

capacity.

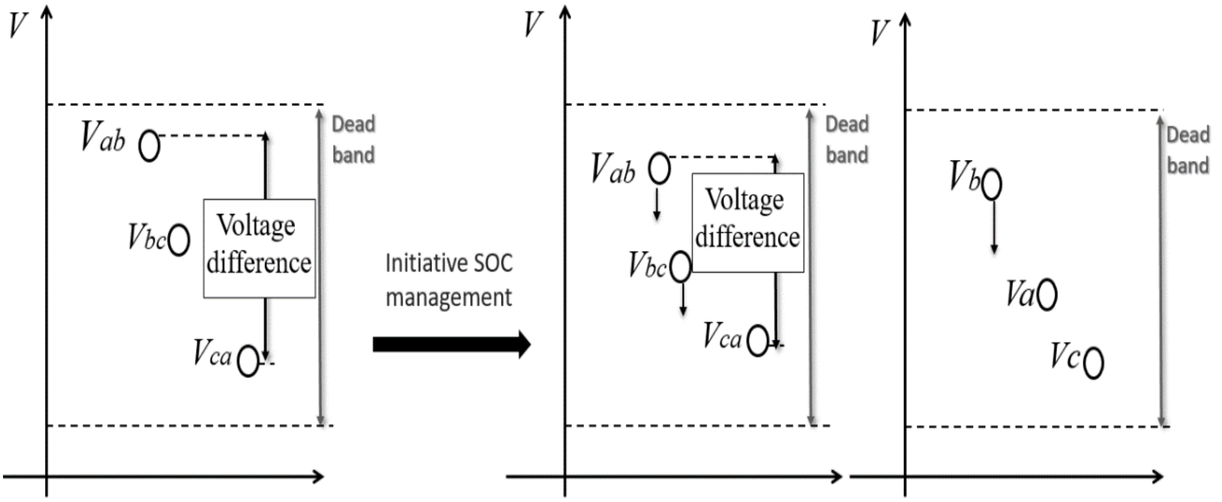

Fig. 3. 9 Image of initiative SOC management in VUF improvement

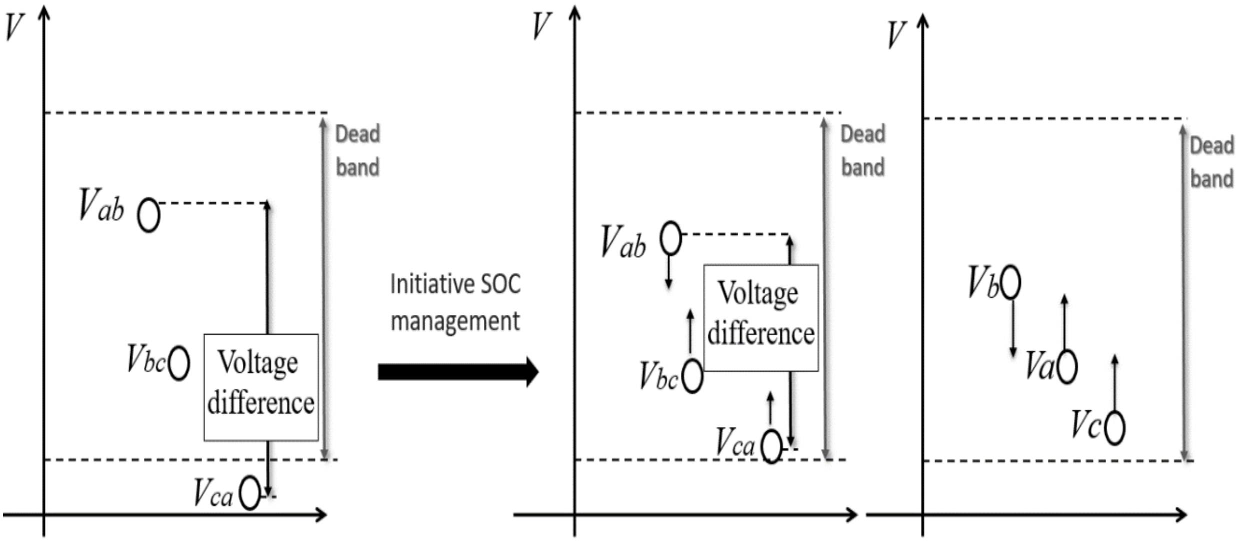

Fig. 3. 10 Image of initiative SOC management in voltage suppression

3.5 Case study

3.5.1 Distribution system model and simulation conditions

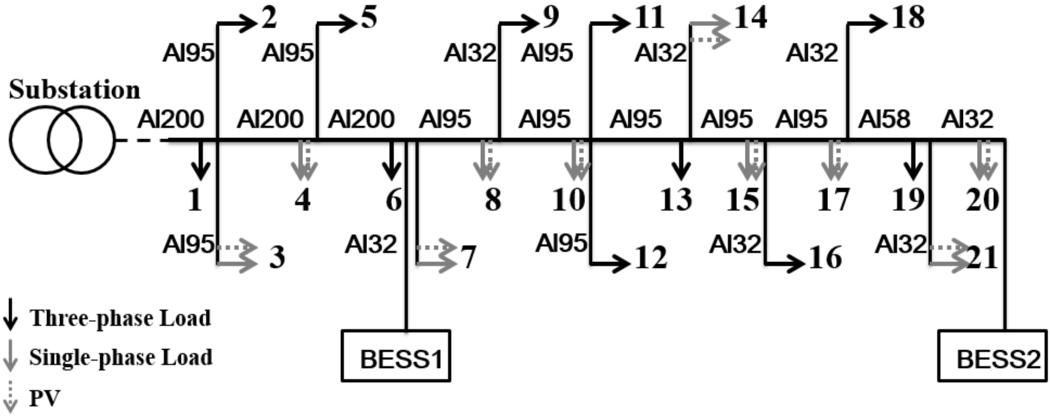

Fig. 3. 11 Distribution system model

Fig. 3. 11 gives the model of PV connected distribution system with BESS located at node 6 and 20. The different color of the arrow stands for three-phase load, single phase load and PV, respectively. The parameter of impedance and single-phase loads connection are shown in Table 3.2 and Table 3.3, respectively.

Table 3.2 Distribution line's data.

Impedance of distribution line	$\mathrm{Al32{:}0.899 + j0.389\Omega/km}$ $\mathrm{Al58{:}0.497 + j0.331\Omega/km}$ $\mathrm{Al95{:}0.301 + j0.315\Omega/km}$ $\mathrm{Al200{:}0.182 + j0.288\Omega/km}$
Total length of the line	3.09km

Table 3.3 Connection of single-phase load.

Connection phase	Load No.
a-b	3, 8, 15, 21
b-c	4, 10, 17, 20
c-a	7, 14

The pattern of three-phase loads, single-phase load is illustrated in Fig. 3. 12 and Fig. 3. 13, respectively. Consumption of three-phase load is 125kW of each one. Single-phase load ranges from 108kW to 648 kW. Fig. 3. 14 illustrated PV output profile in cloudy day. The capacity of PV equals to the 1.5 times of single-phase load consumption. All of them are given in standardization.

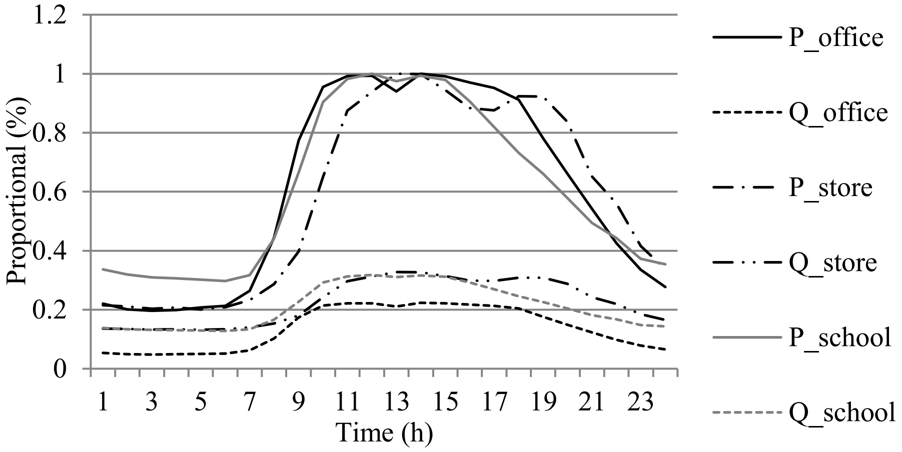

Fig. 3. 12 Three-phase load’s pattern

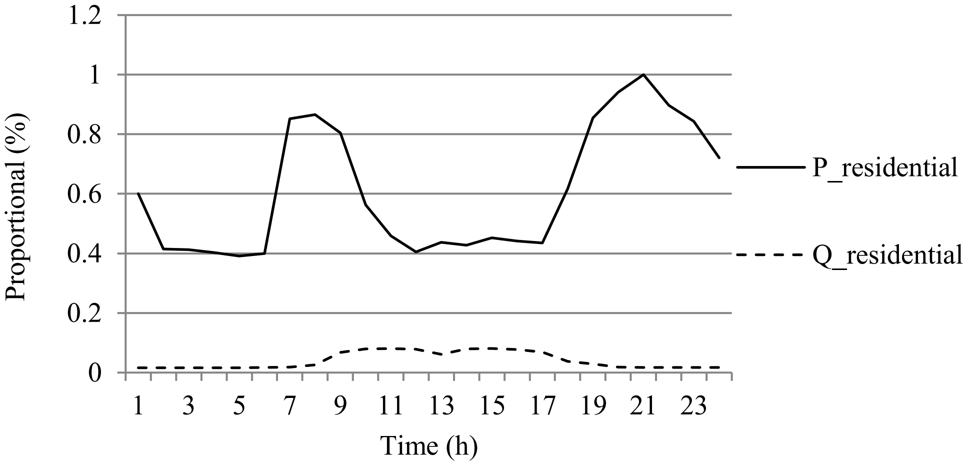

Fig. 3. 13 Single-phase load’s pattern

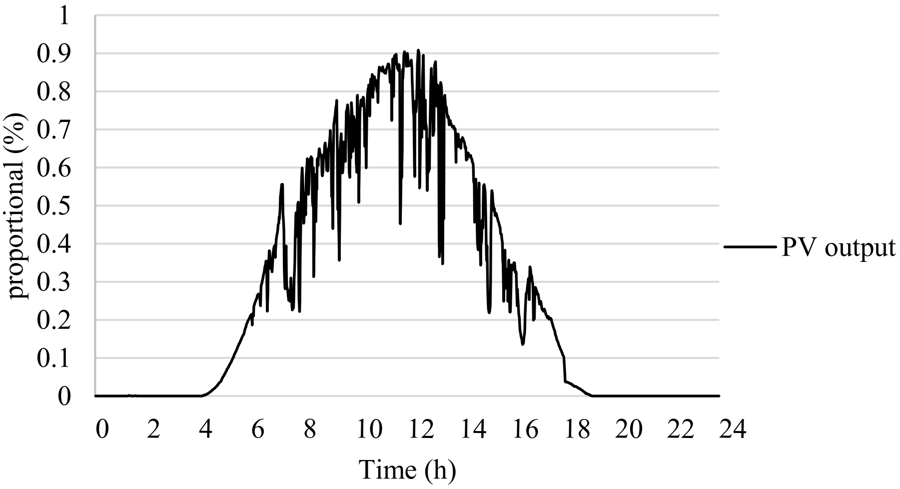

Fig. 3. 14 PV output in cloudy day

The time step of the simulation is 1 min. Table 3.4 gives the simulation conditions. Voltage is conversed to low voltage side with voltage ratio (= 6600/105).

Table 3.4. Simulation conditions.

Simulation time	24hours
Simulation interval	1 min
Adequate range's $V_{\text{upper limit}}$	107V (up voltage)
Adequate range's $V_{\text{lower limit}}$	102V (low voltage)
Ratio of voltage	6600/105
Sending voltage of substation	6600V
Initial SOC of BESS	50%
Capacity of battery	100kWh, 500kWh and 2.3MWh
SOC limit	20%-90%
VUF limit	1%

Table 3.5 shows the case to verify the proposed method. Case 1 is taken as reference with no connection of BESS. Case 2 has two BESS connected at node 6 and 20 without proposed cooperation. Case 3 verify the proposed cooperation method of BG in voltage suppression and VUF improvement. Case 4 discusses the effect of proposed ICD in BESS operation in voltage management.

Table 3.5 Simulation cases.

Case	Cooperation of BG	ICD
Case 1	No BESS	
Case 2	No	No
Case 3	Proposed	No
Case 4	Proposed	Proposed

3.5.2 Simulation results

Fig. 3. 15 and Fig. 3. 16 give the voltage profile and VUF of node 21, respectively. Based on the simulation constraints, voltage and VUF violation appear with the increasing output of PV and load consumption.

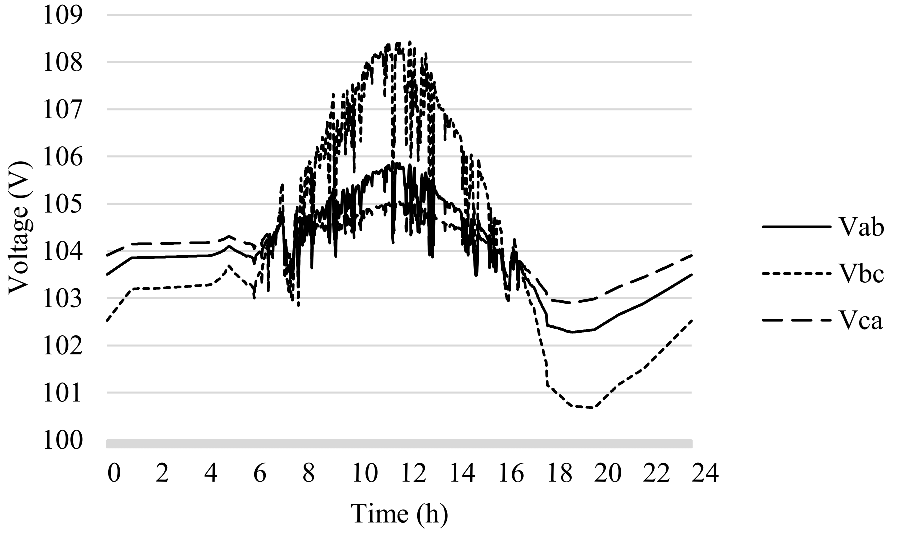

Fig. 3. 15 Voltage of node 21 in case 1

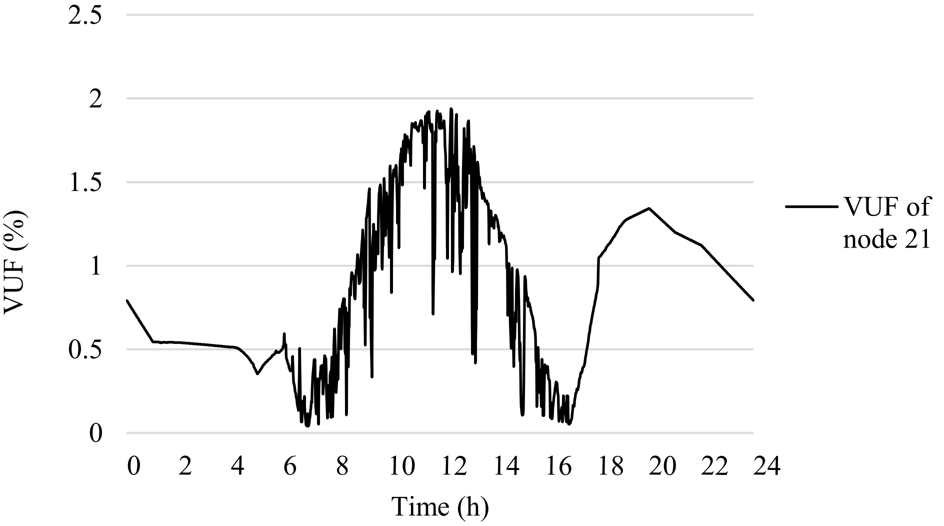

Fig. 3. 16 VUF of node 21 in case 1

In case 2, BESS1 and 2 without cooperation and ICD. The output of BESS decided by the voltage and VUF of its connected node. And BESS2 connected at the end of distribution line where has the largest voltage violation. BESS2 gives output for voltage and VUF suppression in management. With the output of BESS2, the voltage and VUF of the whole radial distribution system is improved, and the voltage and VUF are well controlled. BESS2 active power output is shown in Fig. 3. 19 with totally prefect control in case 2. And with the initial SOC of 50% and constraint of SOC, capacity of BESS is 2.3MWh which is too large compared to its load consumption. BESS1 is in non-operation state because of no voltage and VUF violation.

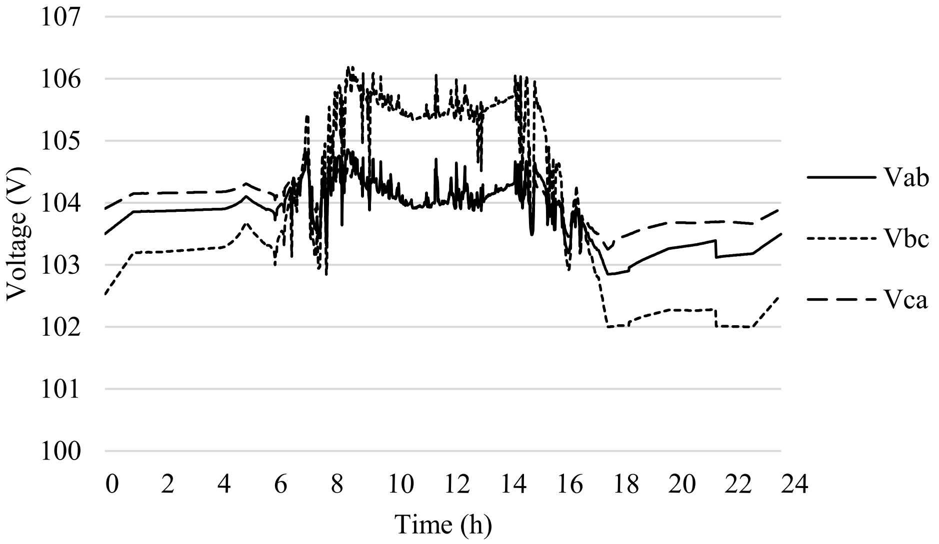

Fig. 3. 17 Voltage of node 21 in case 2

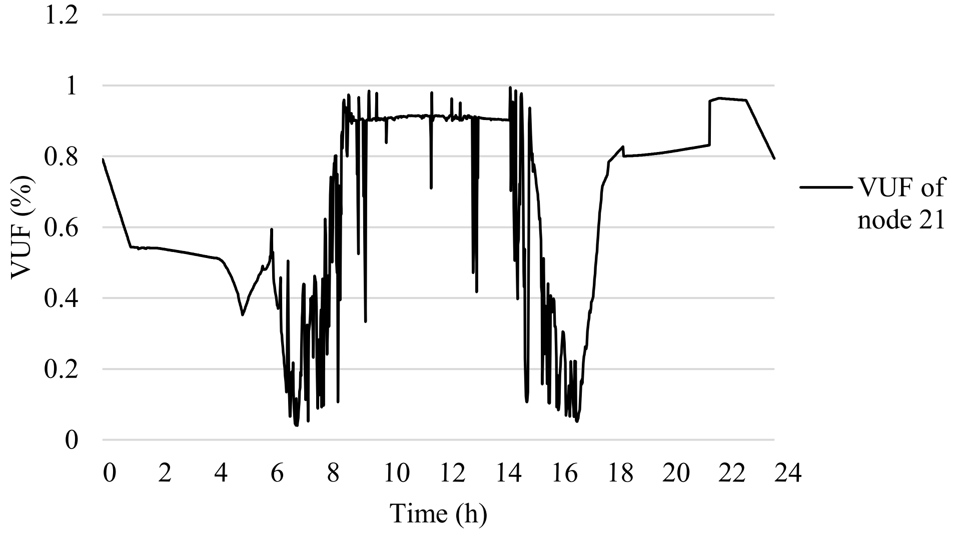

Fig. 3. 18 VUF of node 21 in case 2

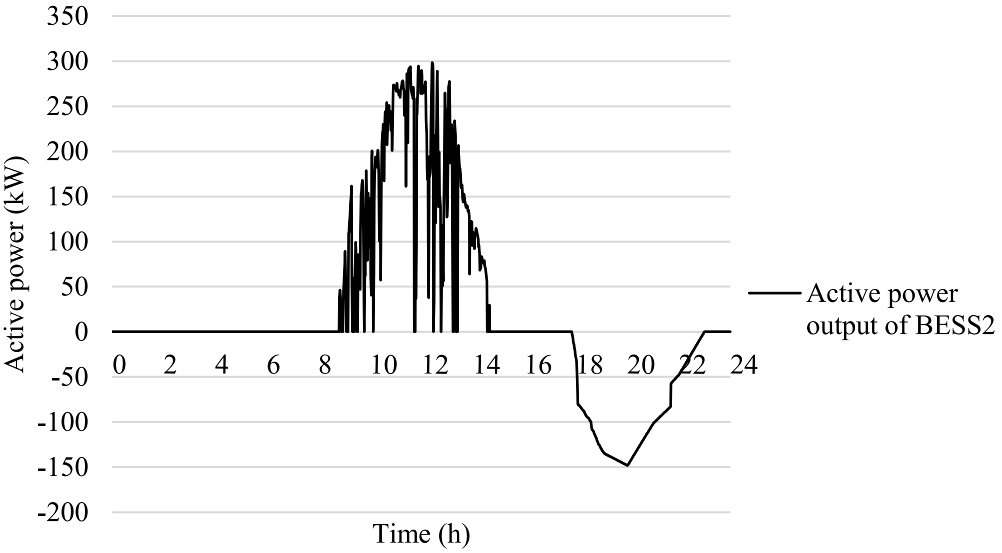

Fig. 3. 19 Active power output of BESS2 in case 2

In case 3, two 500kWh BESSs cooperate in voltage control without ICD. With the given capacity of BESS, SOC is shown in Fig. 3. 22 and cooperation of the two BESS works well. With the limit of SOC, BESS enters to no-operation period. And violation of voltage and VUF still exist in Fig. 3. 20 and Fig. 3. 21..

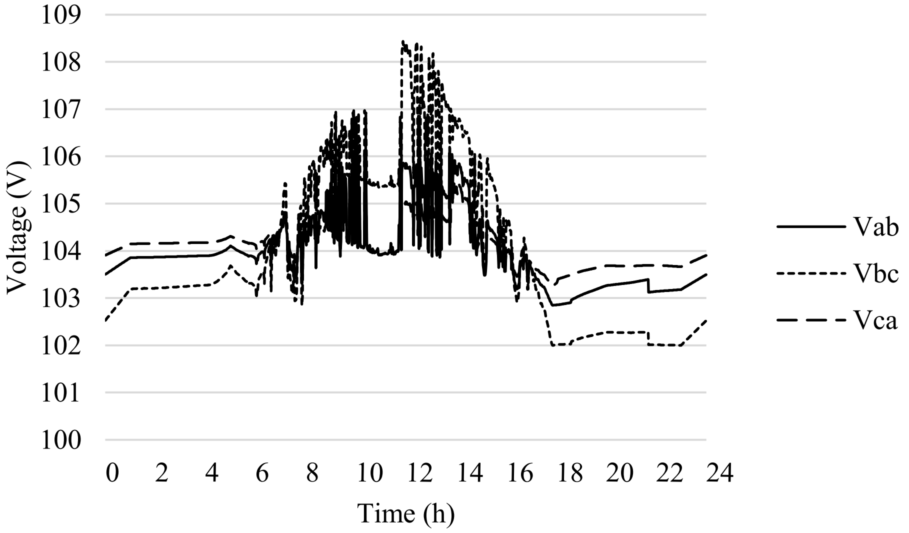

Fig. 3. 20 Voltage of node 21 in case 3

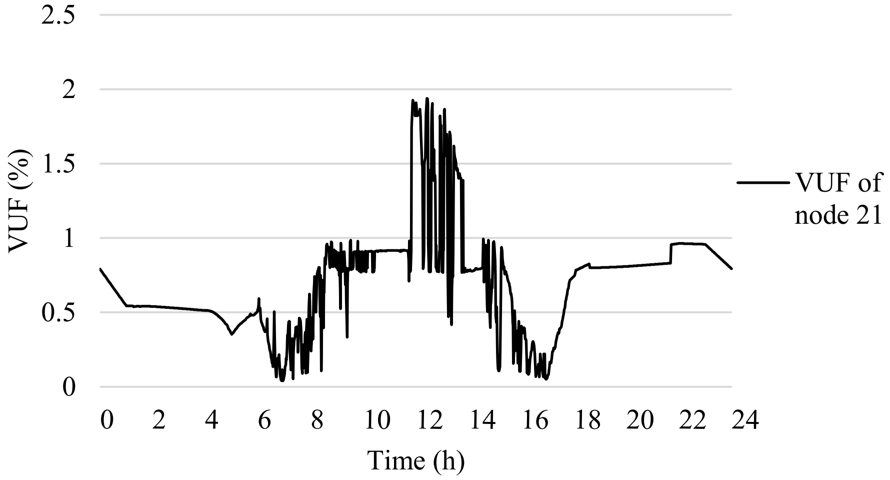

Fig. 3. 21 VUF of node 21 in case 3

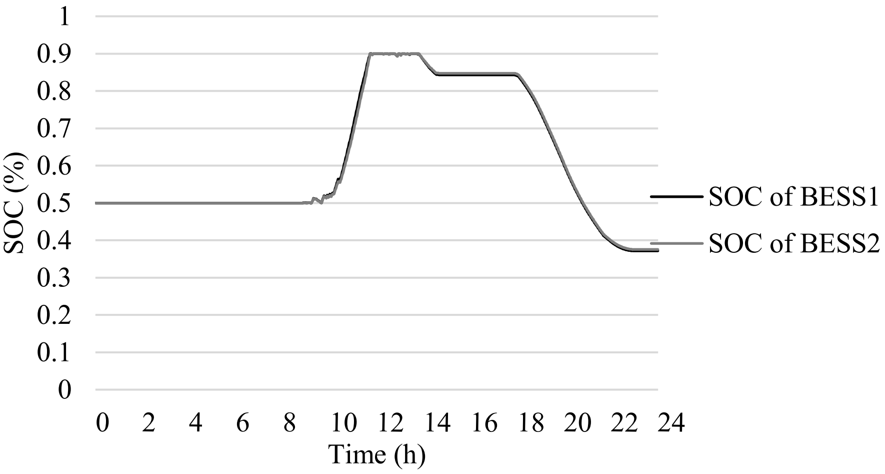

Fig. 3. 22 SOC of BESS in case 3

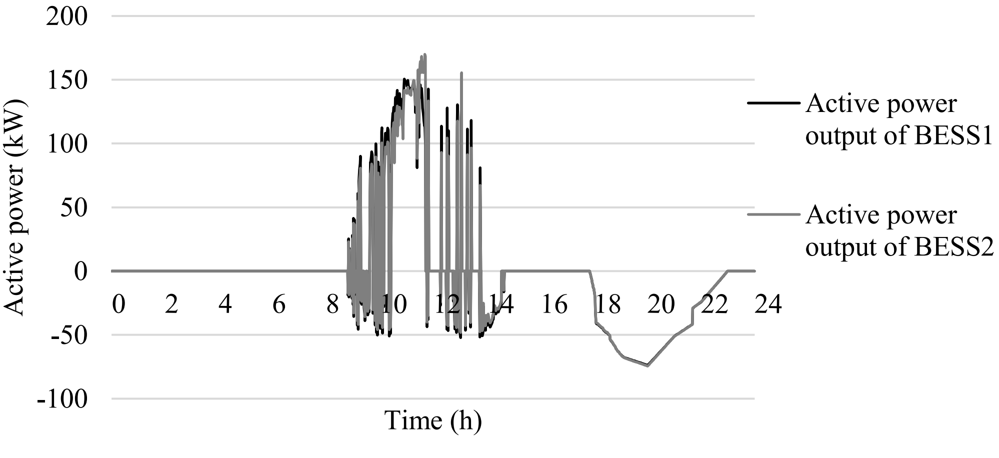

Fig. 3. 23 Active power output of BESS in case 3

Case 4 has two BESS with the capacity of 100kWh. Comparing to case 2 and 3, the capacity of BESS in case 4 is largely reduced. With the proposed ICD and cooperation method. The voltage and VUF is well controlled in day time. And SOC is always in is adequate range. The excellent control ability of BESS with proposed method is verified.

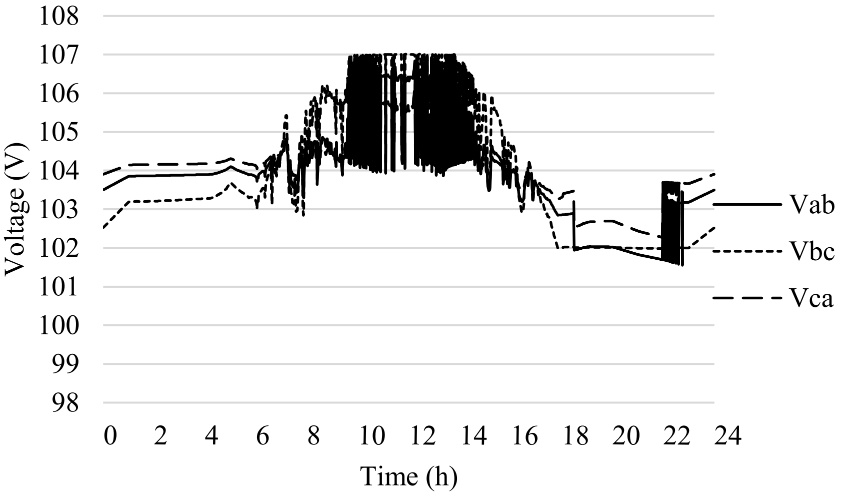

Fig. 3. 24 Voltage of node 21 in case 4

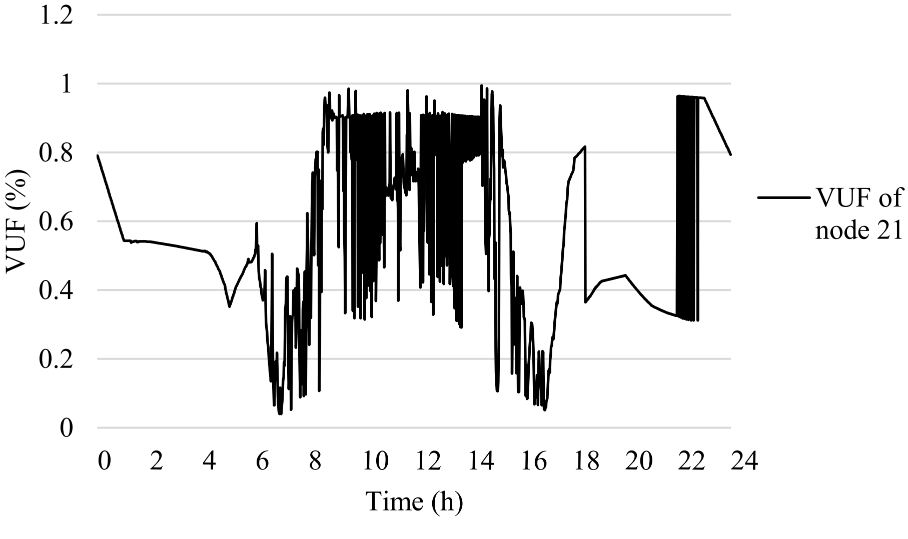

Fig. 3. 25 VUF of node 21 in case 4

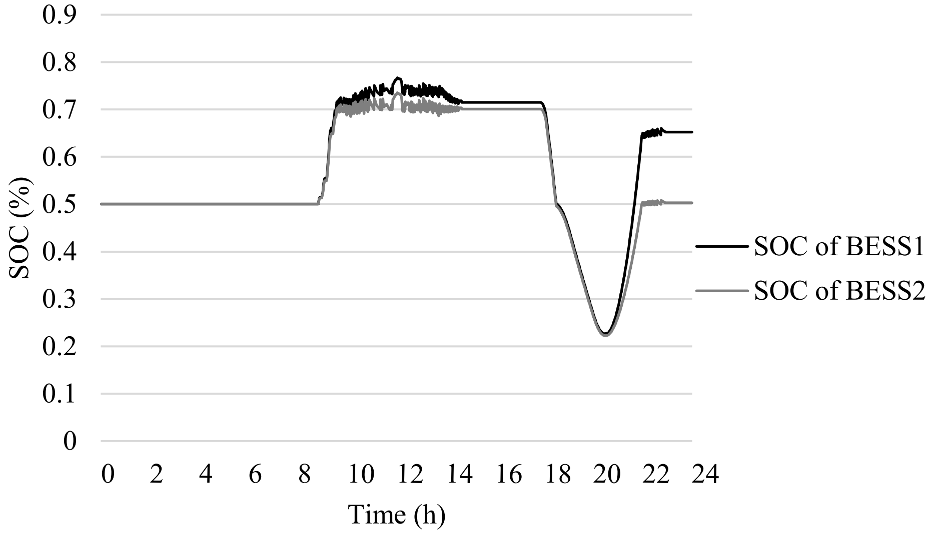

Fig. 3. 26 SOC of BESS in case 4

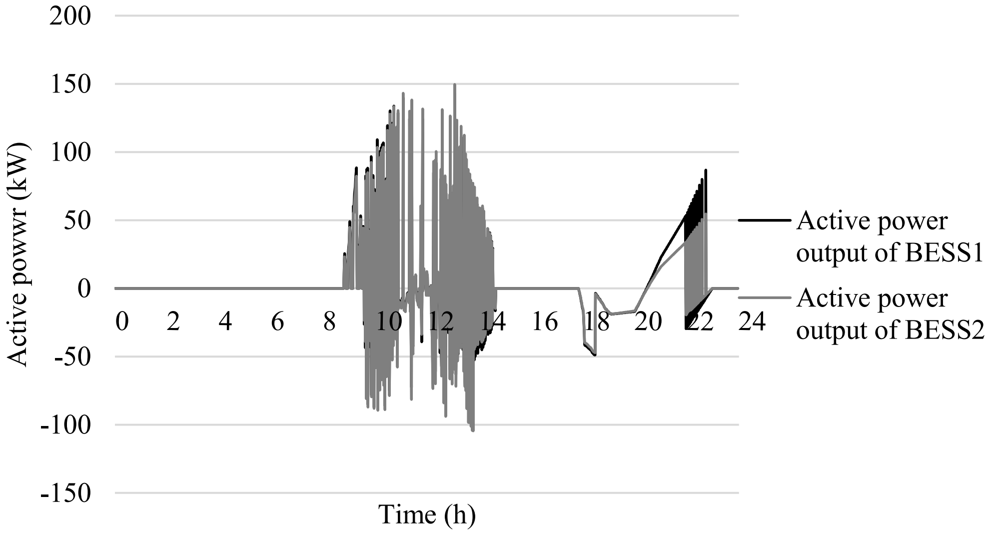

Fig. 3. 27 Active power output of BESS in case 4

3.5 Discussion and summary

In this chapter, the cooperation of BESS group with ICD is proposed in voltage control. The proposed cooperation of BESS group increases the operation period of each BESS. ICD in voltage control has largely reduced the capacity of BESS. In the promotion of BESS application, high cost of BESS limits the utilization of large-scale BESS. However, small-scale BESS is insufficient in its operation with the existed method. The proposed method makes the utilization of small-scale BESS be possible.

The discussion of BESS group in this chapter assumes no power loss in charge/discharge of BESS, therefore, the power loss needs to be considered for more accurate control of BESS. The operation of BESS group is decided by the BESS connected at the end of distribution line. More information of other BESS in BG is wanted for superior utilization of BESS. In future work, the effect of established devices on BESS group operation is important issue to be discussed.

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Chapter 4

Voltage and VUF suppression via cooperation of SVR and SBG (Small-scale BESS Group) in PV connected distribution system

4.1 Introduction

In previous chapter, novel method in voltage and voltage unbalance suppression via BESS and SC has been discussed. SC is relatively cheaper than BESS, therefore, BESS cooperated with SC aims to use the excellent control ability of BESS as well as decrease the capacity of BESS for cost reduction. And the cooperation of BESS and SC does realize the prefect suppression of voltage and unbalance factor. However, with the development of BESS, the research of BESS need to change from single BESS to BESS group. And with the purpose of realization of effective utilization of BESS, the cooperation with established devices is needed. This chapter pays attention on the cooperation of SVR and BESS group in voltage and unbalance factor control in PV connected distribution system.

PV penetrates in distribution system as renewable resource, and with the unexpected effect on voltage by unpredictable PV's output, the job of providing stable voltage to consumer needs more advanced management by voltage control devices. Besides established voltage control devices like LRT and SVR, BESS are applied in voltage regulation as an assistance for those tap-change devices [1]-[3].With the well development of energy storage devices like HEMS and EV, a novel view on these devices is to take them as backup of BESS, and they are equal to dispersal BESS located in distribution system [4]-[6]. Therefore, rather than reactive power compensation devices which need extra construction cost, the advance application of these backup BESS, in other words, small-scale BESS group (SBG) needs to be discussed in dealing with the voltage problem caused by PV in distribution system.

To realize the application SBG as well as established device SVR in voltage control, two main parts compose the advanced method. The first part is the cooperation of SVR and SBG. In the cooperation of SVR and SBG, to perfectly suppress the voltage violation during the period of SVR's mechanical delay, the available capacity of SBG in the cooperation with SVR is crucial. Normally, for accurate voltage control, the prior study with complex control method around PV's output prediction has done a lot. And management of voltage is based on the prediction result. However, error always exists no matter which kind of the prediction method is. In this chapter, for simplicity, standard deviation and expected value realize the prediction of PV's curve. With the prediction PV's output, the voltage violation during SVR's delay period is calculated. And

SBG deals with the voltage violation with its reserved capacity.

The other part is the management of SBG. For the management of SBG, the proposed method realizes relatively average output of each BESS' in voltage suppression. In the cooperation in SBG, BESS with more available capacity provides more output during voltage control, and in this way, balances the SOC of each BESS to avoid uncertain BESS from overcharge/discharge. In the cooperation of SVR and SBG, the equivalent available capacity of SBG is calculated via summation of BESS, and reflected on SOC which is the index of SVR's operation. During the whole voltage suppression period, several times tap-change of SVR is necessary. To deal with the voltage violation during each mechanical delay of SVR's operation, the proposed initiative charge/discharge of BESS of SBG ensures the available capacity for it.

This chapter is composed by 5 sections. The cooperation of SVR and SBG according to PV prediction is proposed in section 4.2, in section 4.3 the management to balance the available capacity of each S-BESS in SBG is presented, and the verification of proposed method is shown in section 4.4. Finally, section 4.5 gives a summary.

4.2 Cooperation of SVR and SBG

4.2.1 Cooperation control of SVR and BESS

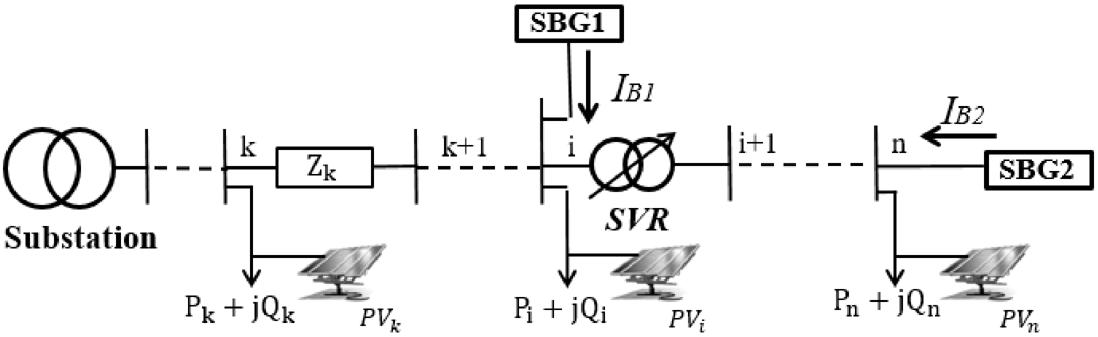

Fig. 4. 1 Model of distribution system with SVR and BESSs

Fig. 4. 1 gives the image of distribution system with SBG and SVR. There is a lot of study around SVR and BESS, however, the management of SBG in the cooperation with SVR hasn't been discussed a lot. During the cooperation, for SVR, the voltage violation in mechanical delay is urgent to be solved. The existed cooperation methods of SVR and BESS normally has BESS firstly to deal with the short period voltage violation in distribution line, and then SVR operates to solve the long period voltage violation. The fixed value of BESS's output or SOC's limit is applied as the constraint of SVR's operation. However, the existed methods ignore the PV's output variation in power flow calculation and to perfectly cooperating with SVR, excess amount is reserved to suppress the voltage into adequate range in BESS's operation. And as the amount of voltage violation changes with PV, constraint with fixed value limits the operation of BESS and

leads to ineffective utilization of BESS. In this section, according to statistics process of PV's output data, a simple prediction of PV is proposed to calculate the capacity of BESS used in voltage suppression during period of SVR's delay. And the proposed initiative charge/discharge is used in covering the voltage violation caused by the prediction error.

4.2.2 Prediction of Voltage Variation in Distribution System

Prior study on prediction of PV's output has been done a lot. With the prediction of PV, the trend of voltage variation is obtained and the operation of voltage control devices becomes more effective. However, no matter how accurate the prediction with computational complexity is, error always exists. In this section, the complexity calculation in PV's prediction isn't adopted, instead, statistical PV's output realizes the prediction.

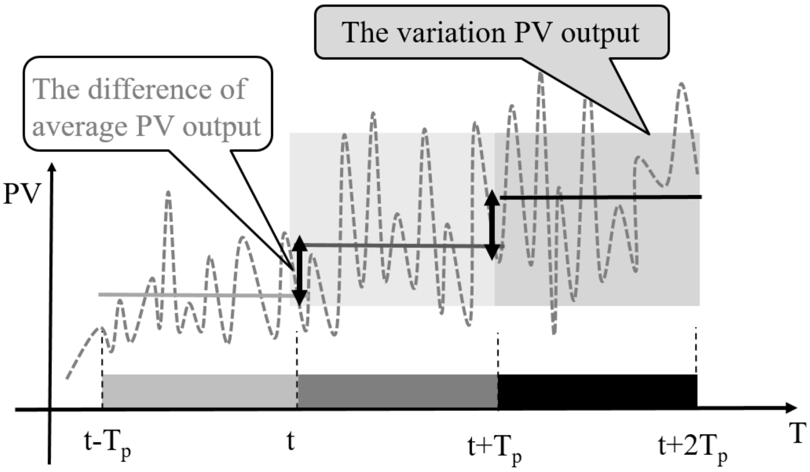

Fig. 4. 2 Image of PV prediction process

Fig. 4.2 shows the image of PV prediction process. To curtail the data of PV's measurement, prediction of PV's output is updated with a duration of Tp, and its calculation is based on the previous output in each Tp. The prediction of PV's output $\mathrm{PV(t)}$ is expressed in ratio. Taking time t as an example, and three periods, [t-Tp, t], [t, t+Tp] and [t+Tp, t+2Tp], are taken into calculation. Equation (4.1) and (4.2) express the mean value of PV's output during [t-Tp, t] and [t, t+Tp], respectively. And in equation (4.3), the average value difference of the two period is shown, and this value is applied in the prediction of PV's output in period [t+Tp, t+2Tp] as the average difference of [t, t+Tp] and [t+Tp, t+2Tp]. In this way, the average value variation is calculated.

$$\overline{\mathrm{PV}}_{[t-Tp,t]} = \frac{1}{Tp} * \int_{t-Tp}^{t} \mathrm{PV(t)}\,dt \quad \text{……………………………….}(4.1)$$

$$\overline{\mathrm{PV}}_{[t,t+Tp]} = \frac{1}{Tp} * \int_{t}^{t+Tp} \mathrm{PV(t)}\,dt \text{……………………………….}\ (4.2)$$

$$\Delta\overline{PV} = \overline{\mathrm{PV}}_{[t,t+Tp]} - \overline{\mathrm{PV}}_{[t-Tp,t]} \quad \text{(4.3)}$$

In equation (4.4), the standard deviation of PV's output in [t, t+Tp] is shown. The calculated deviation of period [t, t+Tp] is applied for the prediction in [t+Tp, t+2Tp]. Taken the regulation of node n's voltage as an example, PV's predicted variation is divided into two modes with node n's voltage magnitude as boundary. equation (4.5) shows the predicted PV's output PV_{pre} during $[\mathrm{t + Tp, t + 2Tp}]$.

$$PV_{MSE[t,t+Tp]} = \sqrt{\frac{1}{Tp} * \int_{t}^{t+Tp} (\mathrm{PV(t)} - \overline{\mathrm{PV}}_{[t,t+Tp]})^2 \, dt} \quad \text{(4.4)}$$

$$PV_{pre}[\mathrm{t + Tp, t + 2Tp}] = \overline{\mathrm{PV}}_{[t,t+Tp]} + PV_{MSE[t,t+Tp]} + \Delta\overline{PV} \quad \text{(4.5)}$$

In equation (4.5), the first part stands for the average value of PV's output, and it gives the basic value of PV's output for prediction. The second part stands for standard deviation of PV's output, and it means the variation range of PV's profile. The third part stands for average value difference between every two Tp, and it gives the average value change between two neighbor periods. In Fig. 4.3, grey curve shows the output pattern of PV in cloudy day with interval of 2s. The black curve in Fig. 4.3 shows PV's output prediction with the proposed method. The approximate PV's output is successfully obtained with simple calculation of the proposed method.

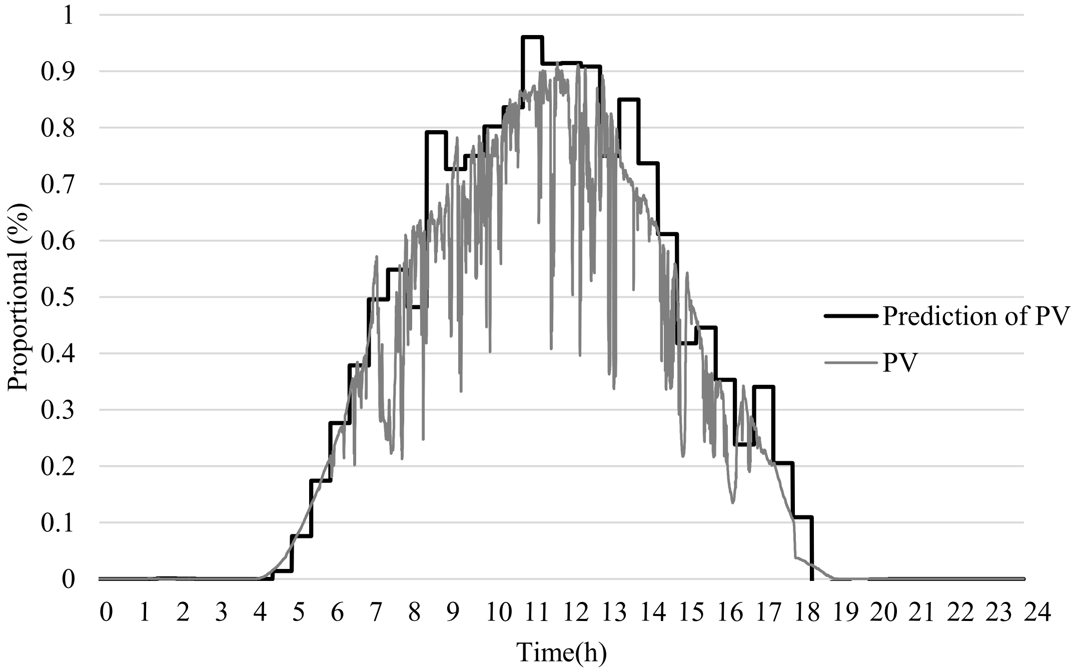

Fig. 4. 3 Image of PV's prediction

4.2.3 Cooperation of SVR and SBG

In distribution system connected with SVR and SBG, the operation time of SVR cooperated with SBG is important. The conventional control normally set a dead band to SVR to realize its operation. In this section, different from the conventional control, SVR's operation time varies along with SBG's state. SBG firstly suppresses voltage violation, and SOC of SBG changes. Value of SOC is the index to decide when SVR takes its operation. It means in the cooperation SBG releases SVR from its dead band limit. The operation image of SVR is illustrated in Fig. 4. 4. The dotted line stands for voltage's bounds. In Fig. 4. 4,with the enlargement of SVR's dead band, the operation time is reduced.

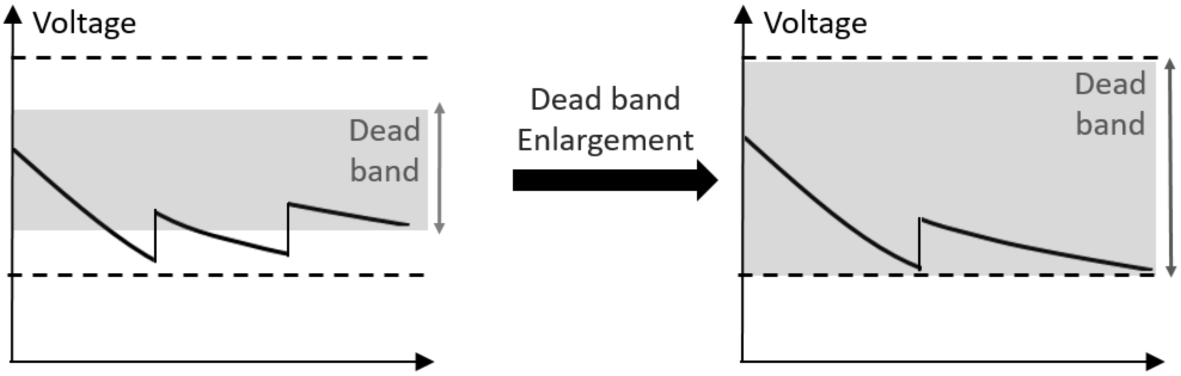

Fig. 4. 4 Enlargement of SVR's dead band

Voltage profile in PV connected distribution system is complex and unable to be controlled by SVR. SBG can provide an excellent management of voltage, moreover, on consideration of cost curtailment of SBG's application, SBG combined with SVR is proposed in this chapter. As Fig. 4. 5 shows, SBG firstly regulates voltage before dotted line, and then SVR operates with tap-change. The problem in the cooperation is to define the time of dotted line, that is, the time when voltage control changes from SBG to SVR.

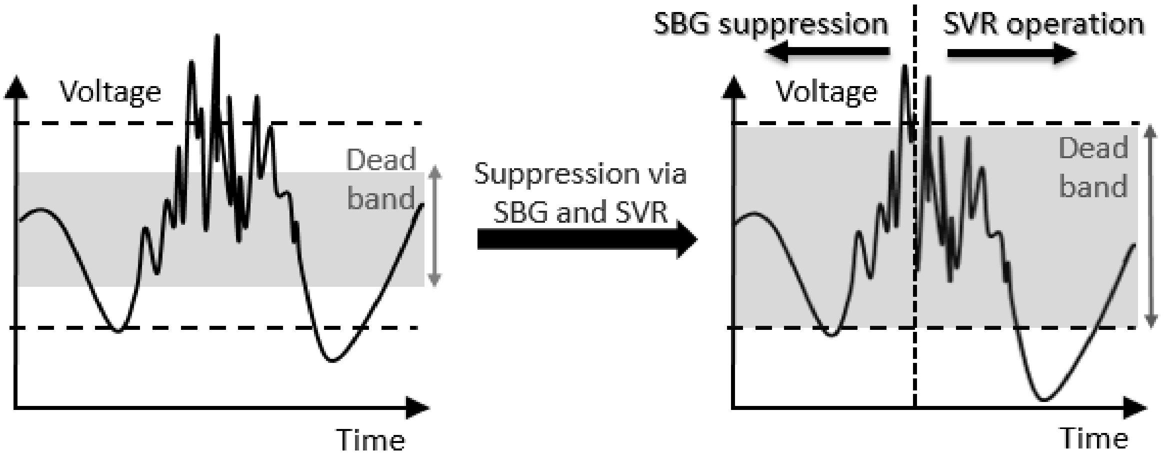

Fig. 4. 5 Image of SBG and SVR cooperation

For simplicity, Fig. 4. 6 gives a simple model of distribution system, and all PV has the same variation with 1.0 as power factor. The load consumption information is known. The voltage regulation of node n is taken as an example. (4.5) shows the predicted voltage $\dot{V}_{n-pre}$ calculated with PV's prediction output in previous section. Equation (4.6) shows the predicted voltage violation of node n. SBG gives an output to suppress the voltage violation, and the calculation of apparent power output of SBG is shown in equation (4.7)-(4.8). The active power output of SBG is shown in equation (4.9).

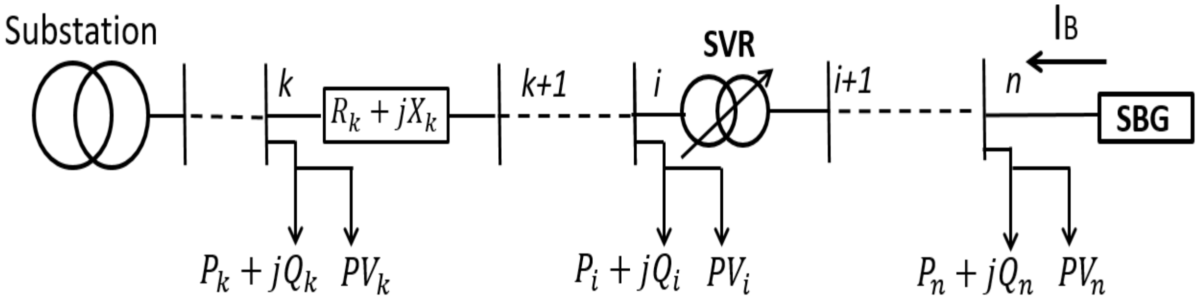

Fig. 4. 6 Simple model of distribution system

$$\dot{V}_{n-pre} = \dot{V}_0 - \frac{\sum_{k=1}^{n}[R_k \sum_{j=k}^{n}(P_j - PV_{pre-j})] + \sum_{k=1}^{n}(X_k \sum_{j=k}^{n} Q_j)}{|\dot{V}_0|} - j\frac{\sum_{k=1}^{n}[X_k \sum_{j=k}^{n}(P_j - PV_{pre-j})] + \sum_{k=1}^{n}(R_k \sum_{j=k}^{n} Q_j)}{|\dot{V}_0|} \quad \ldots\ldots(4.5)$$

$$\Delta\dot{V}_{n-pre} = \begin{cases} \dot{V}_{upperlimit} - \dot{V}_{n-pre} & if\ |\dot{V}_{n-pre}| > |\dot{V}_{upperlimit}| \\ \dot{V}_{n-pre} - \dot{V}_{lowerlimit} & if\ |\dot{V}_{n-pre}| < |\dot{V}_{lowerlimit}| \end{cases} \quad \ldots\ldots(4.6)$$

$$\Delta\dot{V}_B = \Delta\dot{V}_{n-pre} = \dot{I}_B * \sum_1^n Z_j \quad \ldots\ldots (4.7)$$

$$\dot{\mathrm{S}}_{\mathrm{B-pre}} = (\dot{V}_n + \Delta\dot{V}_{n-pre}) * \dot{\mathrm{I}}_{\mathrm{B}}^{\ *} \quad \ldots\ldots (4.8)$$

$$\mathrm{P}_{\mathrm{B-pre}} = real(\dot{\mathrm{S}}_{\mathrm{B-pre}}) \quad \ldots\ldots (4.9)$$

Where, P_j and Q_j are loads' active and reactive consumption, respectively. PV_{pre-j} is the prediction of PV's output at node j, R_k and X_k are resistance and reactance from node j-1 to node j in distribution line, $\dot{V}_{upperlimit}$ and $\dot{V}_{lowerlimit}$ are upper and lower bound of voltage, $\dot{I}_B$ is SBG's output current, Z_j is impedance of distribution line, $\dot{V}_n$ is node n's voltage before BESS's regulation.

The available capacity of SBG in voltage control is divided into two parts. The first part is to give an immediate suppression of voltage, and the other is to reserve proper capacity for voltage suppression during the mechanical delay of SVR. The definition of the second part start time is important because it also is the time when sent request to SVR.

The mechanical delay of SVR is defined as T_d, during the delay of SVR, the reservation capacity, C_{pre}, of SBG is expressed in equation (4.10) and conversed into SOC in equation (4.11). C is SBG's capacity.

$$\mathrm{C}_{pre} = \int_t^{t+T_d} P_{B-pre}\, dt \quad \ldots\ldots (4.10)$$

$$\mathrm{SOC}_{pre} = \frac{\mathrm{C}_{pre}}{C} * 100 \quad \ldots\ldots (4.11)$$

SBG always measures the voltage of node n. When violation appears, SOC of SBG varies with the active power output. According to the proposed reservation of capacity, the constraint of SOC is updated in equation (4.12) and (4.13). $\mathrm{SOC}_{upper/lowerlimit}$ is upper/lower limit of SOC. Active power output and SOC variation are in equation (4.14) and (4.15). $\Delta\dot{V}_n$ is voltage violation of node n, T_{sup} is the sampling interval. N is sampling time. The request of SVR operation is decided in equation (4.16).

$$\begin{cases} \mathrm{SOC}_{upperlimit-new} = \mathrm{SOC}_{upperlimit} - \mathrm{SOC}_{pre} \\ \mathrm{SOC}_{lowerlimit-new} = \mathrm{SOC}_{lowerlimit} \end{cases} \quad \text{if } \mathrm{SOC}_{pre} > 0 \quad \text{……….}(4.12)$$

$$\begin{cases} \mathrm{SOC}_{upperlimit-new} = \mathrm{SOC}_{upperlimit} \\ \mathrm{SOC}_{lowerlimit-new} = \mathrm{SOC}_{lowerlimit} - \mathrm{SOC}_{pre} \end{cases} \quad \text{if } \mathrm{SOC}_{pre} < 0 \quad \text{………..}(4.13)$$

$$\mathrm{P_B} = real((\dot{V}_n + \Delta\dot{V}_n) * \dot{\mathrm{I}}_{\mathrm{B}}{}^{*}) \quad \text{……………………………….. } (4.14)$$

$$\mathrm{SOC}_{sup} = \frac{\int_t^{t+\sum_1^N T_{sup}} P_B dt}{C} * 100 \quad \text{……………………………….. } (4.15)$$

$$\begin{cases} Tap = 1 \quad if\ \mathrm{SOC}_{sup} < \mathrm{SOC}_{lowerlimit-new} \\ Tap = 0 \quad if\ \mathrm{SOC}_{lowerlimit-new} < \mathrm{SOC}_{sup} < \mathrm{SOC}_{upperlimit-new} \\ Tap = -1 \quad if\ \mathrm{SOC}_{sup} > \mathrm{SOC}_{upperlimit-new} \end{cases} \quad \text{………… } (4.16)$$

In equation (4.16), if SOC_{sup} is lower than its bound $\mathrm{SOC}_{lowerlimit-new}$, SVR takes one tap up to increase the voltage. If SOC_{sup} is in its adequate range, SVR keeps its state. If SOC_{sup} runs larger than its bound $\mathrm{SOC}_{upperlimit-new}$, SVR takes one step up to decrease voltage. SOC of SBG is always measured. SBG sents the request to SVR based on the constraint in equation (4.16).

In the application of SBG, the constraint of SOC prevents battery from over charge/discharge. In the operation of SVR, the delay of control makes it unable to provide an immediate regulation of voltage. In this section, the cooperation of SBG and SVR is proposed with the consideration of the mentioned problem above with updated limit of SOC. Furthermore, in the case that more than one SBG locate in distribution line, the one near the objective node is applied to send request to SVR in the cooperation.

4.3 Cooperation of small-scale BESS in SBG

In this chapter, the SBG composed by small-scale BESS (S-BESS) is used in distribution system. Along with the application of small-scale BESS, HEMS and EV fitted with battery is also under well development. These energy storage devices are potential backup of BESS that disperse in distribution system, and from this view, the control method of dozens small-scale BESS in distribution system is meaningful. And in future smart-grid, all these energy storage devices instead of intentional construction of BESS is promising in the liberalization of power market. Therefore, this section focuses on the management of dispersal S-BESS in distribution system. The simple model of SBG in distribution system is shown in Fig. 4. 7. SBG locates in distribution line. For simplicity, SBG1 and SBG2 are defined to be the equivalent of the aggregation composed by dozens of S-BESS as the dotted line zone shown in Fig. 4. 7. j is number of S-BESS from 1 to

n. And for simplicity, the line impedance of each S-BESS is ignored.

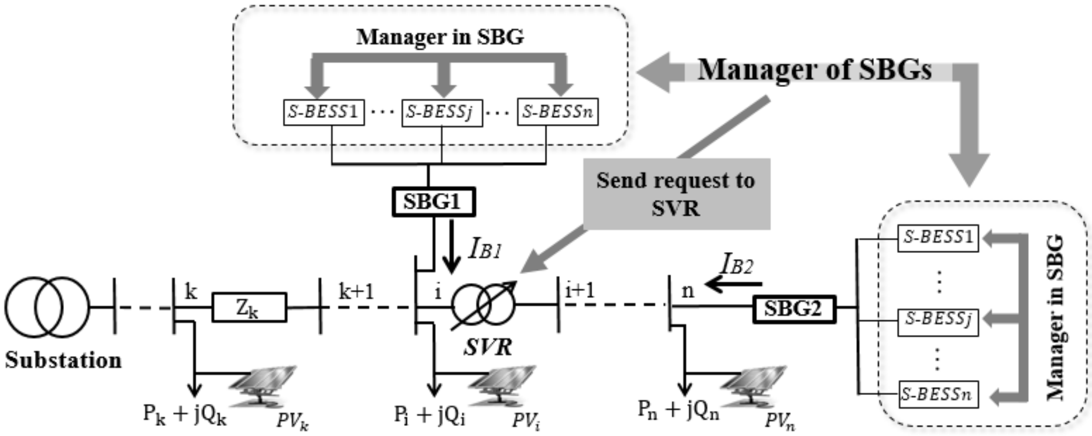

Fig. 4. 7 Image of SBG in distribution system

In prior chapter, the cooperation of BESS is proposed. In this section, for simplicity, image of SBG in Fig. 4. 7 is taken as an example. In this cooperation of S-BESS in SBG, the issue is to make sure the equivalent SOC of each SBG for cooperation with SVR. Therefore, the capacity and SOC of each S-BESS is needed. From equation (4.17) to (4.18), the available capacity of each S-BESS and equivalent SBG is calculated with SOC. And the summation of S-BESS available capacity and capacity give the equivalent capacity and SOC of each SBG.

$$\begin{cases} AC_j(\mathrm{t}) = \left(\mathrm{SOC}_{upperlimit} - SOC_j(\mathrm{t})\right) * C_j \\ AC_j(\mathrm{t}) = \left(SOC_j(\mathrm{t}) - \mathrm{SOC}_{lowerlimit}\right) * C_j \end{cases} \quad \cdots\cdots (4.17)$$

$$AC_{SBG-k}(\mathrm{t}) = \textstyle\sum_1^n AC_j(\mathrm{t}) \quad \cdots\cdots (4.18)$$

$$C_{SBG-k}(\mathrm{t}) = \textstyle\sum_1^n C_j(\mathrm{t}) \quad \cdots\cdots (4.19)$$

$$SOC_{SBG-k}(\mathrm{t}) = \frac{AC_{SBG-k}(\mathrm{t})}{C_{SBG-k}(\mathrm{t})} \quad \cdots\cdots (4.20)$$

$$w_{SBG-k}(\mathrm{t}) = \frac{AC_{SBG-k}(\mathrm{t})}{\sum AC_{SBG-k}(\mathrm{t})} \quad \cdots\cdots (4.21)$$

Where, $SOC_j(\mathrm{t})$ is SOC of S-BESS at time t. C_j is capacity of each S-BESS, j is the number of S-BESS in each SBG, n is the total number of S-BESS in each SBG, k is the number of SBG.

For suppression of voltage in node n, the equality constraint is shown in equation (4.22). With the equality constraints, the output division of each SBG is obtained.

$$\left|\Delta\dot{V}_n\right| = w_{SBG-k}(\mathrm{t}).*\left|\Delta\dot{V}_n\right| + w_{SBG-j\neq k}(\mathrm{t}).*\left|\Delta\dot{V}_n\right| \quad \cdots\cdots (4.22)$$

[step 2]

For simplicity, the line impedance between S-BESS in each SBG is ignored, and the connection number of S-BESS is unchanged. Based on equation (4.17), the available capacity of each S-BESS is obtained, the weight coefficient w_{SBESSj} of each S-BESS to decide its output is shown in equation (4.25). Based on step 1, the apparent power and active power output of each SBG $\dot{\mathrm{S}}_{SBG-\mathrm{k}}$ and $\mathrm{P}_{SBG-\mathrm{k}}$ is shown in equation (4.23) and (4.24) with power flow calculation, respectively. And active power of each S-BESS, P_{BESSj}'s division is decided in equation (4.25). $\dot{V}_k$, $\Delta\dot{V}_{Bk}$ is voltage of the node connected with SBG, and voltage variation caused by SBG, respectively. Z is impedance of distribution line. In this way, with the share in SBG's output, the synchronous operation of each S-BESS with consideration of its capacity and SOC in voltage suppression is realized.

$$\dot{\mathrm{S}}_{SBG-\mathrm{k}} = (\dot{V}_k + \Delta\dot{V}_{Bk} + \Delta\dot{V}_{Bj<k} + \Delta\dot{V}_{Bj>k} * \frac{\sum_1^k Z_j}{\sum_{j>k}^n Z_j}) * (\frac{\Delta\dot{V}_{Bk}}{\sum_1^k Z_j})^* \quad \text{........} \; (4.23)$$

$$\mathrm{P}_{SBG-\mathrm{k}} = \mathrm{real}(\dot{\mathrm{S}}_{SBG-\mathrm{k}}) \quad \text{..............................} \; (4.24)$$

$$w_{SBESSj}(\mathrm{t}) = \frac{AC_j(\mathrm{t})}{\sum_1^n AC_j(\mathrm{t})} \quad \text{.......................................} \; (4.25)$$

$$P_{\mathrm{BESSj}}(t) = w_{SBESSj}(\mathrm{t}) * P_{\mathrm{SBG-k}}(t) \quad \text{................................} \; (4.26)$$

Fig. 4. 8 gives the flowchart of this chapter. With the proposed method and BESS output calculation in [7], SBG composed by S-BESS cooperating with SVR realizes the voltage and VUF control.

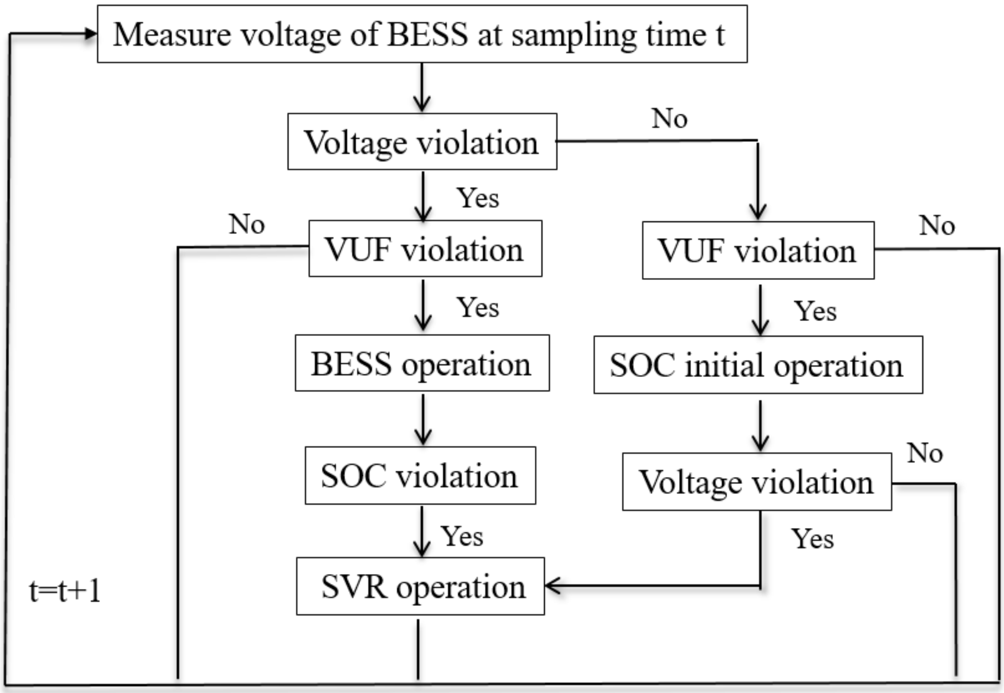

Fig. 4. 8 Flowchart of proposed method.

4.4 Case study

4.4.1 Distribution system model and simulation conditions

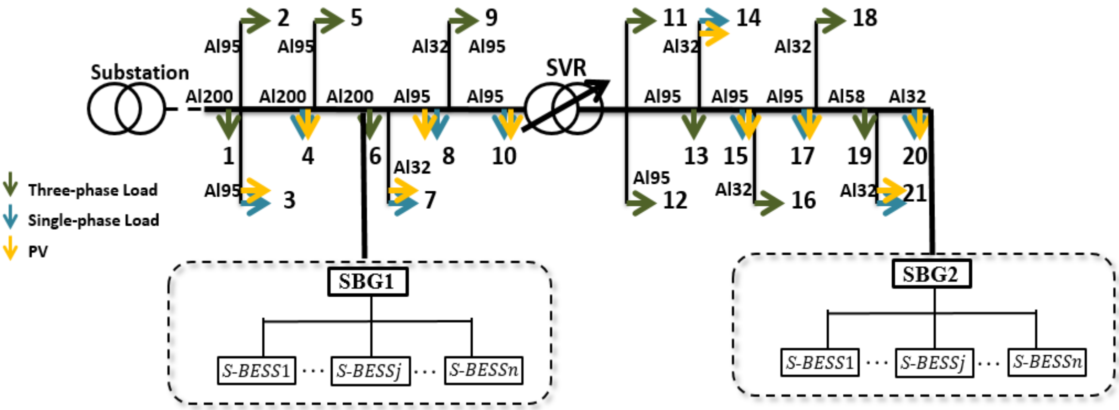

Fig. 4. 9 Distribution system model

Fig. 4. 9 is model of distribution system which has 21 loads with PV. The green arrows stand for three-phase loads. The blue arrows stand for single-phase loads that are residential load. PV is connected with single-phase loads. SBGs separately set at node 6 and the end of distribution line. SVR is set in the middle of distribution line to verify the cooperation of SBG and SVR. Table 4.1 shows the parameters. Table 4.2 shows the single-phase load's placement.

Table 4.1. Distribution line's data.

Impedance of distribution line	Al32:0.899 + j0.389Ω/km Al58:0.497 + j0.331Ω/km Al95:0.301 + j0.315Ω/km Al200:0.182 + j0.288Ω/km
Total length of the line	3.09km

Table 4.2 Connection of single-phase load.

Connection phase	Load No.
a-b	3, 8, 15, 21
b-c	4, 10, 17, 20
c-a	7, 14

The pattern of three-phase loads is illustrated in Fig. 4. 10 and consumption is 125kW of each one. Fig. 4. 11 shows the load pattern of single-phase load which ranges from 108kW to 648 kW. Fig. 4. 12 illustrated the output in cloudy day. The capacity of PV equals to the 1.5 times of single-phase load consumption. All of them are given in standardization.

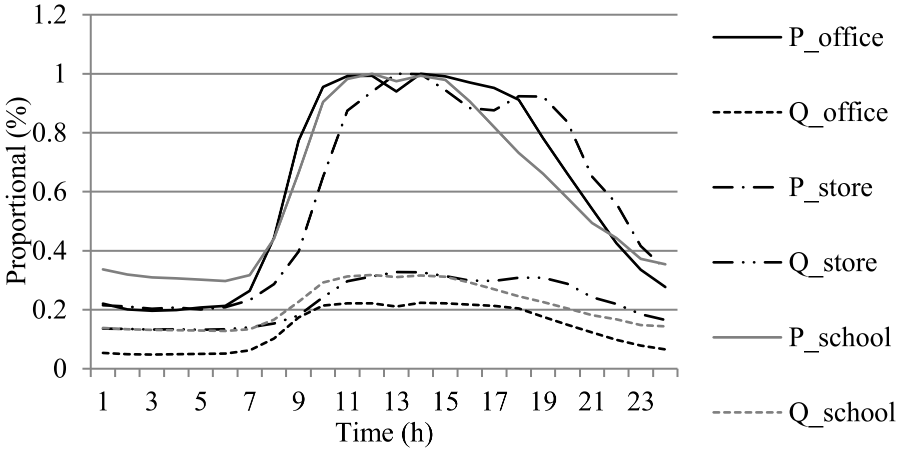

Fig. 4. 10 Three-phase load's pattern

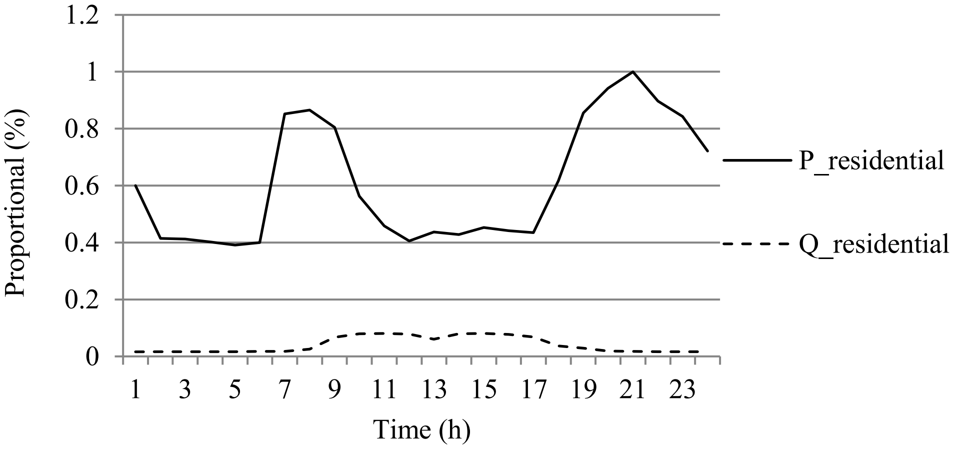

Fig. 4. 11 Single-phase load's pattern

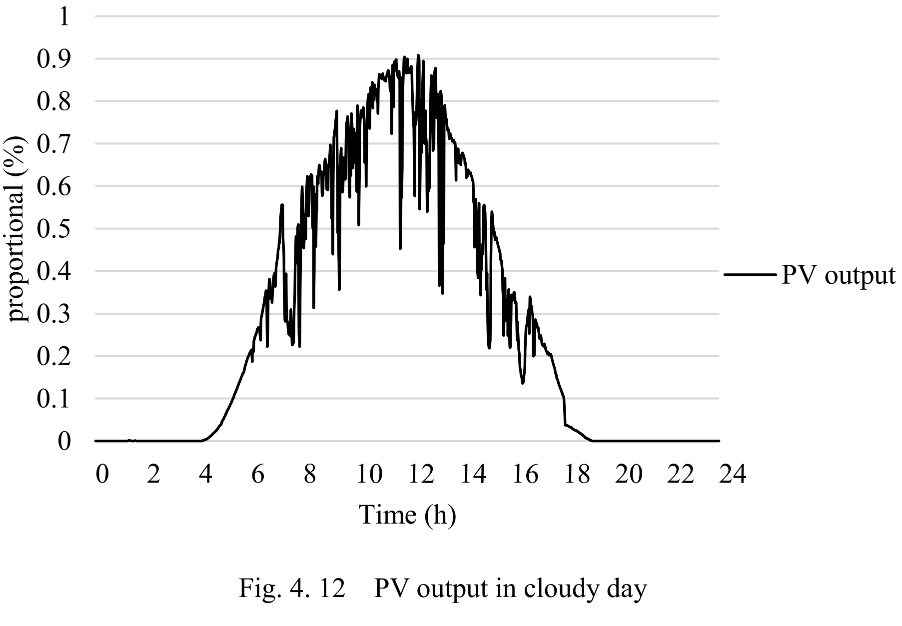

Fig. 4. 12 PV output in cloudy day

The time step of the simulation is 10 s. The adequate range of line voltage is from 102 to 107 conversed to low voltage side using voltage ratio (= 6600/105). In Table 4.3 gives the simulation conditions.

Table 4.3. Simulation conditions.

Simulation time	24hours
Simulation interval	10s
Adequate range's $\mathrm{V_{upper\ limit}}$	107V (up voltage)
Adequate range's $\mathrm{V_{lower\ limit}}$	102V (low voltage)
Ratio of voltage	6600/105
Sending voltage of substation	6600V
Initial SOC of S-BESS	30%,40%,50%, 60% and 70%
One tap of SVR	75V
SVR dead band (conventional)	3%
Delay of tap-change	8.0s
Delay of SBG setting time	2.0s
Capacity of each S-BESS	1kWh
Number of S-BESS in SBG	5
SOC limit	20%-90%
VUF limit	1%

Table 4.4 shows the simulation cases. Voltage management of the end of distribution line is taken to verify the proposed method. Case 1 is distribution system without BESS and SVR, and it is taken as a reference case. Case 2 only has SVR regulates the voltage. In case 3, SVR and SBG are deal with voltage violation without cooperation. Case 4 has two SBG cooperating with SVR, but no cooperation between SBG. In case 5, SBGs and SVR is operated with proposed method, but no cooperation between S-BESS in SBG. Case 6 verifies the proposed method with SVR and SBG.

Table 4.4 Simulation cases.

Case	SBG in operation	Cooperation of SVR and SBG	Cooperation of S-BESS
Case 1	No SVR and BESS		
Case 2	Only SVR operation		
Case 3	SBG2	No	No
Case 4	SBG2	Proposed	No
Case 5	SBG1 and SBG2	Proposed	No
Case 6	SBG1 and SBG2	Proposed	Proposed

4.4.2 Simulation results

[case 1]

Fig. 4. 13 and Fig. 4. 14 shows the voltage profile and VUF variation in case 1. The voltage is conversed to low voltage side. With the output of PV, voltage rans out of its adequate range [102V, 107V] at around 12pm. And with the increasing consumption of consumer, voltage excesses its lower limit at around 19 pm. VUF profile has a significant relation with power consumption change in single -phase load.

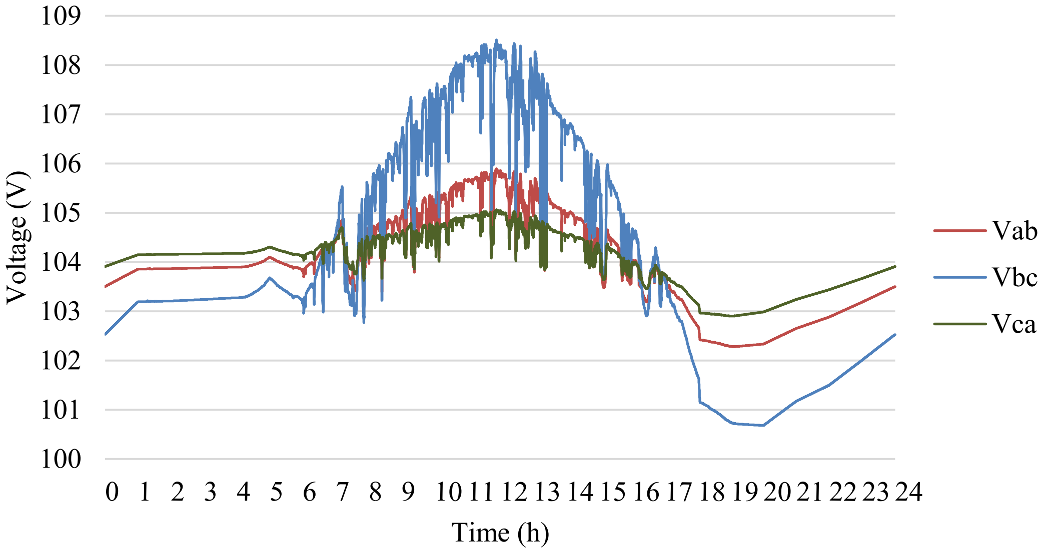

Fig. 4. 13 Voltage of node 21 in case 1

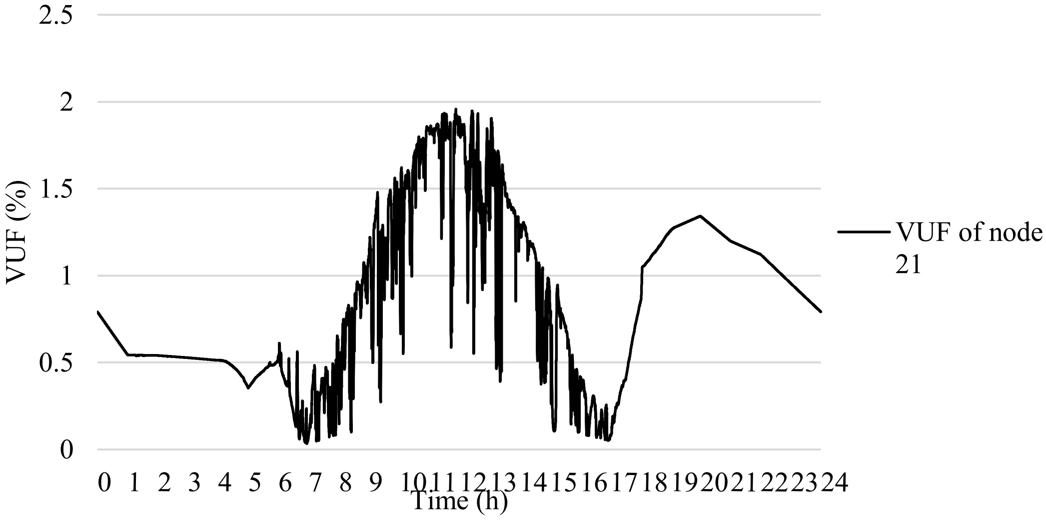

Fig. 4. 14 VUF of node 21 in case 1

[case 2]

In case, voltage violation is control by SVR with 3% width of dead band. SBG measures the voltage and send request to SVR to call for its operation. From the result of voltage profile, the problem of SVR for voltage management in PV connected system is obvious. Because of sudden and variable voltage change caused by PV, the operation of SVR is in high frequency and the fixed regulation amount in voltage magnitude leads to unexpected violation around 12 pm. The frequency tap-change is damage to SVR 's life time. Also, no improvement appears at VUF with the operation of SVR. In conclusion, voltage management in PV connected distribution system can't be perfectly control just with SVR.

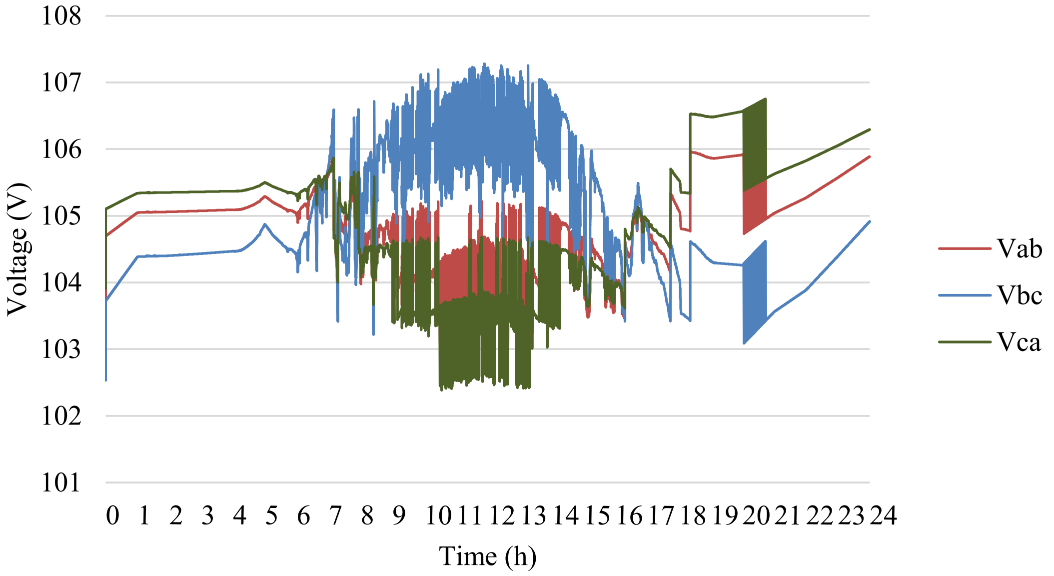

Fig. 4. 15 Voltage of node 21 in case 2

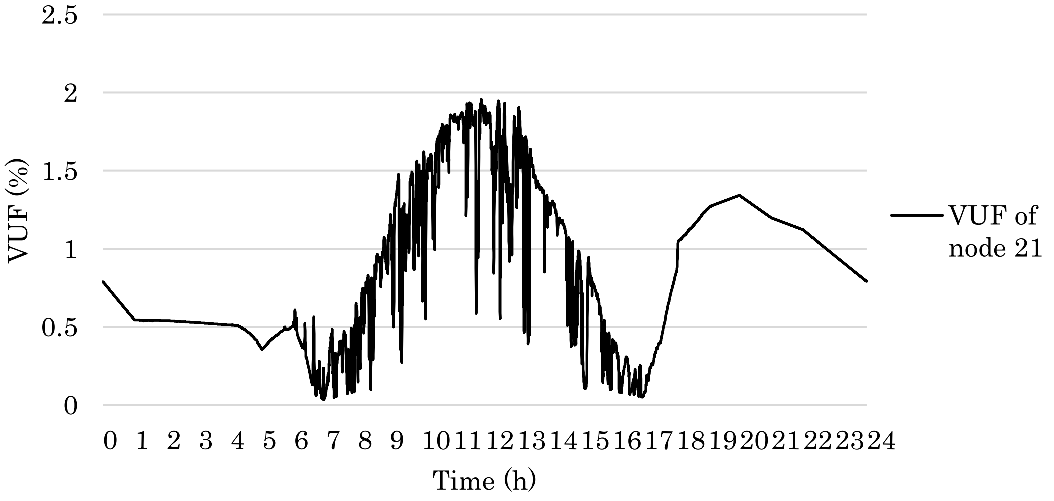

Fig. 4. 16 VUF of node 21 in case 2

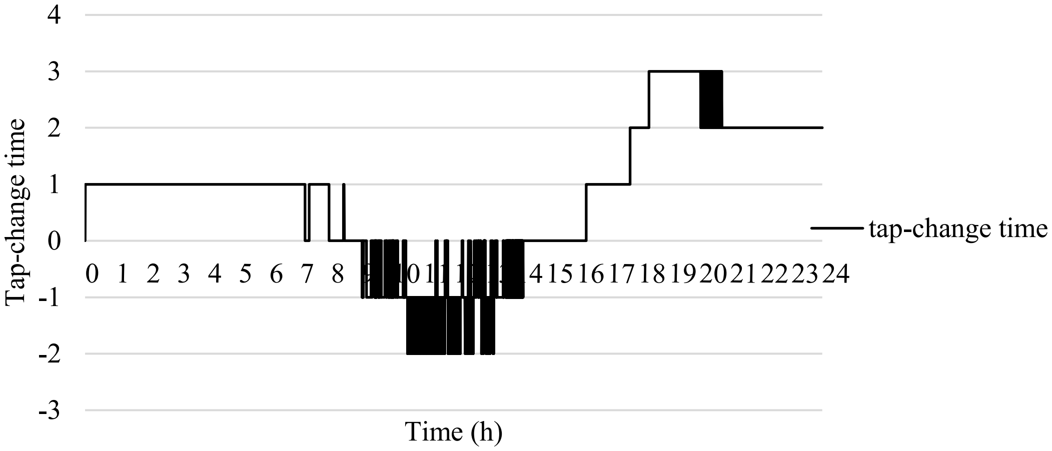

Fig. 4. 17 SVR tap change in case 2

[case 3]

In case 3, SBG and SVR work together in voltage control. SBG2 sends request to SVR based on its SOC variation. And according to conventional method in cooperation of SVR and BESS, SOC is set with the fixed limit [30%, 80%] comparing to its adequate range [20%, 90%]. With the assistance of BESS in dealing with the sudden voltage variation, SVR's dead band is enlarged to [102V,107], and it does significant reduce the tap-change time of SVR. However, there is still violation around 9 am and 13 pm. It occurs because the constraint set in SOC, and it can't sufficient for all voltage violation suppression during the cooperation. The operation period of SBG2 is short in voltage suppression and it leads to poor utilization of SBG. Also, VUF improvement has been done during voltage suppression. The voltage measured by SBG1 is always in its proper range, and SBG1 gives no output.

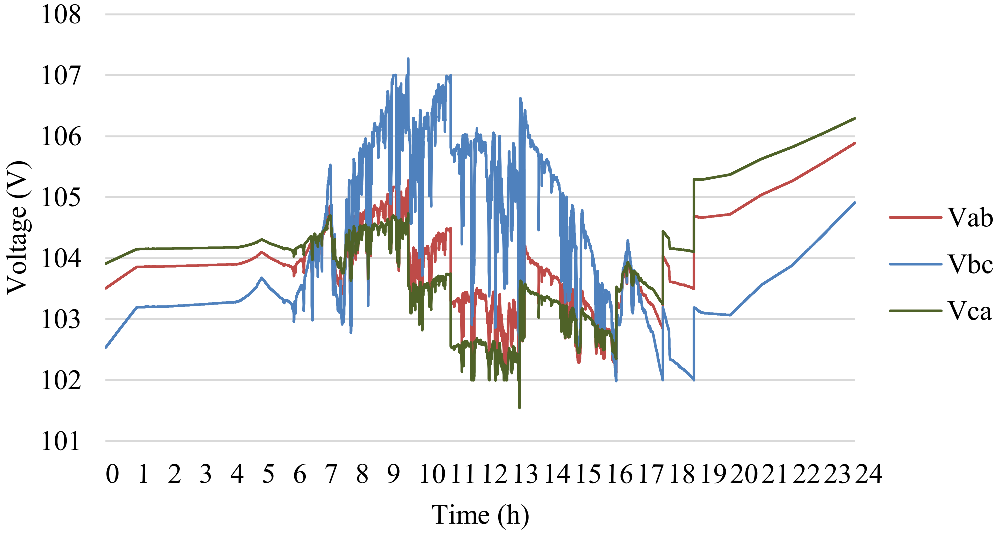

Fig. 4. 18 Voltage of node 21 in case 3

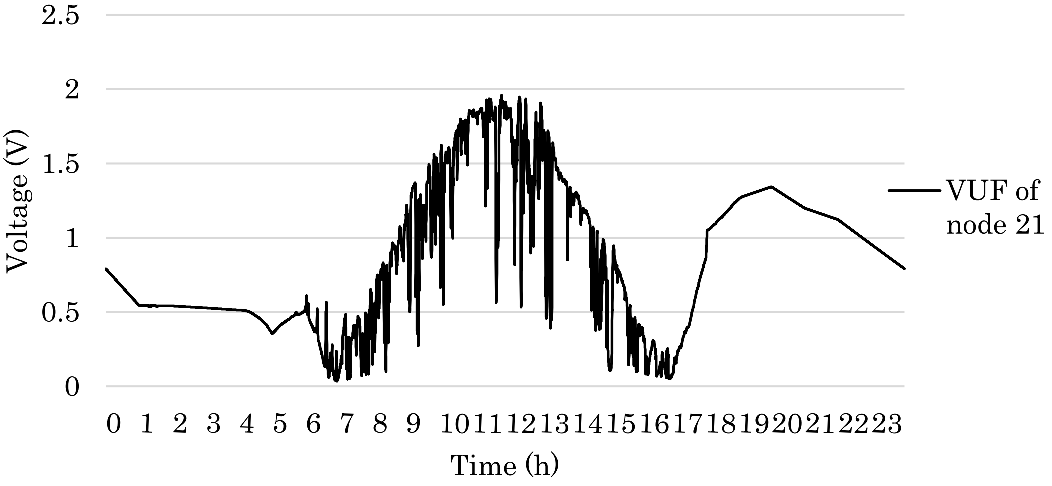

Fig. 4. 19 VUF of node 21 in case 3

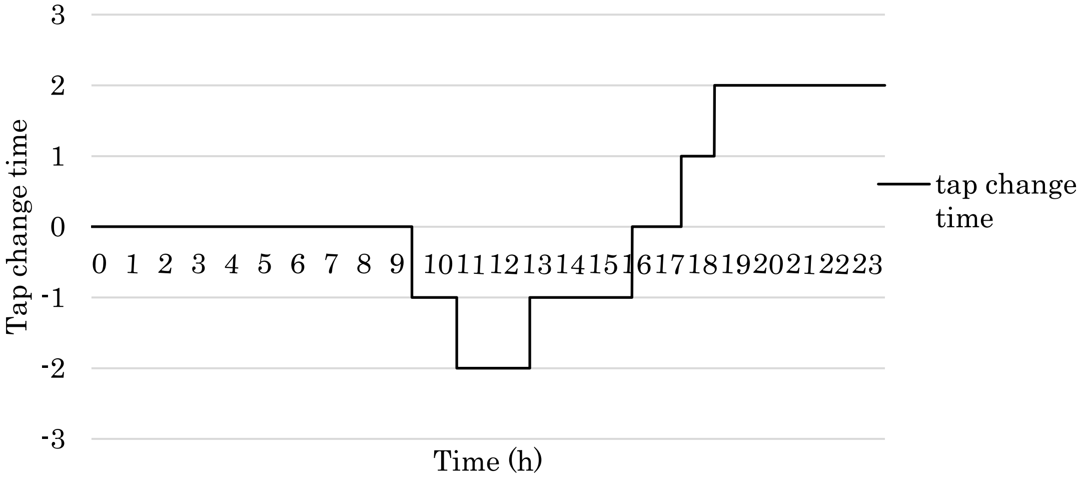

Fig. 4. 20 SVR tap change in case 3

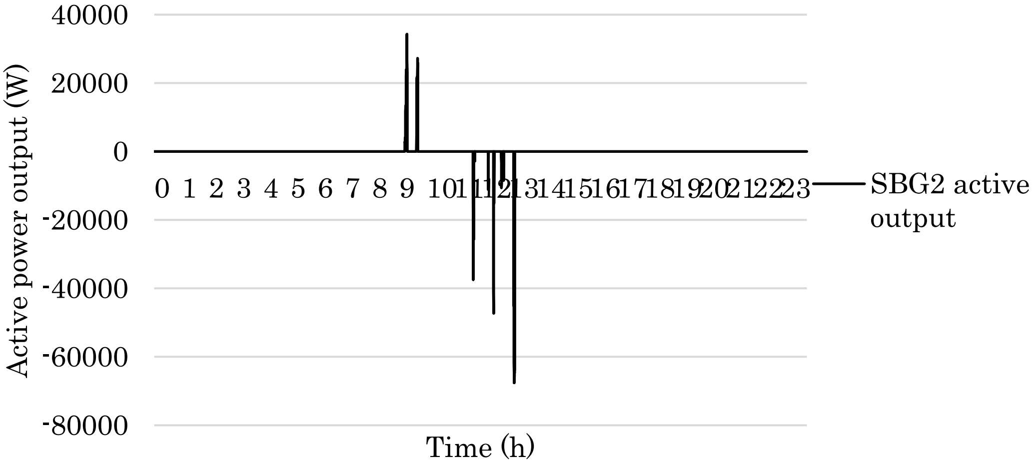

Fig. 4. 21 SBG active power output in case 3

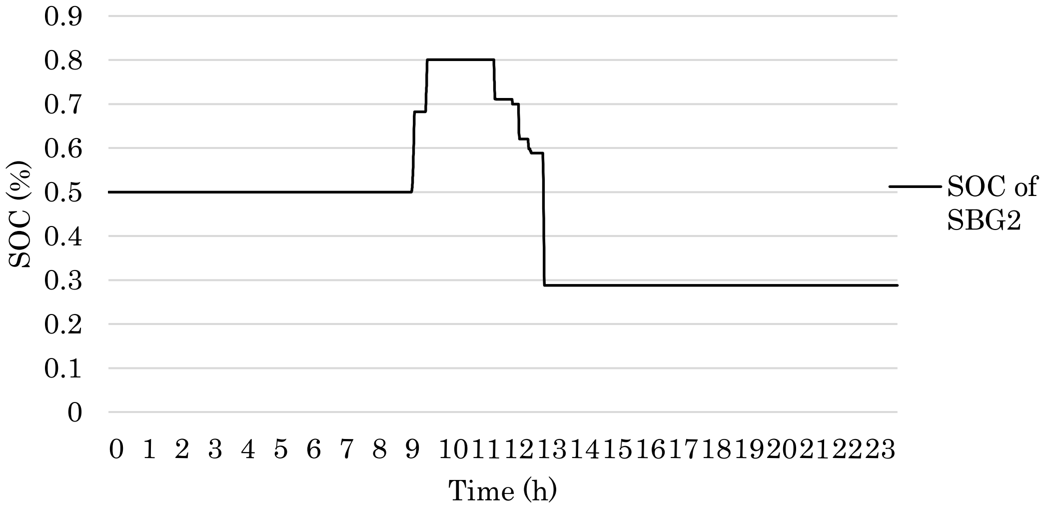

Fig. 4. 22 SOC in case 3

[case 4]

Comparing to case 3, during the cooperation of SVR and SBG, case 4 enlarges SOC's range to [20%, 90%] with consideration of reserved amount of SOC discussed in section 3.2.3. And VUF improvement is operated with initiative charge/discharge discussed in section 3.4. Voltage and VUF is perfectly managed, and SOC of SBG2 is always regulated to 0.5 during the whole period with initiative charge/discharge. The peak value of SBG active power output is around 300kW. Although tap-change time is more than case 3, from the view of voltage and VUF results, the increased tap-change times is meaningful. SBG1 gives no output, because voltage and VUF measured by SBG1 are in their adequate range. And cooperation of SBG isn't operated in case 4.

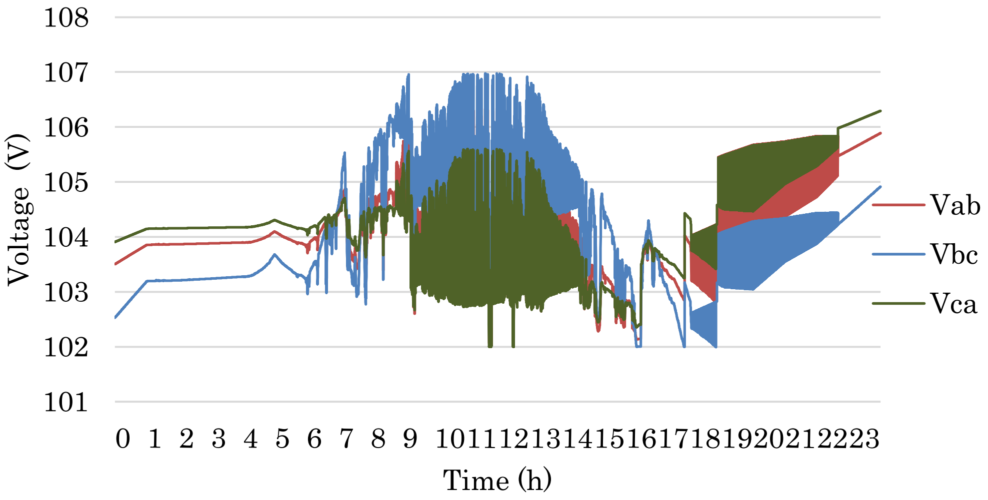

Fig. 4. 23 Voltage of node 21 in case 4

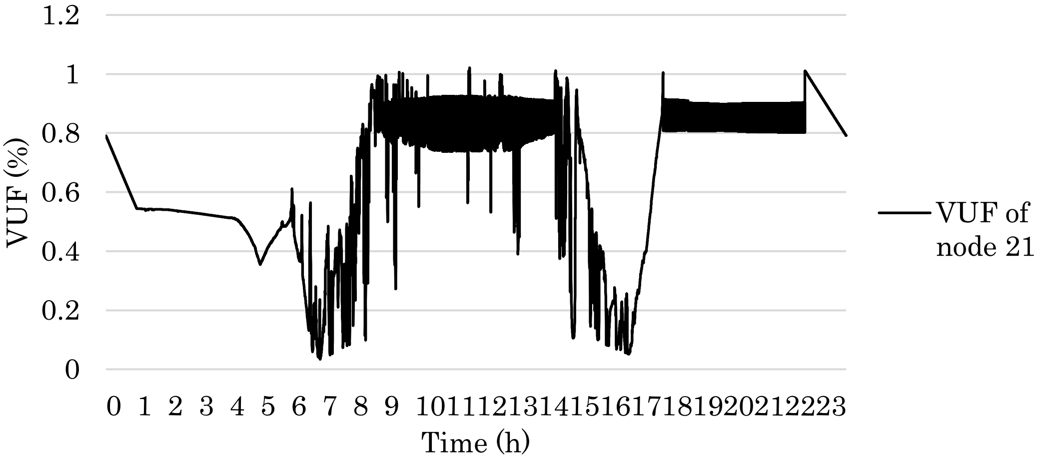

Fig. 4. 24 VUF of node 21 in case 4

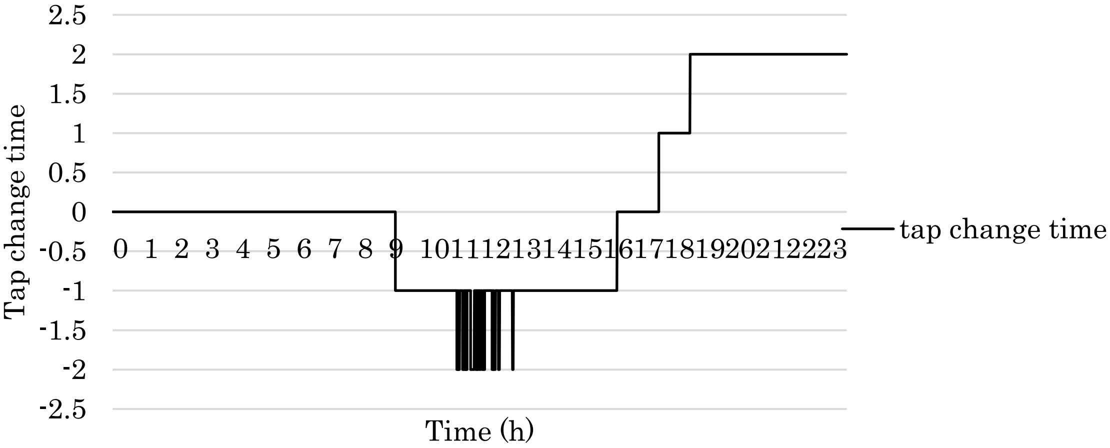

Fig. 4. 25 SVR tap change in case 4

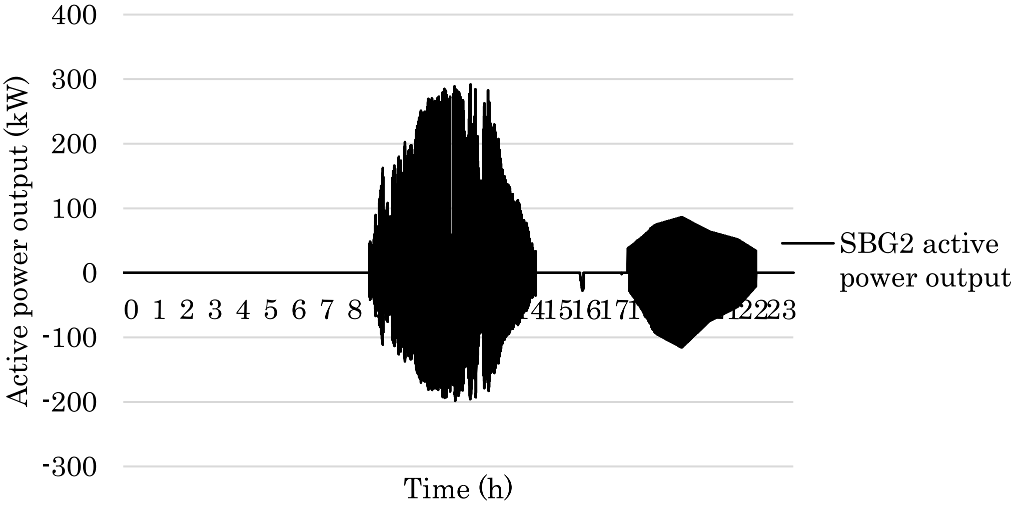

Fig. 4. 26 SBG active power output in case 4

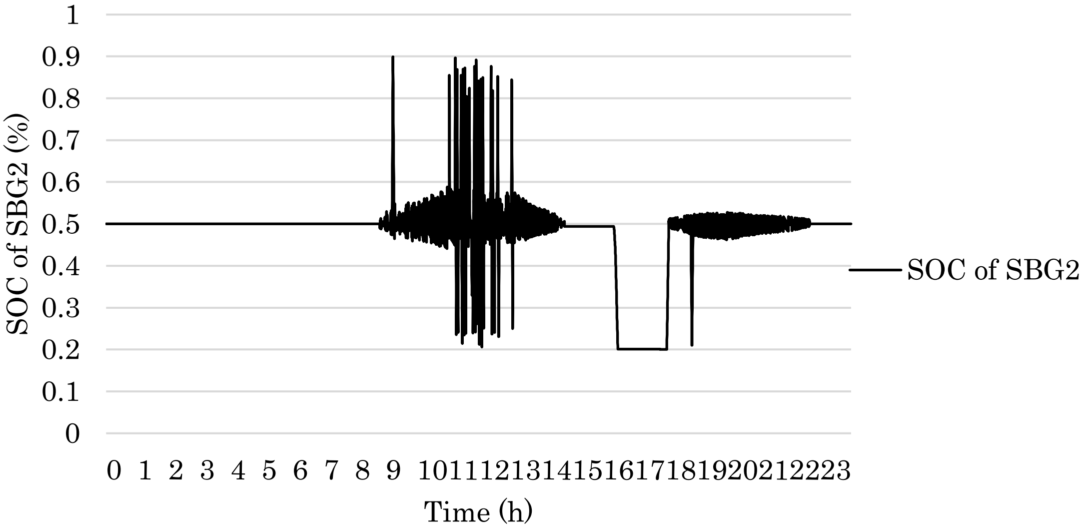

Fig. 4. 27 SOC in case 4

[case 5]

In case 5, the cooperation between SVR and SBG, and SBGs is done. And each SBG is composed by 5 S-BESSs. The initiative SOC of each S-BESS is set from 30% to 70% with 10% as interval. The cooperation between S-BESS isn't operated.

From the result of voltage, the proposed cooperation presents well. SOC of S-BESS is always in its adequate range. The cooperation of the two SBGs reduce the peak value of active power output to around 170kW comparing to case 4. However, VUF violation appears around 12pm. The reason of the violation is insufficient output of SBGs. In Fig. 4. 32 and Fig. 4. 33, it can be seen that S-BESS reaches its bound by turns and enters to no-operation period. Because SOC of SBG is still in proper range, assistance from SVR won't appear. With the increasing of no-operation S-BESS number, the total output of SBG is decreased as SBG's output is the summation of all S-BESS. Therefore, the insufficient SBG's output leads to the violation of VUF. Although after SVR operation, SOC of each S-BESS gets closed value for average operation period of each S-BESS, the difference of SOC still has bad effect on VUF suppression. The verification of cooperation of S-BESS is done in SBG1. A sudden difference of SOC is added to S-BESS in SBG1 at around 20 pm. From the result of SOC, the difference between S-BESS always exists. And in future application of S-BESS, large amount of S-BESS with different SOC leads to the difficult management and ineffective utilization like VUF violation in case 5.

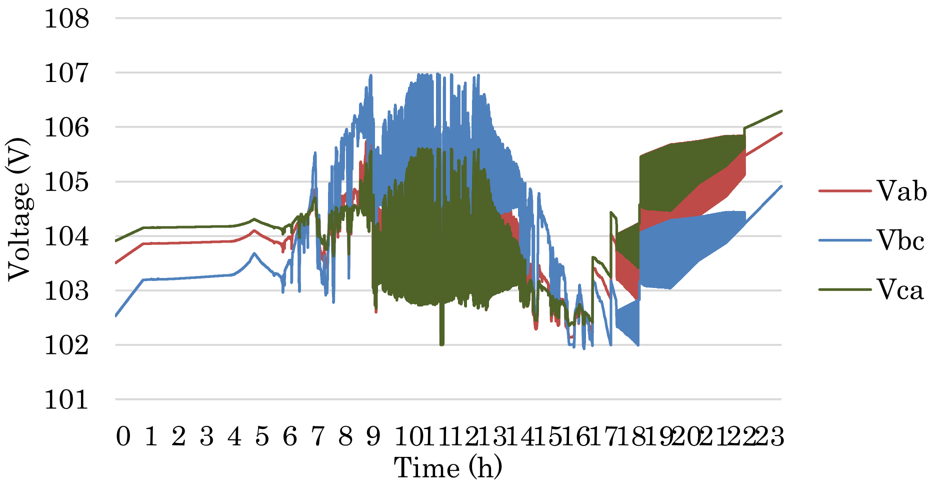

Fig. 4. 28 Voltage of node 21 in case 5

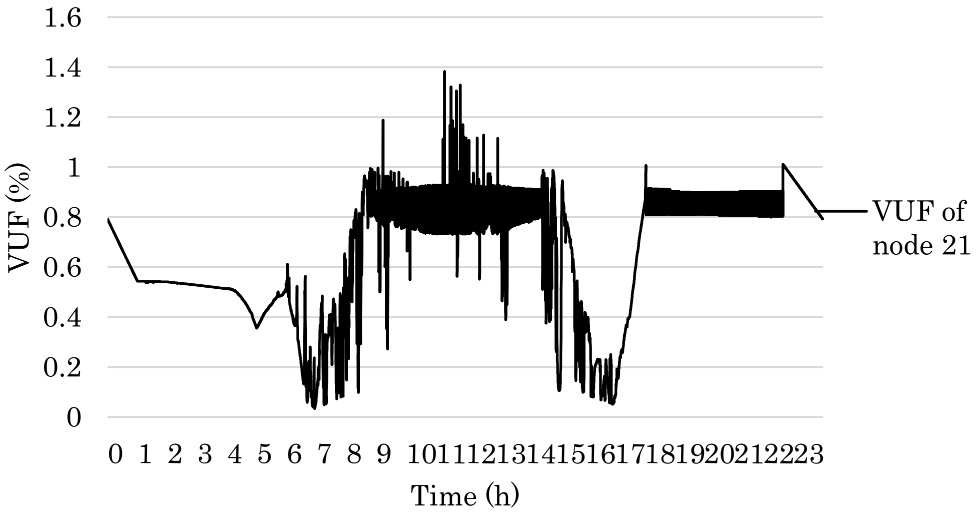

Fig. 4. 29 VUF of node 21 in case 5

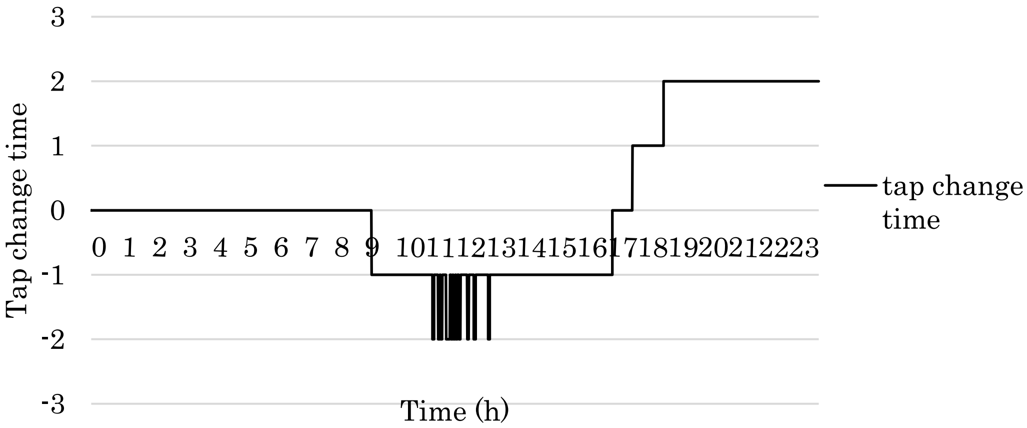

Fig. 4. 30 SVR tap change in case 5

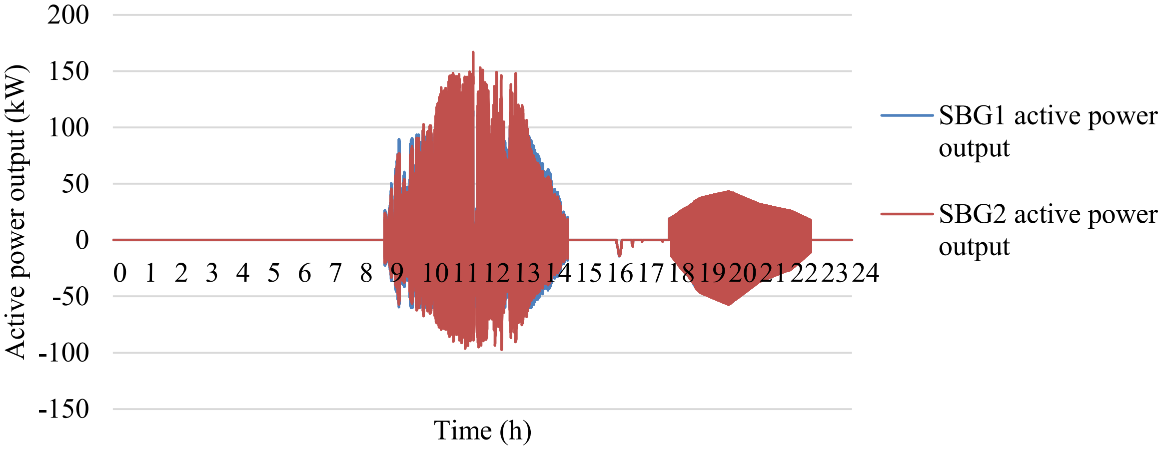

Fig. 4. 31 SBG active power output in case 5

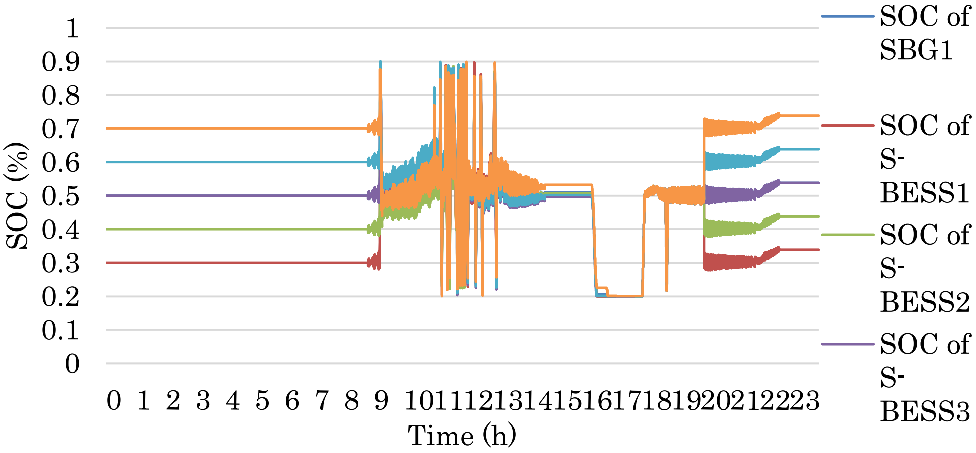

Fig. 4. 32 SOC of SBG1 in case 5

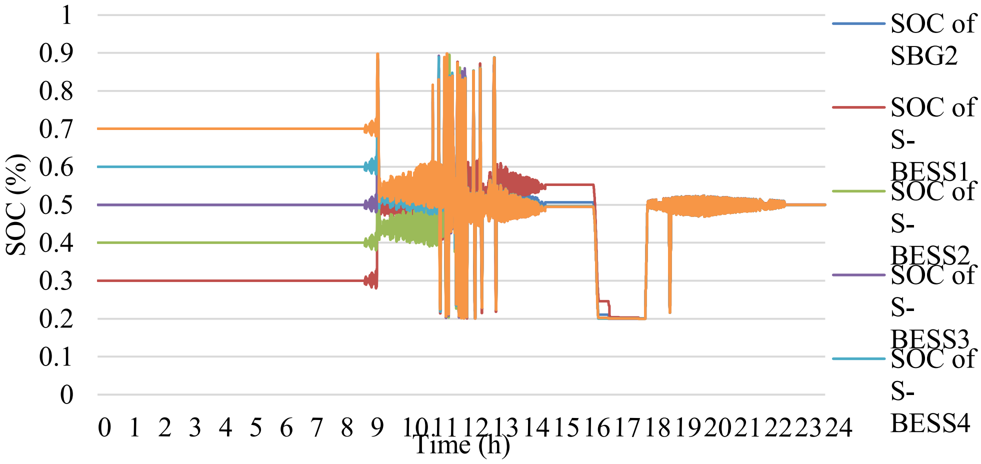

Fig. 4. 33 SOC of SBG2 in case 5

[case 6]

Case 6 has the same simulation conditions with case 5, and besides cooperation in SVR and SBG, and SBGs, cooperation of S-BESS in SBG is verified here. Voltage and VUF results show the excellent control. Also comparing to case 4, the peak active power output is reduced with the cooperation of SBG. Different from case 5, with the cooperation of S-BESS, SOC of each S-BESS is regulated to approximate value even before the tap-change of SVR.

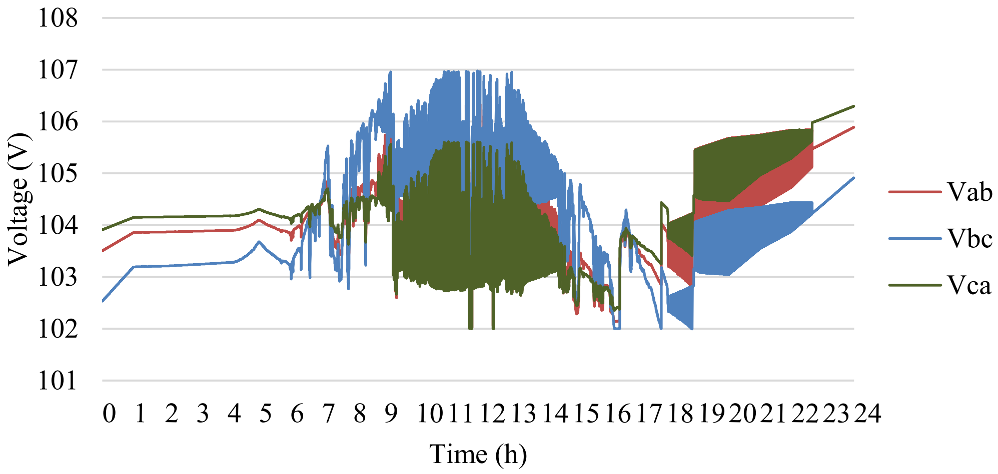

Fig. 4. 34 Voltage of node 21 in case 6

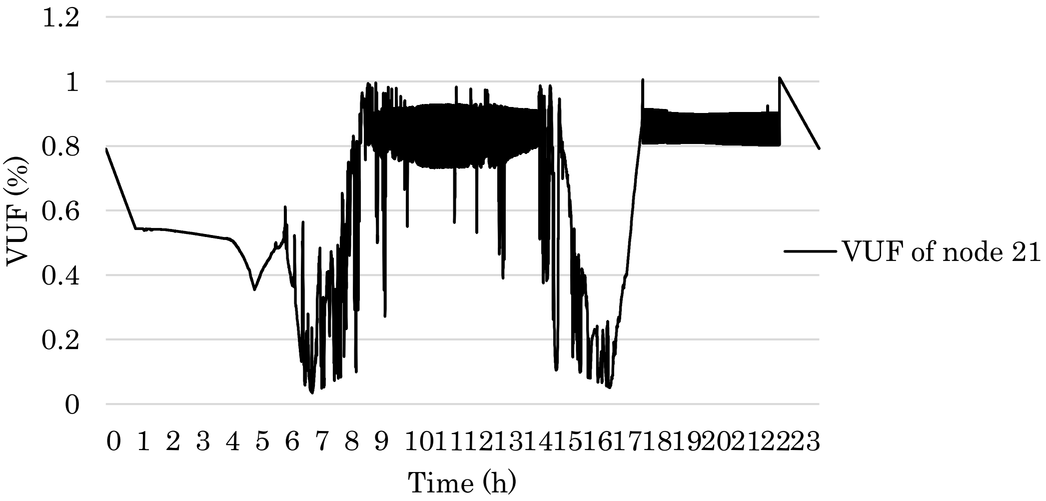

Fig. 4. 35 VUF of node 21 in case 6

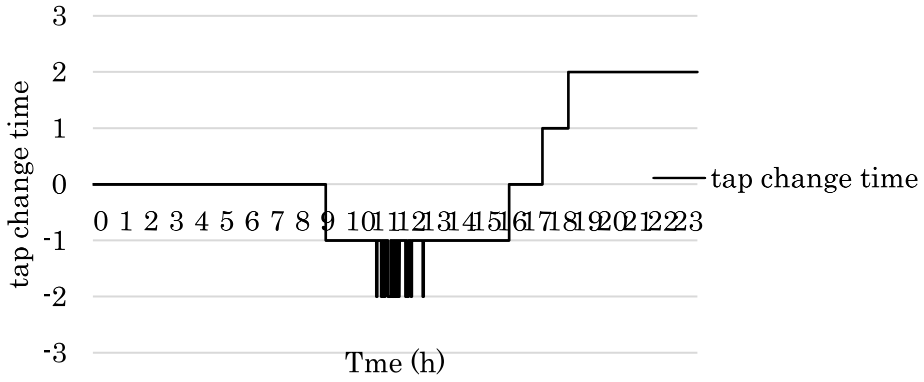

Fig. 4. 36 SVR tap change in case 6

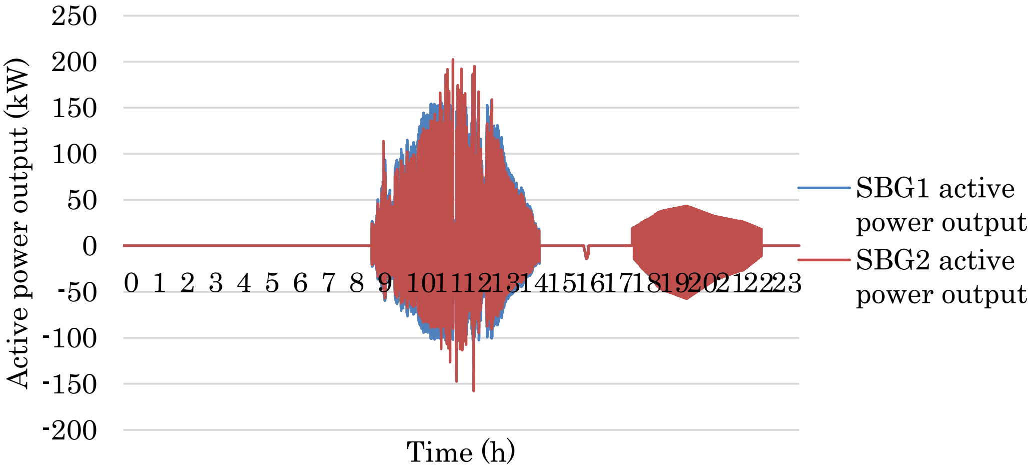

Fig. 4. 37 SBG active power output in case 6

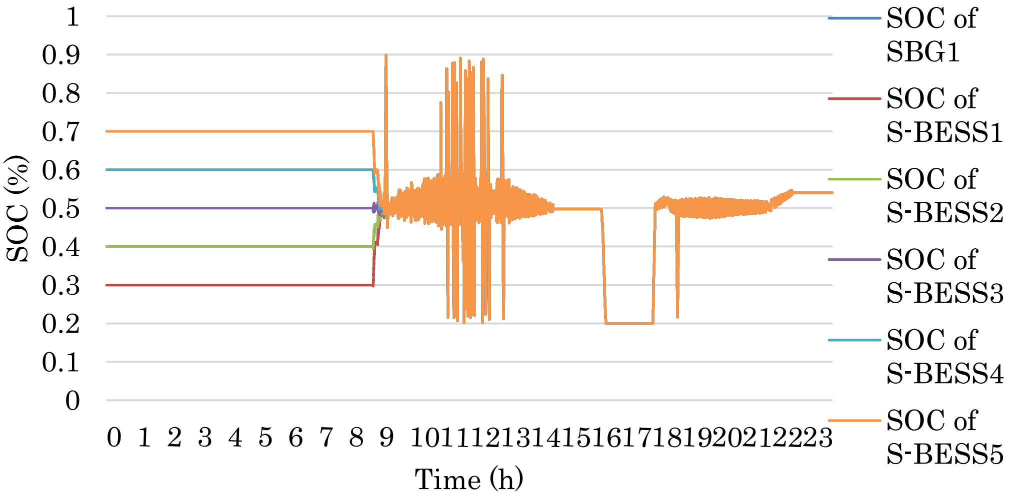

Fig. 4. 38 SOC of SBG1 in case 6

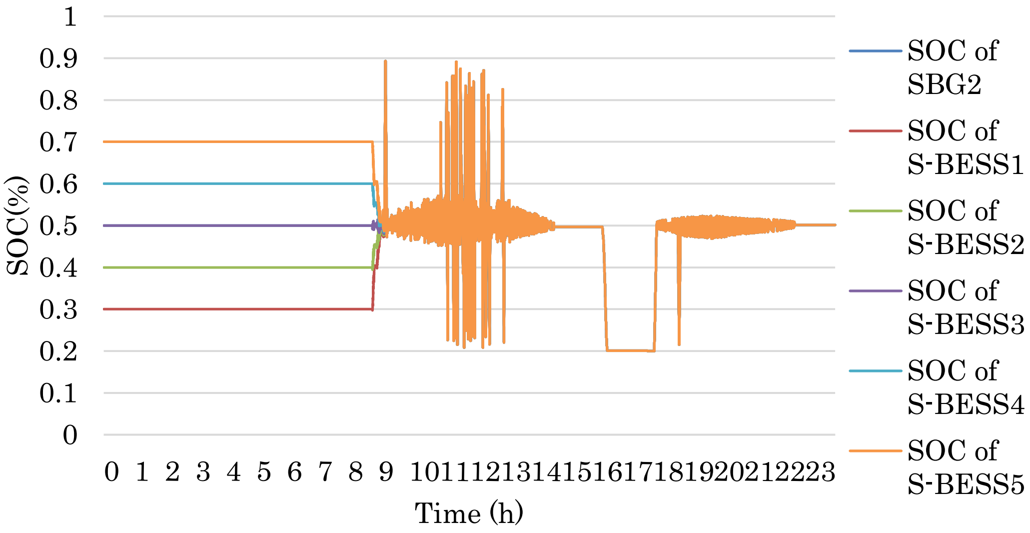

Fig. 4. 39 SOC of SBG2 in case 6

4.5 Discussion and summary

This chapter proposes a novel method in S-BESS cooperation, SBG cooperation and cooperation of SBG and SVR in voltage and VUF management in PV connected distribution system. The control result proves the effective proposed method. The initiative charge/discharge of SBG makes more available capacity in voltage management. Especially the cooperation of S-BESS is hopeful to promote the application of BESS in future.

In future work, the effect of proposed initiative charge/discharge on SBG's cycle time needs to be discussed. The voltage fluctuation caused by proposed initiative charge/discharge is wanted to be suppressed for further stable power supply. And variable situation of SBG like connected number and S-BESS's SOC initial value is necessary to be studied. Also, the definition of SBG by S-BESS in distribution system needs to be decided.

4.6 References

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Chapter 5

Voltage fluctuation suppression via cooperation of energy storage devices in PV connected distribution system

5.1 Introduction

PV is used in distribution system as a clean power generation resource, and with the increasing of PV, the voltage fluctuation becomes worse to provide stable voltage to consumers. The established tap-change devices like SVR and LRT only regulate voltage by fixed magnitude via one tap-change, and they are insufficient to suppress voltage fluctuation. In previous chapter, novel method in voltage and voltage unbalance suppression via BESS, SC and SVR has been discussed. In voltage control of distribution system, BESS cooperates with established devices to solve the voltage violation operation delay. With the development of BESS, the development of other energy storage devices like HEMS and EV in distribution system also draws author's attention. In distribution system, especially remote area, the large amount of PV causes severe fluctuation of voltage and leads to poor power quality [1]-[3]. Besides the application of BESS for voltage control, the utilization of HEMS and EV on voltage management is hopeful via power retail system. Therefore, this chapter focuses on the cooperation of these energy storage devices in distribution system to suppress voltage fluctuation for stable voltage supply.

BESS provides excellent control in dealing with the voltage problem caused by PV [4]-[7]. With the promotion of energy storage devices' application in smart-grid, besides BESS, HEMS largely locate in distribution system and has the same feature with BESS. Also, another energy storage device EV randomly appears in distribution system. In solving the voltage problem by BESS, HEMS and EV are wanted to share the control job with BESS for reduction of BESS's capacity, and promote power market liberalization in voltage management. And this becomes one point of this chapter. The other point of the proposed cooperation of these energy storage devices is to deal with the bad effect on voltage caused by quick-charge of EV with uncertain location and number in distribution system. With all these energy storage devices, the objective of this chapter is to propose the cooperation of these three-type energy storage devices in voltage fluctuation suppression in PV connected distribution system.

This chapter is composed by 5 sections. The proposed voltage fluctuation suppression via BESS is shown in section 5.2, in section 5.3 the cooperation of energy storage devices is presented, and the proposed method is verified by case study in section 5.4. Finally, section 4.5 gives a summary.

5.2 Suppression of voltage fluctuation via energy storage devices

5.2.1 BESS's output in voltage control

The fast growth of PV in distribution causes the complex voltage profile, and BESS compared with other devices is capable to deal with the voltage problem caused by PV. Considering of the unique element in BESS, the capacity of battery draws the author's attention for cost reduction because utilization of battery is limited with its recycle time. In prior research, the study of capacity reduction of battery hasn't been done a lot. In this section, during the voltage control via BESS, the optimal active power output of BESS is proposed for capacity reduction of battery.

In this section, the optimal active power output is discussed for voltage control. BESS is taken as the current resource. During the voltage regulation, the exact current from BESS for minimal active power output is obtained.

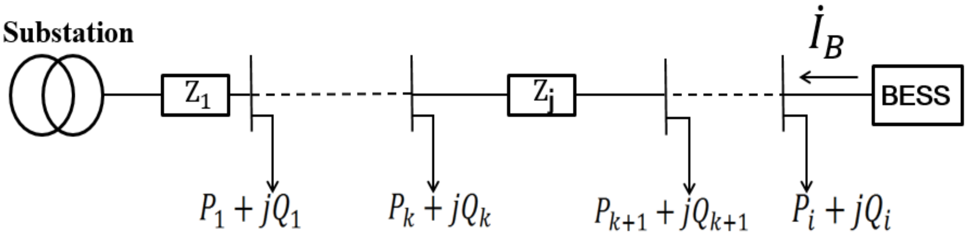

Fig. 5. 1 Model of distribution system

In Fig. 5. 1, a simple distribution system is illustrated. P_i and Q_i are the load consumption. Z_j is the impedance of distribution line. BESS is connected at node i and gives an output current $\dot{I}_B$. The voltage of node i is $\dot{V}_i$, and the reference voltage of node i is $\dot{V}_{ref}$. When the voltage of node i runs out of its adequate range, BESS regulates $\dot{V}_i$ to its reference voltage $\dot{V}_{ref}$. Voltage variation caused by BESS is $\Delta\dot{V}_B$. In equation (5.1) and (5.2), voltage variation by BESS is shown. The apparent power of BESS is shown in equation (5.3). By substituting $\dot{I}_B$ in equation (5.1) and $\dot{V}_i'$ in equation (5.2) to (5.3), the apparent power output of BESS is arranged in equation (5.4).

$$\Delta\dot{V}_B = \dot{I}_B * \textstyle\sum_1^i Z_j \quad \dots\dots \quad (5.1)$$

$$\dot{V}_{ref} = \dot{V}_i + \Delta\dot{V}_B \quad \dots\dots \quad (5.2)$$

$$\dot{S}_B = \dot{V}_{ref} * \dot{I}_B{}^* \quad \dots\dots \quad (5.3)$$

$$\dot{S}_B = (\dot{V}_i + \Delta\dot{V}_B) * \left(\frac{\Delta\dot{V}_B}{\sum_1^i Z_j}\right)^* \quad \dots\dots \quad (5.4)$$

After arrangement, equation (5.5) is derived.

$$\dot{S}_B = \frac{\Delta V_B{}^2}{\sum_1^i Z_j{}^*} + \dot{V}_i * \left(\frac{\Delta\dot{V}_B}{\sum_1^i Z_j}\right)^* \quad \dots\dots \quad (5.5)$$

Here, to obtain the accurate active power output from BESS, the apparent power output of BESS is changed from Cartesian coordinates to Polar coordinates as shown in equation (5.6). And the active power output of BESS is shown in equation (5.7). θ_Z, θ_{V_i} and $\theta_{\Delta VB}$ are the angle of $\sum_1^i Z_j$, $\dot{V_i}$ and $\Delta\dot{V_B}$ in Polar coordinates, respectively.

$$\dot{S}_B = \frac{\Delta V_B{}^2}{\sum_1^i Z_j}\angle\theta_Z + V_i * \frac{\Delta V_B}{\sum_1^i Z_j}\angle(\theta_{V_i} - \theta_{\Delta V_B} + \theta_Z) \ldots\ldots\ldots\ldots \text{(5.6)}$$

$$P_B = \frac{\Delta V_B{}^2}{\sum_1^i Z_j}\cos\theta_Z + V_i * \frac{\Delta V_B}{\sum_1^i Z_j}\cos(\theta_{V_i} - \theta_{\Delta V_B} + \theta_Z) \ldots\ldots\ldots \text{(5.7)}$$

In equation (5.7), for the regulation of $\dot{V_i}$, two variables, ΔV_B and $\theta_{\Delta VB}$, decide the value of P_B. With the variation of the magnitude and angle of $\Delta\dot{V_B}$, P_B is changed. Therefore, the extreme value of P_B is decided by $\Delta\dot{V_B}$. The regulation of voltage is divided into two cases.

In Fig. 5. 2, the image of voltage control by BESS is illustrated. The left side gives the case that voltage V_i is larger than its reference voltage, and the right side shows the case that V_i is smaller than its reference voltage.

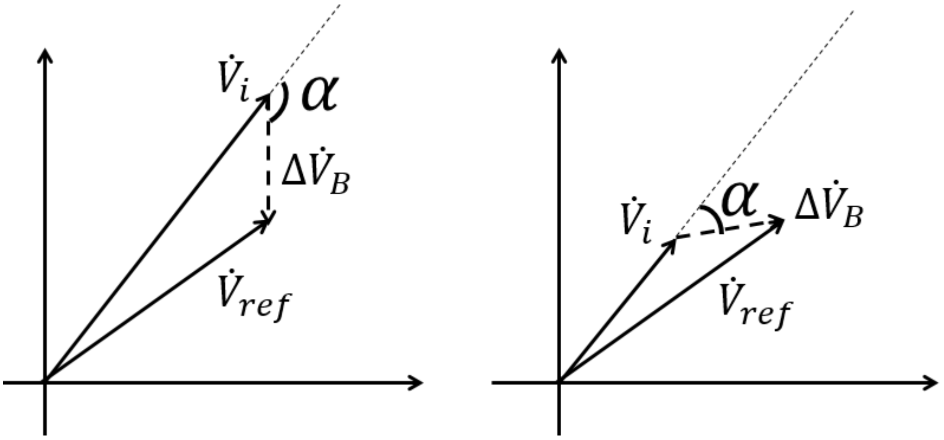

Fig. 5. 2 Image of voltage's angle

The difference of $\dot{V_i}$ and $\Delta\dot{V_B}$'s angle is set as a variable α. In the triangle composed by $\dot{V}_{ref}$, $\dot{V_i}$ and $\Delta\dot{V_B}$, the relation shown in equation (5.8) is derived from cosine theorem.

$$\cos(\pi - \alpha) = \frac{V_i{}^2 + \Delta V_B{}^2 - V_{ref}{}^2}{2 * V_i * \Delta V_B} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.8)}$$

In equation (5.8), the value of $\dot{V_i}$ and $\dot{V}_{ref}$ are always known. After arrangement, the relation of α and ΔV_B is shown in equation (5.9). From equation (5.9), the magnitude of $\Delta\dot{V_B}$ is derived by the difference of $\dot{V_i}$ and $\Delta\dot{V_B}$'s angle α. It means the two variables in equation (5.7) changes to one. And the optimization of active power from BESS is discussed in two cases below.

$$\Delta V_B = V_i * \cos(\pi - \alpha) \pm \sqrt{(V_i * \cos(\pi - \alpha))^2 - \left(V_i{}^2 - V_{ref}{}^2\right)} \ldots\ldots\ldots\ldots \text{(5.9)}$$

[Case 1]

In Fig. 5. 3, the image of voltage control when voltage of node i $\dot{V}_i$ is larger than its reference voltage $\dot{V}_{ref}$ is illustrated, the black dotted curve stands for the value of its reference voltage $\dot{V}_{ref}$, and the arrows in blue dotted line stand for the angle in the blue index. To regulate $\dot{V}_i$ to its reference voltage, the included angle of $\dot{V}_i$ and $\Delta\dot{V}_B$ is obtuse angle, and the limit value of their included angle is $\theta_{V_i} + \theta_Z \pm 0.5 * \pi$.

From the view of $\theta_{\Delta VB}$, according to equation (5.7), when $\theta_{\Delta VB} = \theta_{V_i} + \theta_Z \pm \pi$, P_B gets the maximal output. For function P_B, intervals $(\theta_{V_i} + \theta_Z + 0.5 * \pi, \theta_{V_i} + \theta_Z + \pi)$ and $(\theta_{V_i} + \theta_Z - 0.5 * \pi, \theta_{V_i} + \theta_Z - \pi)$ are symmetric interval, therefore, the interval $(\theta_{V_i} + \theta_Z + 0.5 * \pi, \theta_{V_i} + \theta_Z + \pi)$ is set as the range of $\theta_{\Delta VB}$. In the range of $\theta_{\Delta VB}$, P_B is a monotonic function.

From the view of ΔV_B, in the range of $\theta_{\Delta VB}$, P_B has a quadratic relation with ΔV_B, and when $\theta_{\Delta VB} = \theta_{V_i} + \pi$, as the right of Fig. 3 illustrated, P_B obtains its minimal value.

Therefore, the range of $\theta_{\Delta VB}$ is updated to $(\theta_{V_i} + \theta_Z + 0.5 * \pi, \theta_{V_i} + \pi)$.

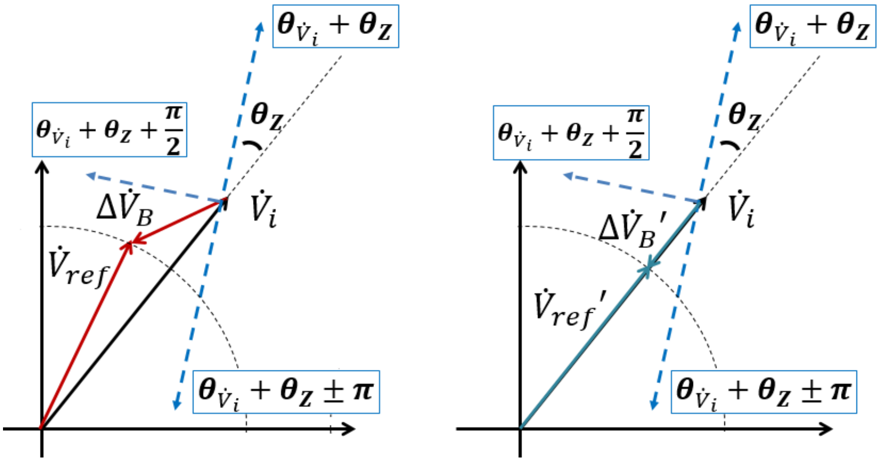

Fig. 5. 3 Image of voltage control

Voltage of node i $\dot{V}_i$ is larger than its reference voltage $\dot{V}_{ref}$. α is an obtuse angle. Based on equation (5.9), ΔV_B in case 1 is shown in equation (5.10).

$$\Delta V_B = V_i * \cos(\pi - \alpha) - \sqrt{(V_i * \cos(\pi - \alpha))^2 - \left(V_i{}^2 - V_{ref}{}^2\right)} \quad \ldots\ldots\ldots\ldots\ldots (5.10)$$

Substituting ΔV_B in equation (5.10) to equation (5.7), the active power output is arranged in equation (5.11).

$$P_B = \frac{(k1 - k2)^2}{\sum_1^i Z_j}\cos\theta_Z + V_i * \frac{(k1 - k2)}{\sum_1^i Z_j}\cos(\alpha + \theta_Z) \quad \ldots\ldots\ldots\ldots (5.11)$$

Where, $k1 = V_i * \cos(\pi - \alpha)$; $k2 = \sqrt{k1^2 - \left(V_i{}^2 - V_{ref}{}^2\right)}$

[Case 2]

As the same with case 1, when voltage of node i $\dot{V}_i$ is smaller than its reference voltage $\dot{V}_{ref}$, as Fig. 5. 4 illustrates, the range of $\theta_{\Delta VB}$ is updated to $(\theta_{V_i} + \theta_Z - 0.5 * \pi,\ \theta_{V_i})$.

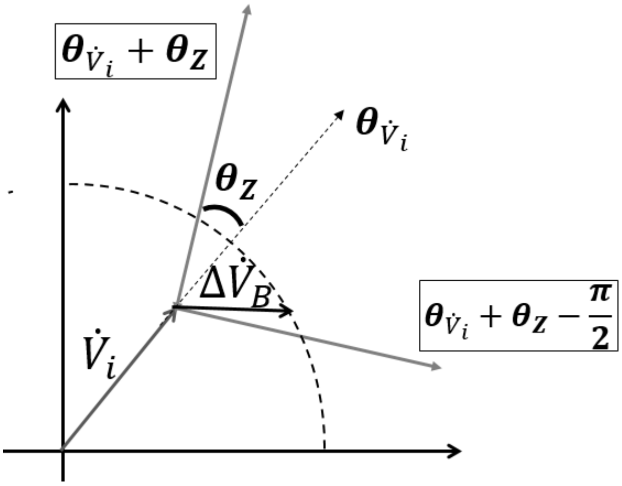

Fig. 5. 4 Image of voltage control

Voltage of node i $\dot{V}_i$ is smaller than its reference voltage $\dot{V}_{ref}$. α is an acute angle. Based on equation (5.9), ΔV_B in case 2 is shown in equation (5.12).

$$\Delta V_B = V_i * \cos(\pi - \alpha) + \sqrt{(V_i * \cos(\pi - \alpha))^2 - \left(V_i^2 - V_{ref}^2\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.12)$$

Substituting ΔV_B in equation (5.12) to equation (5.7), the active power output is arranged in equation (5.13).

$$P_B = \frac{(k1+k2)^2}{\sum_1^i Z_j}\cos\theta_Z + V_i * \frac{(k1+k2)}{\sum_1^i Z_j}\cos(\alpha + \theta_Z) \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.13)$$

In equation (5.11) and (5.13), the variable of P_B is reduced to one, and the optimal active power output is decided by α, as the angle of $\dot{V}_i$ is known, therefore, extreme value of P_B relies on $\Delta\dot{V}_B's$ angle $\theta_{\Delta VB}$.

Based on the proposed range of angle $\theta_{\Delta VB}$, the extreme value of P_B is calculated through equation (5.14). When the derivative of P_B is larger than zero or smaller than zero, the exact $\theta_{\Delta VBfinal}$ for optimal P_B equals to its limit $\theta_{\Delta VB}limit$; and if the derivative equals to zero, the $\theta_{\Delta VB}extreme$ for extreme value of P_B distributes in its range. And the magnitude ΔV_{Bfinal} of $\Delta\dot{V}_B$ is shown in equation (5.15). Based on equation (5.1), with the calculated voltage variation $\Delta\dot{V}_{Bfinal}$, the output current $\dot{I}_B$ of BESS is shown inequation (5.16).

$$\begin{cases} \text{if } \frac{\partial P_B}{\partial \theta_{\Delta VB}} > 0 \ \theta_{\Delta VBfinal} = \theta_{\Delta VB}\text{limit} \\ \text{if } \frac{\partial P_B}{\partial \theta_{\Delta VB}} < 0 \ \theta_{\Delta VBfinal} = \theta_{\Delta VB}\text{limit} \\ \text{if } \frac{\partial P_B}{\partial \theta_{\Delta VB}} = 0 \ \theta_{\Delta VBfinal} = \theta_{\Delta VB}\text{extreme} \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots \ (5.14)$$

$$\Delta V_{Bfinal} = V_i * \cos\left(\pi - (\theta_{V_i} - \theta_{\Delta V_B final})\right) \pm \sqrt{(V_i * \cos(\pi - (\theta_{V_i} - \theta_{\Delta V_B final})))^2 - \left(V_i^2 - V_{ref}^2\right)}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5.15)$$

$$\dot{I}_B = \Delta\dot{V}_{Bfinal}/\textstyle\sum_1^i Z_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5.16)$$

With the proposed method, the relation of active power output and the voltage variation caused by BESS is presented. The minimal active power output during voltage regulation is obtained, therefore, the reduction of battery’s capacity is realized.

5.2.2 Voltage fluctuation suppression

PV’s output in distribution system totally relies on insolation, and the sudden increase and decrease of PV’s output leads to the severe voltage fluctuation. To suppress the voltage fluctuation, BESS gives output according to the amount of voltage variation. With the same model in Fig. 5. 1, voltage fluctuation suppression of node i is taken as an example. The calculation of voltage fluctuation suppression amount is shown below with interval T. n is sampling times in T.

$$\Delta\overline{V_r}(T) = \sqrt{\frac{\sum_1^n(\Delta V_{rt}(t))^2}{n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5.18)$$

$$\Delta V_{rt}(t)_{t\in T} = V_i(t)_{t\in T} - \frac{\sum_1^n V_i(t)_{t\in T-1}}{n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5.19)$$

Where, t is sample time, $\Delta\overline{V_r}(T)$ is average voltage magnitude difference during period T, ΔV_{rt} is average voltage magnitude difference of every sample time, $V_i(t)$ is voltage magnitude at time t.

With the calculated average voltage magnitude difference in equation (5.18) and (5.19), the voltage suppression amount ΔV_B via BESS is shown in equation (5.20). Based on power flow calculation in section 4.2.1, the output of BESS is calculated.

$$\begin{cases} \Delta V_B(t+1) = \Delta\overline{V_r}(t) + V_i(t) - V_i(t+1) & if\ \Delta\overline{V_r}(t) + V_i(t) < V_i(t+1) \\ \Delta V_B(t+1) = \left(V_i(t) - \Delta\overline{V_r}(t)\right) - V_i(t+1) & if\ V_i(t) - \Delta\overline{V_r}(t) > V_i(t+1) \end{cases}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (5.20)$$

In the development of energy storage devices in distribution system, the utilization of HEMS and EV is increasing. The connection number of EV and HEMS is normally effected by their owner, and the unscheduled connection leads to the inaccurate of proposed voltage amount in equation (5.20). Therefore, an update of equation (5.20) is proposed in equation (5.21) and (5.22). With the regulation of voltage suppression amount by BESS, unnecessary increase or decrease of voltage by BESS output in fluctuation suppression is avoided. And in this way, output reduction of BESS is realized.

$$if\ \mathrm{V}_i(\mathrm{t}) - \Delta\overline{V_r}(\mathrm{t}) > \mathrm{V}_i(\mathrm{t}+1)\ and \sum_j^k \Delta V_B(t+1) > \Delta Vlimit$$

$$\Delta V_B(t+1)_{t>k} = \left(\mathrm{V}_i(\mathrm{t}) - \Delta\overline{V_r}(\mathrm{t})\right) - \mathrm{V}_i(\mathrm{t}+1) - Dv \quad \ldots\ldots\ldots\ldots\ldots\ (5.21)$$

$$if\ \mathrm{V}_i(\mathrm{t}) + \Delta\overline{V_r}(\mathrm{t}) < \mathrm{V}_i(\mathrm{t}+1)\ and \sum_j^k \Delta V_B(t+1) > \Delta Vlimit$$

$$\Delta V_B(t+1)_{t>k} = \left(\mathrm{V}_i(\mathrm{t}) + \Delta\overline{V_r}(\mathrm{t})\right) - \mathrm{V}_i(\mathrm{t}+1) + Dv \quad \ldots\ldots\ldots\ldots\ldots\ (5.22)$$

$$Dv = \frac{(\left(\mathrm{V}_i(\mathrm{t})+\Delta\overline{V_r}(\mathrm{t})\right)-\mathrm{V}_i(\mathrm{t}+1)+\left(\mathrm{V}_i(\mathrm{t})-\Delta\overline{V_r}(\mathrm{t})\right)-\mathrm{V}_i(\mathrm{t}+1))}{2} \ldots\ldots\ldots\ldots\ldots\ (5.23)$$

Where, $\Delta Vlimit$ is constant, j and k are sampling time.

5.2.3 Cooperation of BESS, HEMS and EV

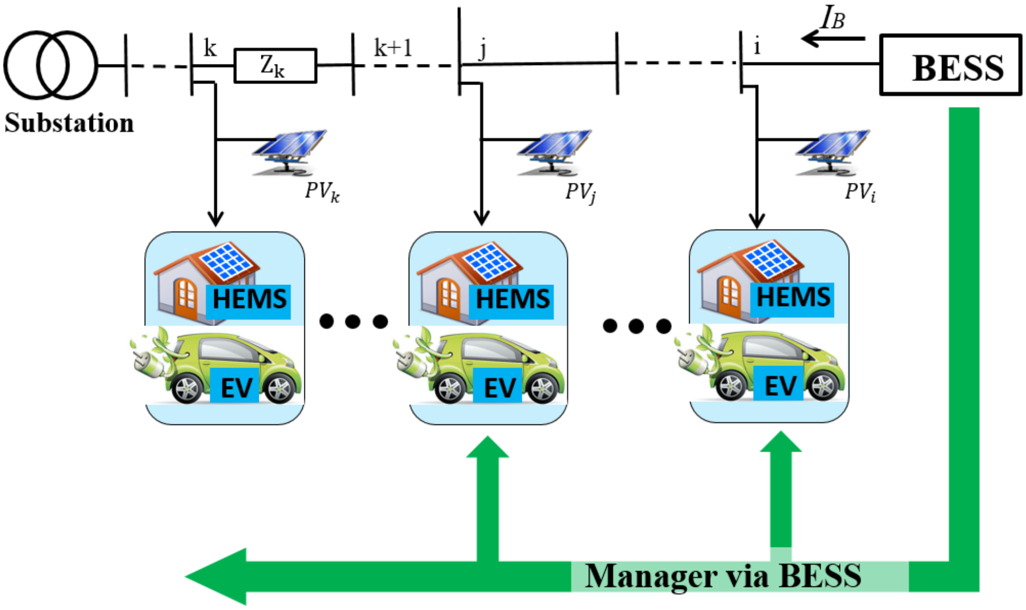

Fig. 5. 5 The image of distribution system with BESS, HEMS and EV.

In prior study of BESS, it's normally cooperated with tap-change devices for capacity reduction. The discussion of HEMS and EV in voltage control hasn't been done a lot. The study of these devices is meaningful for future power retail business in smart-grid. In this section, the cooperation of BESS, EV and HEMS in voltage fluctuation suppression is proposed. Fig. 5. 5 gives the image of distribution system with these energy storage devices. In radial distribution system, the most severe fluctuation of voltage appears at the end of distribution line, and it's also the location of BESS to provide immediate control. HEMS is single-phase load and distributed in system. EV which has uncertain location and number randomly connected in distribution system. The process of the cooperation is shown below.

[step 1]

BESS measures the voltage of its connected node, and judge the necessary of BESS's operation. Based on section 4.2.1, the apparent output of BESS S_B is calculated. And the inequality constraint is shown in equation (5.24). In equation (5.24), the value of S_B is smaller than capacity of BESS inverter. And to prevent battery from overcharge/discharge, SOC is in the range $[SOC_{lowerlimit}, SOC_{upperlimit}]$.

$$\begin{cases} S_B < S_{inverter\_bess} \\ SOC_{lowerlimit} < \mathrm{SOC} < SOC_{upperlimit} \end{cases} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.24)$$

[step 2]

BESS can't meet the inequality constraint in step 1, HEMS is wanted to assist BESS in voltage fluctuation suppression. In the operation of BESS, the charge/discharge cycle is an index of battery cycle life. To relatively average the consumption of battery life time in each HEMS. The operation order is shown in Fig. 5. 6, HEMS that is nearest to the end of distribution line firstly starts operation. And when it finishes a cycle of charge/discharge, it keeps non-operation until the other HEMS finished the cycle of charge/discharge or the opposite charge/discharge starts. The constraint of HEMS is shown in equation (5.25). HEMS's apparent power is limited by its inverter, and proper SOC is in $[SOC_{lowerlimit}, SOC_{upperlimit}]$. The choice of HEMS to assist BESS is based on equation (5.26).

$$\begin{cases} S_{hemsj} < S_{inverter\_hemsj} \\ SOC_{lowerlimit} < \mathrm{SOC}_{hemsj} < SOC_{upperlimit} \end{cases} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.25)$$

$$\sum_{i}^{j<i} S_{hemsj} + S_{inverter\_bess} > S_B \ldots\ldots\ldots\ldots\ldots\ldots (5.26)$$

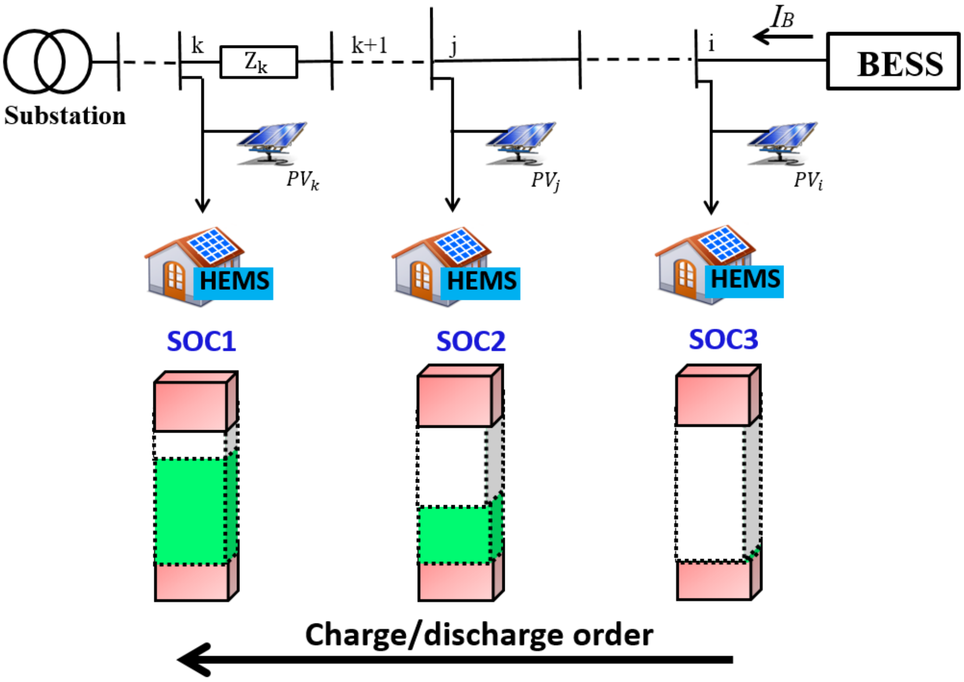

Fig. 5. 6 The image of HEMS operation based on its location and SOC

[step 3]

Fig. 5. 7 gives the image of EV connected case. There are several EV charge station in distribution system. The problem in dealing with EV is the uncertain location and number of it in distribution system. And the random SOC is also an obstacle to manage the operation period of EV. Here, for simplicity, instead of management the operation of EV, the voltage variation caused by EV charge is used to reflect EV's effect on voltage profile.

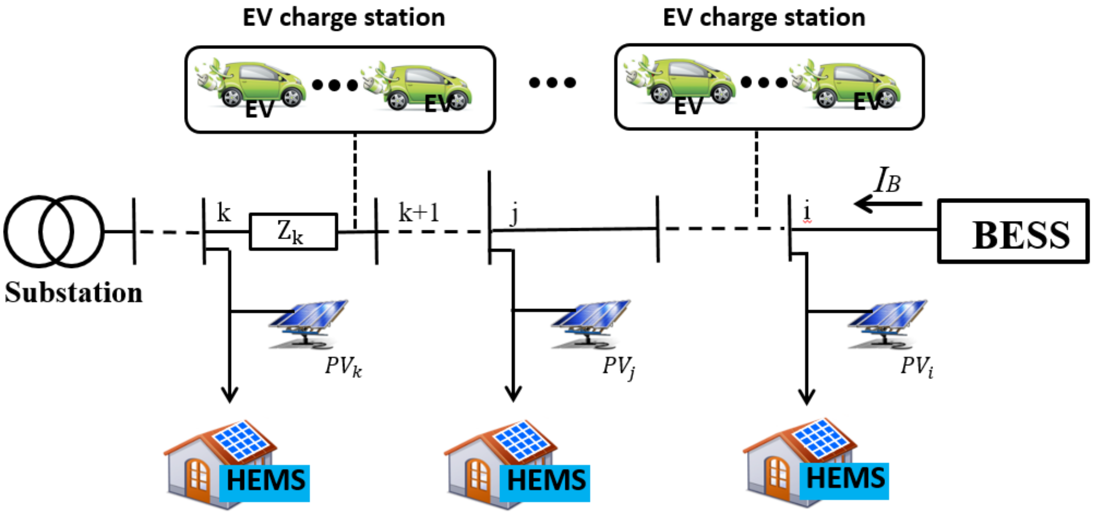

Fig. 5. 7 The image of EV in distribution system

5.3 Case study

5.3.1 Distribution system model

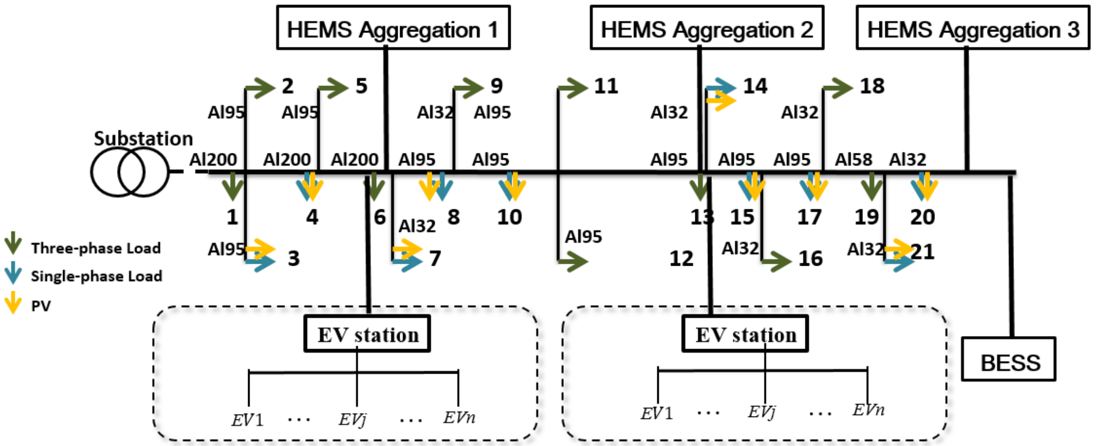

Fig. 5. 8 Model of distribution system with HEMS, EV and HEMS

Fig. 5. 8 shows the model of distribution system connected with EV station, HMES and BESS at the end

of distribution line. In this model, the green arrow and blue arrow stand for three-phase and single-phase load, respectively. PV is connected as roof-top solar as the yellow arrows shows. EV station connected as three-phase load, and HEMS connected as single-phase load. HEMS aggregation 1, 2, 3 are connected with phase c, b and a, respectively. Table 5.1 shows the parameters. Table 5.2 shows the single-phase load's placement.

Table 5.1 Distribution line's data.

Impedance of distribution line	Al32: $0.899 + j0.389\Omega/\mathrm{km}$ Al58: $0.497 + j0.331\Omega/\mathrm{km}$ Al95: $0.301 + j0.315\Omega/\mathrm{km}$ Al200: $0.182 + j0.288\Omega/\mathrm{km}$
Total length of the line	3.09km

Table 5.2 Connection of single-phase load.

Connection phase	Load No.
a-b	3, 8, 15, 21
b-c	4, 10, 17, 20
c-a	7, 14

Fig. 5. 9, Fig. 5. 10 and Fig. 5. 11 are three-phase consumption, single-phase consumption, and PV profile. Capacity of PV equals to the 1.5 times of single-phase load consumption. All of them are given in standardization.

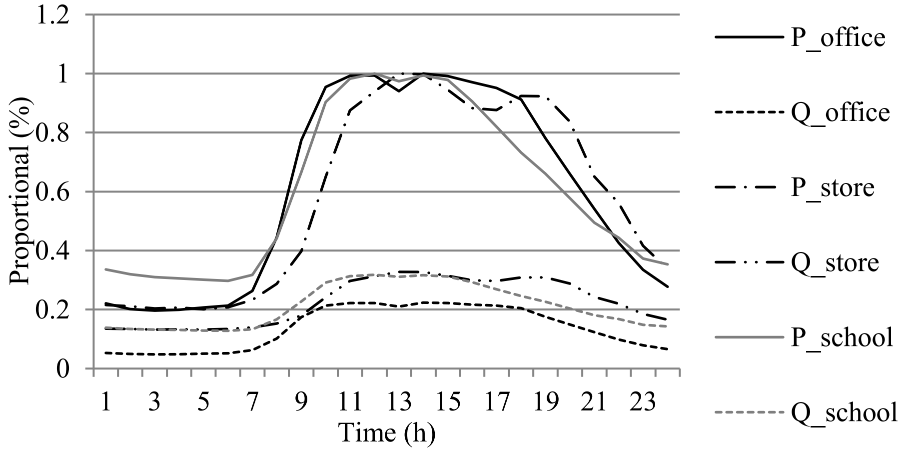

Fig. 5. 9 Three-phase load's pattern

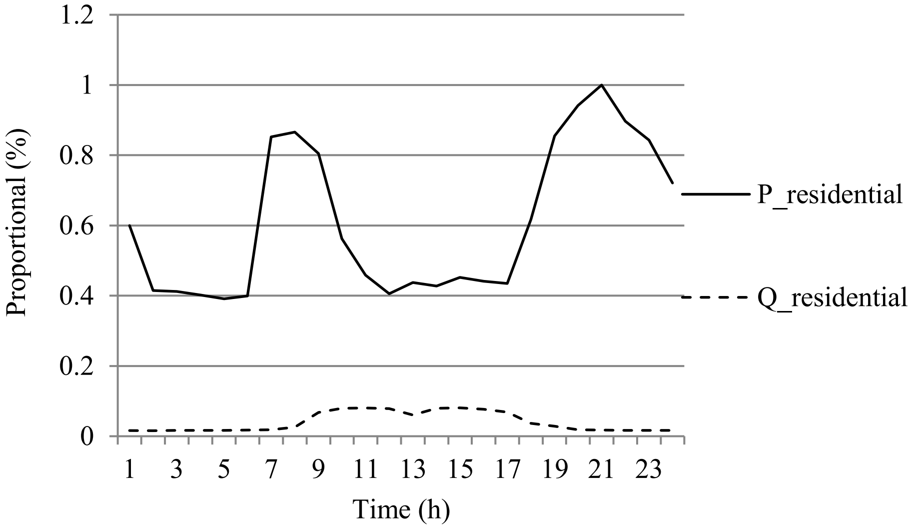

Fig. 5. 10 Single-phase load’s pattern

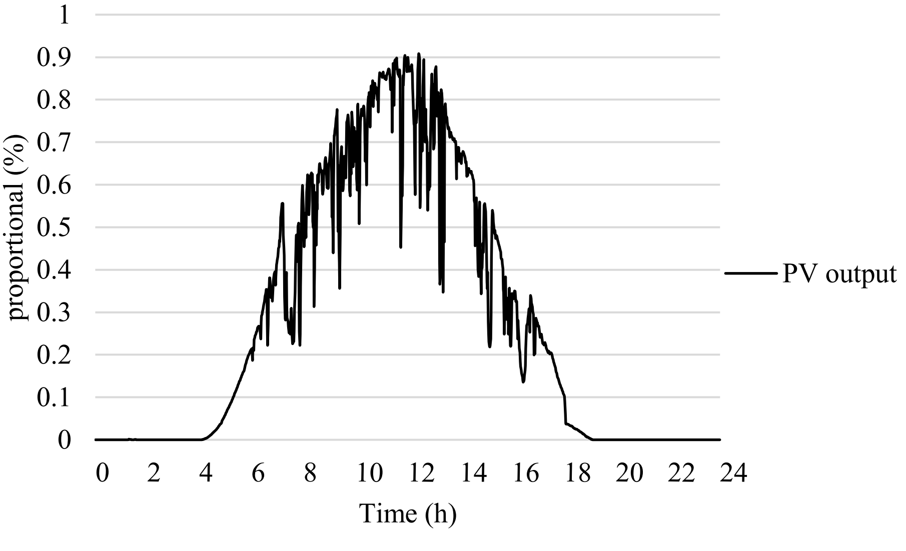

Fig. 5. 11 PV output in cloudy day

The adequate range of line voltage is from 102 to 107 conversed to low voltage side using voltage ratio (= 6600/105). In Table 4.3 gives the simulation conditions.

Table 5.3 Simulation conditions.

Simulation time	12pm-13pm
Simulation interval	10s
Adequate range's $V_{\text{upper limit}}$	107V (up voltage)
Adequate range's $V_{\text{lower limit}}$	102V (low voltage)
Ratio of voltage	6600/105
Sending voltage of substation	6600V
EV charge rate	3kW
EV total number	90
HEMS inverter capacity	10kVA
HEMS connection	node 6 (phase ab), node 13 (phase bc), node 21(phase ca)
BESS inverter capacity	300kVA

Table 5.4 shows the simulation cases. This chapter focuses on voltage fluctuation suppression with energy storage devices. Normally, voltage at the end of distribution line has the largest fluctuation, node 21 is taken to verify the proposed method. Case 1 is taken as reference. Case 2 with one BESS at the end of distribution line for voltage suppression, and the reference voltage for regulation is calculated with proposed method. Case 3 has EV in charge state, and the voltage variation with EV's connection is covered by BESS. In case 4, HEMS assists BESS to suppress the voltage fluctuation, and the simple cooperation model of BESS and HEMS is an attempt for future power retail in smart grid and it's also the point of this chapter.

Table 5.4 Simulation cases.

Case	BESS	EV	HEMS
Case 1	No	No	No
Case 2	YES	No	No
Case 3	Yes	Yes	No
Case 4	Yes	Yes	Yes

5.3.2 Simulation results

Fig. 5. 12, voltage profile from 12pm to 13 pm is shown. From the Fig., around 15 min and 30 min, severe voltage fluctuation occurs, and it's the suppression objective.

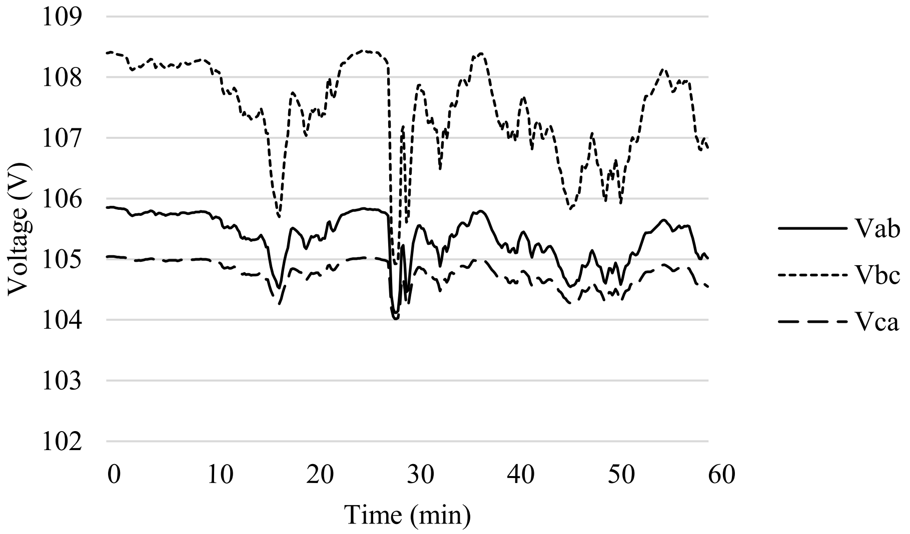

Fig. 5. 12 Voltage profile of node 21 in case 1

Case 2 has one BESS at the end of distribution line, and the voltage suppression amount is based on proposed method in section 4.2.1. From the result, it can be seen that voltage profile is well suppressed. And Fig. 5. 14 gives the active power and apparent power output of BESS. The maximal apparent is around 300kVA.

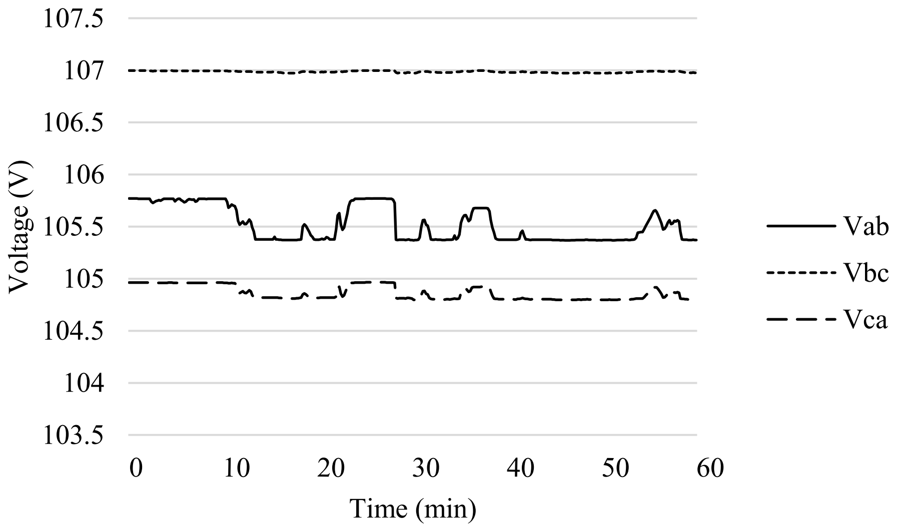

Fig. 5. 13 Voltage profile of node 21 in case 2

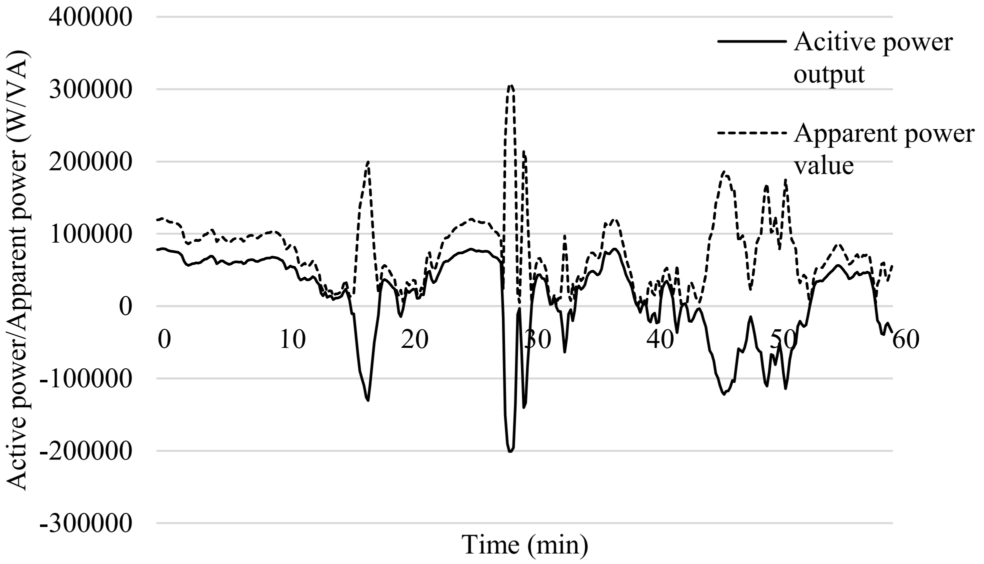

Fig. 5. 14 Active power and apparent power of BESS in case 2

Case 3 shows the voltage change when EV connects to distribution system. Because the simulation period is chosen from 12pm to 13 pm that usually is lunch time. And the charge of EV is set to three-phase commercial load. From Fig. 5. 15 voltage changes a lot around 25 min. The reason is the connection of EV updates the reference regulation amount of voltage. And BESS output in Fig. 5. 16 has relatively reduced comparing to case 2.

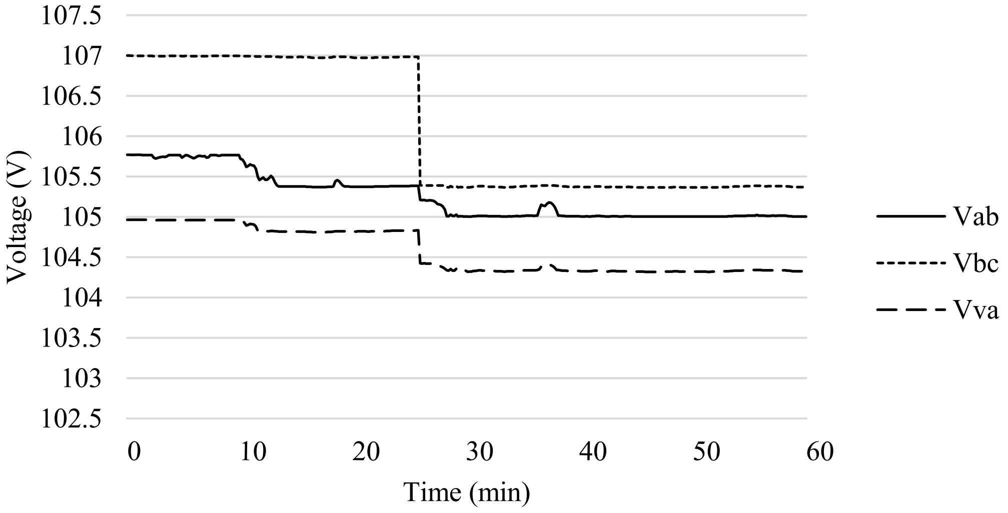

Fig. 5. 15 Voltage profile of node 21 in case 3

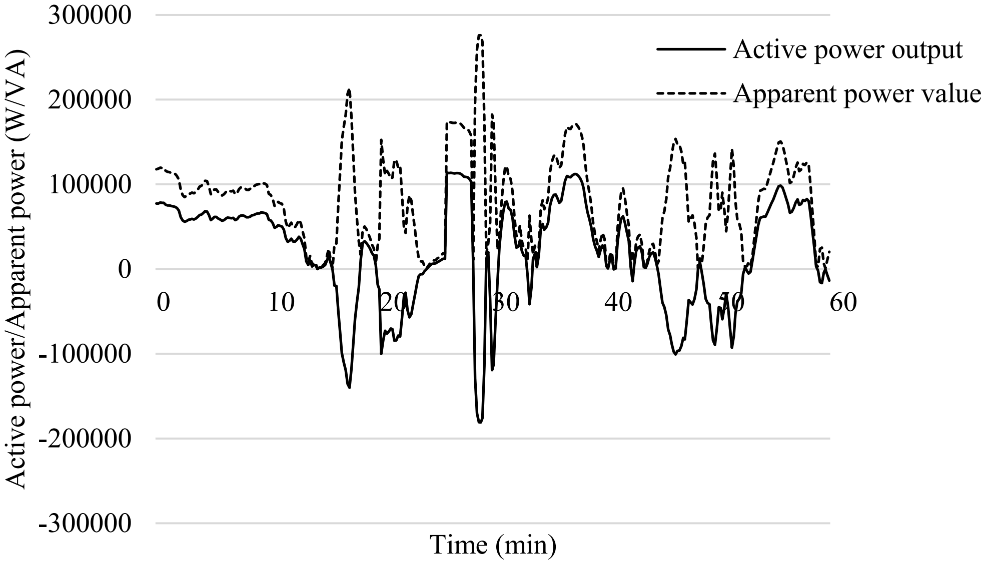

Fig. 5. 16 Active power and apparent power of BESS in case 3

In case 4, apparent power limit (150kVA) is set to BESS. The limit value is set based on the result of BESS output in case 2 and 3, because apparent output value mostly distributes under 150kVA. From this view, HEMS is applied to cooperate with BESS to deal with the rest part in voltage control. From the result, the short output period and small output value of HEMS covers the shortcoming of BESS.

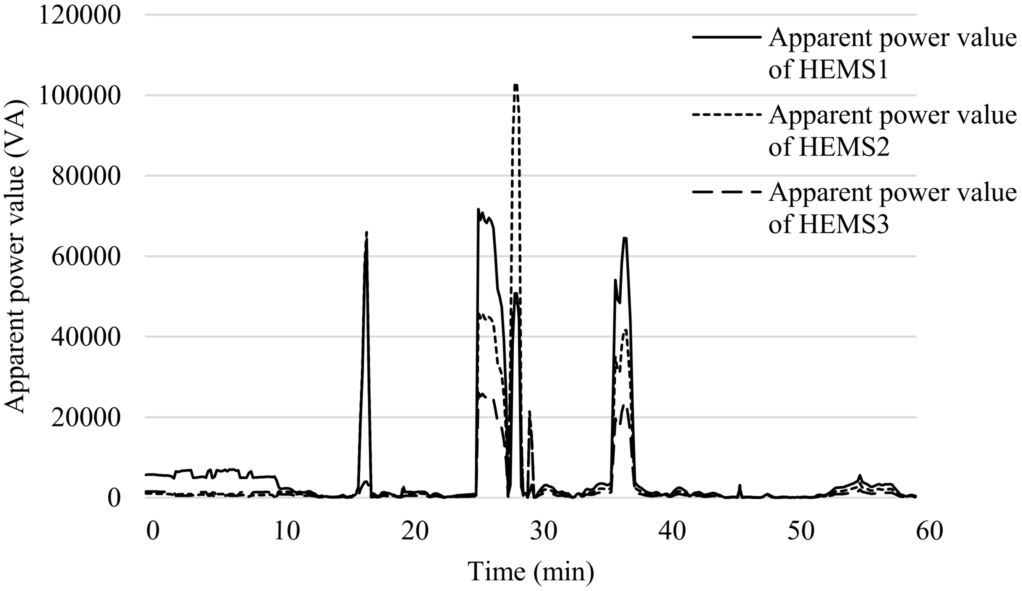

Fig. 5. 17 Apparent power of HEMS in case 4

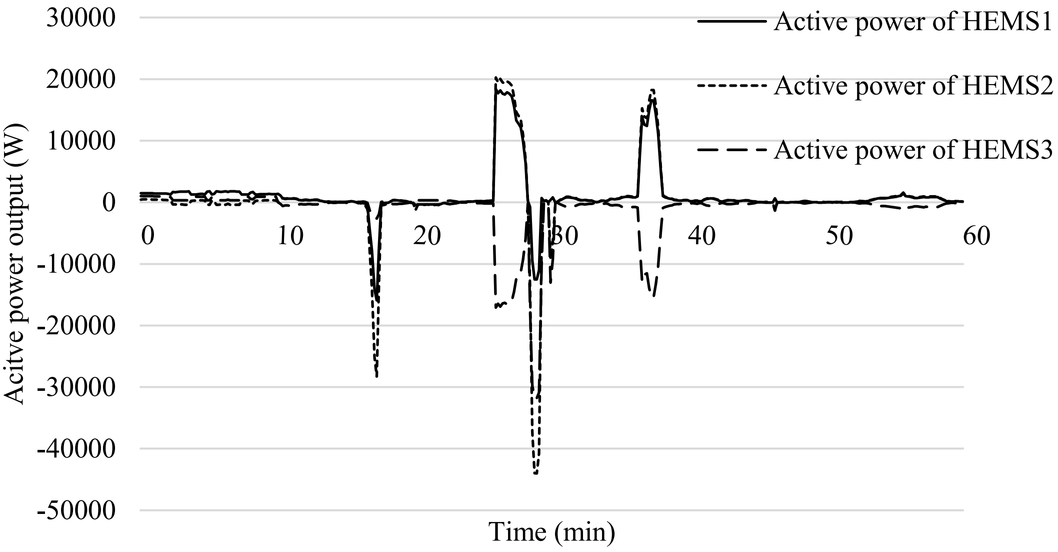

Fig. 5. 18 Active power output of HEMS in case 4

5.4 Discussion and summary

This chapter proposes a new construction of energy storage devices in distribution system. Case study shows the cooperation between BESS, HEMS and EV. It brings a new point in future smart grid with power retail between energy storage devices.

In future work, to pursue excellent control and economic application of these devices. The best charge/discharge cooperation is an issue, moreover, battery in energy storage devices is an important index to discuss their effective application. The balance of consumption of devices and benefit is very important topic.

5.5 References

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Chapter 6

Summary and future research

6.1 Summary

In this paper, several novel methods are proposed in dealing with voltage problem as well as promote application of BESS. With the penetration of PV, voltage problem is urgent to be solve in distribution system. With established devices, it's difficult to achieve excellent control of voltage. Therefore, BESS attached with power conditioner system is applied to solve the voltage problem caused by PV with its excellent control ability. Because BESS can provide both active and reactive power to system, it makes BESS be more capable in dealing voltage problem than other reactive power compensators. However, with the highlight of BESS, the cost is a big obstacle in promoting its application. Therefore, novel method in promoting the application of BESS is focuses on it in voltage control of PV connected distribution system.

Chapter 2 gives an advanced management of VUF via cooperation with BESS and SC. VUF deterioration in distribution system caused by single-phase load and the connection of roof-top solar. In the improvement of VUF, the normal device like SC has the problem of time delay because of the switch-change feature. SVC is also used for VUF suppression with its excellent control, however, with the increasing of energy storage devices, the necessary of SVC construction with extra cost needs to be discussed. To solve the VUF violation, BESS is chosen as a capable device. In the application of BESS, the biggest issue is the cost in large-scale BESS. To reduce its capacity, SC with relatively cheap cost is cooperated here. A novel VUF suppression method realizes accurate control of VUF without unnecessary suppression. The distributed control of BESS cooperated with SC in VUF improvement works well and realize capacity reduction of BESS.

In chapter 3, cooperation of BESS group composed by multiple BESS and novel SOC management is proposed in VUF and voltage control. In prior study of BESS, the cooperation of BESS hasn't been discussed a lot. In radial distribution system, voltage violation and unbalance factor deterioration become severe along distribution line. Therefore, in voltage control, BESS near the end of distribution line firstly gets over charged/discharged while BESS near substation side still has available capacity. On consideration of management convenience in BESS group, the different state of BESS is unexpected. The proposed cooperation in BESS group for voltage and VUF control realizes the reduction of BESS capacity and increase the utilization of rest available capacity of BESS. For the other essential element, SOC management, in BESS application, based on previous study, BESS especially small-scale BESS stops providing output during its full charged/discharged period unless opposite charge/discharge happens. The existed passive SOC management with long non-operation period of BESS leads to low utilization of BESS. The proposed initiative charge/discharge of BESS makes more available capacity and prolongs the operation period of BESS for more effective utilization. With the proposed method, centralized control of BESS with relatively small capacity and proper SOC is realized.

In chapter 4, the application of SBG composed by multiple small scale BESS cooperated with SVR for voltage and VUF suppression is illustrated. Large scale BESS is normally chosen because it can provide more available capacity and realize long operation period in voltage control. However, with the consideration of cost, large scale BESS is unexpected. To use the excellent control of BESS in dealing with voltage problem caused by PV with relatively low cost, small scale BESS draws author's attention. In the application of small scale BESS, rapid full charge/discharge is the significant shortcoming. Therefore, SVR assists small scale BESS in its application. With the proposed method, dead band of SVR is enlarged and the tap-change number is reduced in voltage violation suppression. From the view of small scale BESS, voltage regulation cooperated with SVR releases it from the pressure of SOC caused by rapid charge/discharge. Proposed cooperation of small scale BESSs in SBG balances their SOC. The reduction of peak value output via cooperation realizes the decreasing of inverter capacity in small scale BESS. Also, it brings the convenience in SBG management. With the proposed method, excellent management in voltage and VUF control is realized with the application of small scale BESS group cooperated with SVR.

Based on the application idea of BESS in distribution system proposed in previous chapter, chapter 5 focuses on the future smart grid with power retail business. The increasing of HEMS and EV in distribution system is notable, and they have the same feature with BESS. Therefore, instead of setting a large-scale BESS by power company, the utilization of these existed energy storage devices is a meaningful choice for liberalization of power market. Since with the application of consumers' devices, the cost of power company in BESS is reduced and profit obtained by consumers in power retail is promoted. However, the confliction with different owner of these devices needs to be considered, and a novel method is needed to achieve win-win result in bringing consumers' devices into voltage control. In chapter 5, an attempt is done with the cooperation of BESS, HEMS and EV in voltage fluctuation suppression.

6.2 Future research

In this thesis, study on BESS realizes effective utilization of BESS in PV connected distribution system. The increasing penetration of PV in distribution system leads to a more difficult situation in voltage control. The regulation via reactive power compensators can't absorb inverse power from PV, and from the view of power utilization, it leads to a waste of power generated from PV. Different from other devices, besides the excellent control ability, BESS has a unique feature in energy storage. And inverse power from PV can be absorbed by BESS and reused for effective utilization of power. However, large scale BESS is always unexpected with its high cost. This thesis proposes the cooperation and initiative SOC management of BESS to achieve excellent control with relatively small scale BESS. And further reduction of BESS is realized via the cooperation with cheap tap-change devices. The proposed method contributes to the promotion of small scale BESS in distribution system. Especially under the well development of HEMS and EV, the effective utilization of these existed devices for voltage management is hopeful.

With the future research on BESS, a smart grid as Fig. 6.1 shows with the utilization of energy devices owned by different owner in voltage management is expected. The utilization of energy devices of consumers' side reduces the extra cost for large scale BESS or other facilities. Because BESS can absorb power from PV, with the increasing penetration of BESS, a self-supporting system composed by PV, BESS and consumer is hopeful. And it's very meaning in emergency, heavy load situation and remote district for providing high quality power to consumers. Also, the increasing available BESS by the anticipation of consumers enlarges the control ability in voltage and releases upper system from the unexpected effect on voltage caused by distribution system. And all these promotes the new construction of power system with the liberalization of power market by power retail of these energy storage devices.

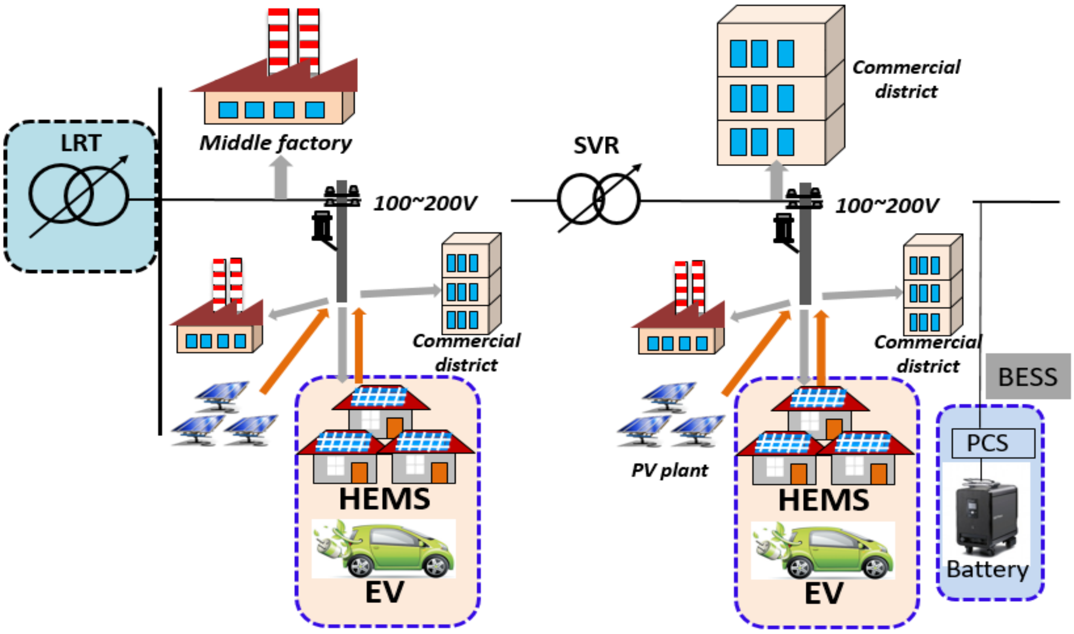

Fig. 6. 1 Image of future utilization of energy storage devices

Based on the work done in this paper, for future research, several points need to be discussed.

[1] The capacity of BESS for different control objective is different. During the cooperation of BESS and established devices, the most economic choice of BESS's capacity is necessary.

[2] The initiative charge/discharge realizes more available capacity of BESS, however, the relation of continuing tiny variation of SOC and cycle life of battery need to be discussed. Because battery is a consumable, and its cycle life relates to effective utilization of BESS. Also, the effect of voltage fluctuation

caused by initiative SOC management on distribution system need to be discussed for high power quality.
[3] The cooperation of BESS, HEMS and EV in voltage fluctuation is done. According to different demand of devices' owners, more details are wanted to achieve a capable and novel control.
[4] From the view of power market liberalization, power retail between consumers and power company need a definition. In this way, accurate benefit for both side is necessary to be simulated.

Appendices

List of Publications

Journal

Chapter 2

[1] Qingyuan Yan, Mutsumi Aoki: “The Improvement of Voltage’s Unbalance via Voltage Magnitude Control with BESS and SC in Distribution System Connected with PV”, IEEJ Trans. PE, Vol.137, No.7, pp.511-519 (2017) (in English)

International conferences

Chapter 3

[1] Qingyuan Yan, Mutsumi Aoki: “VUF control via BESS and SC with SOC management in PV connected distribution system”, The International Conference on Electrical Engineering 2016 (ICEE 2016), (2016)

Chapter 4

[1] Qingyuan Yan, Mutsumi Aoki: “Suppression of Voltage Violation in PV Connected Distribution System via Cooperation of Battery Energy Storage System and SVR”, The International Conference on Power System Transients 2017 (IPST 2017), (2017)

National/Regional conferences

Chapter 2

[1] Qingyuan Yan, Mutsumi Aoki: “The Improvement of Voltage’s Unbalance via Voltage Magnitude Control with BESS and SC in Distribution System Connected PV”, The 2016 Annual Conference of Power & Energy Society, IEEJ, 2016(in English)

[2] Qingyuan Yan, Mutsumi Aoki: “Improvement of unbalance of voltage and distribution line loss in distribution system with SC and BESSs”, Joint Technical Meeting on Power Engineering and Power Systems Engineering, IEEJ 2015, 2015(in English)

Chapter 3

[1] Qingyuan Yan, Mutsumi Aoki: “Voltage Management and VUF Suppression in Distribution System applying Centralized Control Mode of BESS”, Tokai Section Joint Conference on Electrical and related Engineering 2016, 2016(in English)

Chapter 4

[1] <u>Qingyuan Yan</u>, Mutsumi Aoki: "Voltage Suppression in PV connected Distribution System via Novel Cooperation Method between BESS Group and SVR", Joint Technical Meeting on Power Engineering and Power Systems Engineering, IEEJ 2017, 2017(in English)

[2] <u>Qingyuan Yan</u>, Mutsumi Aoki: "Voltage Control in PV Connected Distribution System via Cooperation Control of BESS and SVR", Annual Conference 2017 on IEEJ, 2017(in English)

<u>Chapter 5</u>

[1] <u>Qingyuan Yan</u>, Mutsumi Aoki: "Voltage Regulation with Unbalanced Voltage Suppression in Distribution Line Connected PV System using BESS in Consideration of its Placement", Joint Technical Meeting on Power Engineering and Power Systems Engineering, IEEJ 2016, 2016(in English)

[2] <u>Qingyuan Yan</u>, Mutsumi Aoki: "Voltage Suppression in Distribution System via BESSs with the Consideration of SOC", Tokai Section Joint Conference on Electrical and related Engineering 2017, 2017(in English)

<u>Others</u>

[1] <u>Qingyuan Yan</u>, Mutsumi Aoki: "Improvement of unbalance factor and power loss of PV connected distribution system with BESS", The 2015 Annual Conference of Power & Energy Society, IEEJ, 2015(in English)

[2] <u>Qingyuan Yan</u>, Mutsumi Aoki: "Reduction of power loss of distribution line considering unbalance factor in distribution system with BESS", Tokai Section Joint Conference on Electrical and related Engineering 2015, 2015(in English)