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A Study on the Voltage Stabilization Method of Distribution System Using Battery Energy Storage System and Step Voltage Regulator

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Abstract – In order to maintain customer voltages within the allowable limit(220±13V) as much as possible, tap operation strategy of SVR(Step Voltage Regulator) which is located in primary feeder, is widely used for voltage control in the utilities. However, SVR in nature has operation characteristic of the delay time ranging from 30 to 150 sec, and then the compensation of BESS (Battery Energy Storage System) during the delay time is being required because the customer voltages in distribution system may violate the allowable limit during the delay time of SVR. Furthermore, interconnection of PV(Photovoltaic) system could make a difficultly to keep customer voltage within the allowable limit. Therefore, this paper presents an optimal coordination operation algorithm between BESS and SVR based on a conventional LDC (Line Drop Compensation) method which is decided by stochastic approach. Through the modeling of SVR and BESS using the PSCAD/EMTDC, it is confirmed that customer voltages in distribution system can be maintained within the allowable limit.

Keywords: SVR(Step Voltage Regulator), BESS(Battery Energy Storage System), Optimal coordination operation algorithm, PSCAD/EMTDC

1. Introduction

Recently, power systems have been deregulated and decentralized according to the technology development of small scale distributed generators including PV systems. They have been actively introduced and operated in distribution systems, and then, many power quality problems such as voltage variations, flicker and harmonic may be occurred. In order to maintain customer voltage within allowable limit, tap operation of SVR installed in primary feeder is usually carried out according to the pre-designed setting value of delay time ranging from 30 to 150 sec. Existing papers regarding SVR operation are only dealt with optimal voltage regulation methods in distribution systems with PV system by SVR to deliver reasonable voltage to as many customers as possible [1-5]. However, there are not considered that power quality problems such as under voltage and over voltage could be occurred during the delay time of SVR. In order to compensate customer voltage during the delay time of SVR, the compensation of BESS is being required because the customer voltages in distribution system may violate the allowable limit during the delay time of SVR. Furthermore, interconnection of PV system could make a difficultly to keep customer voltage within the allowable limit. Therefore, this paper presents an optimal coordination operation algorithm between BESS and SVR based on a conventional LDC method which is decided by stochastic approach. In other words, tap operation of SVR is basically decided by conventional LDC method and a modified tap control mode is performed during the operation of BESS, which is excluding BESS current from passing current of SVR when customer voltage violates the allowable limit during the delay time of SVR. Based on the modeling of SVR and BESS with the PSCAD/EMTDC, it is confirmed that customer voltages in distribution system can be maintained within allowable limit.

2. Operation Strategy of BESS Depending on SVR Control Mode

Tap position of SVR is generally decided by compensation-rate of SVR based on the conventional LDC method, and tap operation is carried out considering a setting value of delay time [6-7]. Therefore, power quality problems such as under voltage and over voltage could be occurred during the delay time. In order to overcome these problems, this paper proposes a coordination operation method between SVR and BESS. At first, during the delay time of SVR, BESS is operated as a discharging mode when customer voltages are lower than the allowable limit

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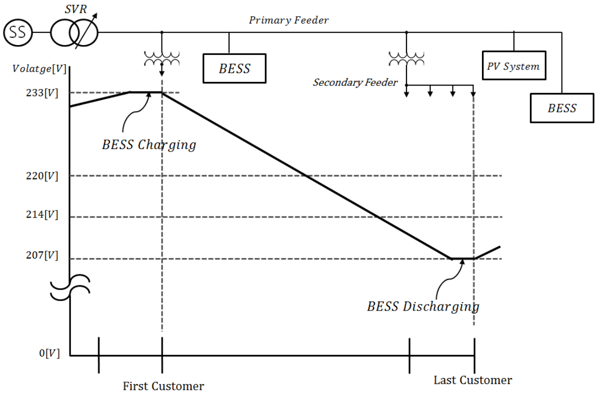


Fig. 1. Voltage regulation of system using the SVR and BESS

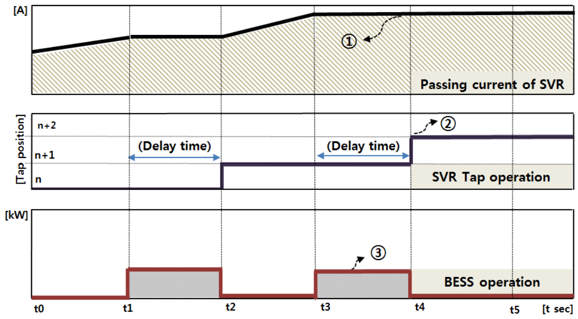


Fig. 2. Concept of tap operation by modified SVR control mode

and as a charging mode when customer voltages are upper than the allowable limit as shown in Fig. 1.

And also, in order to obtain a proper introduction capacity of BESS, this paper presents a modified tap control mode of SVR. As shown in Fig. 2, the idea of modified mode is to exclude BESS current from passing current of SVR when customer voltage violates the allowable limit during the delay time of SVR. Where, ① of Fig. 2 shows a profile of passing current in SVR excluding BESS current and ② of Fig. 2 represents a concept of tap operation in SVR, which is performed after the delay time when variation amount of passing current in SVR reaches to tolerance level. And also, ③ of Fig. 2 is a mechanism to operate BESS considering ① and ② of Fig. 2, at which BESS is operated only during the delay time to keep customer voltages within the allowable limit.

3. Coordination algorithm of SVR and BESS

3.1 Operation algorithm of SVR

LDC method of SVR which is located at primary feeder to compensate the voltage variations as shown in Fig. 3 is to find the optimal setting values (V_{ce}, Z_{eq}) and optimal sending voltages ($V_{send}(t)$) in order to deliver suitable voltages to many customers as possible. It firstly determines

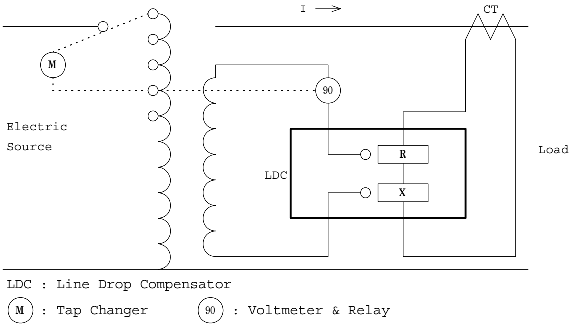


Fig. 3. Concepts for LDC method

the ideal optimal sending voltages which can be expressed by the optimal compensation rates of SVR, and then obtains optimal setting values by statistical analysis according to the relationship between ideal optimal sending voltages and total passing currents.

Optimal sending voltages have a general relationship with LDC setting values as shown in Eq. (1). Therefore, the optimal setting values of SVR can be obtained by solving the equation for V_{ce} and Z_{eq} [8-10].

$$V_{send}(t) = V_{ce} + Z_{eq} \times I_{pass}(t) \tag{1}$$

where, V_{send} is optimal sending voltage, V_{ce} is load center voltage, Z_{eq} is equivalent impedance, and I_{load} 7 is total load currents of main transformer.

In addition, in order to curb increment for introduction capacity of BESS, Eq. (1) can be transformed to Eq. (2) at tap control mode of SVR which is to exclude BESS current from passing current of SVR when customer voltage violates the allowable limit during the delay time of SVR.

$$V_{send}'(t) = V_{ce} + \left(I_{pass}'(t)\right) Z_{eq} \tag{2}$$

where, $V_{send}'(t)$ is optimal sending voltage at tap control mode of SVR and $I_{pass}'(t)$ is passing current excluding current of BESS.

In other words, $I_{pass}'(t)$ can be expressed by Eq.(3).

$$I_{load}'(t) = I_{pass}(t) \pm I_{B,ct}(t) \tag{3}$$

where, $I_{B,ct}(t)$ is current value of BESS considering charging and discharging mode.

Therefore, the operation procedure of the SVR is categorized by 3 steps as below.

[Step 1] SVR tap is determined by the compensation-rate of sending voltage which is calculated by the relationship between optimal sending voltage of LDC method and the reference tap voltage of SVR.

[Step 2] The current of BESS at modified control mode of SVR is excluded from passing current of SVR when customer voltage violates the allowable

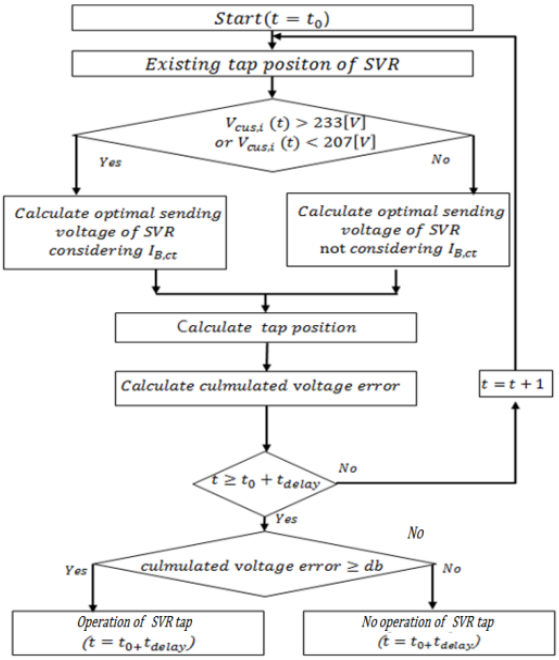


Fig. 4. Operation algorithm of SVR

limit during the delay time.

[Step 3] The tap of SVR will be changed only when the cumulated voltage error between optimal sending voltage and tap voltage of SVR violates bandwidth of 50% during the delay time.

Based on the above procedure, the operation algorithm of SVR can be expressed as shown in Fig. 8.

3.2 Operation algorithm of BESS

Operation strategy of BESS at the SVR control mode is expressed as shown in Fig. 5. At first, in order to keep customer voltage within allowable limits(220±13V), a voltage compensation range of BESS($V_{com}(\mathrm{t})$) can be calculated by comparing allowable limit with customer voltage, which are converted to primary voltage. And then, the operation capacity of BESS is obtained by relationship between voltage compensation range of BESS and total line impendence from substation to location of BESS in distribution system as shown in Eq. (4).

$$C_{BESS}(\mathrm{t}) = (V_{com}(\mathrm{t}))/(\textstyle\sum_{i=1}^{nb} Z_i) \tag{4}$$

$$V_{com}(\mathrm{t}) = (\mathrm{Vstd} - \mathrm{V(t)}) \cdot \mathrm{Vtap} \tag{5}$$

where, $C_{BESS}(\mathrm{t})$ is an operation capacity of BESS, $V_{com}(\mathrm{t})$ is a voltage compensation range of BESS, Z_i is a line impedance of section i, i is a section number in primary feeder, nb is a section of BESS location, V(t) is customer voltage, Vstd is allowable limit and Vtab is customer voltage converted to primary voltage.

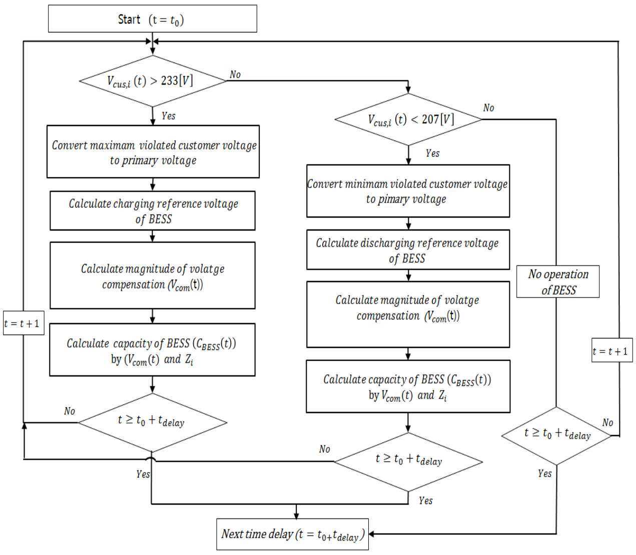


Fig. 5. Operation algorithm of BESS

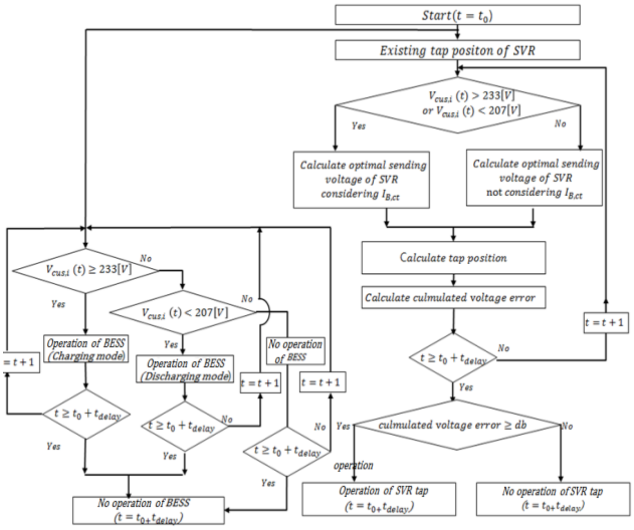


Fig. 6. Coordination algorithm of SVR and BESS

3.3 Coordination algorithm of SVR and BESS

Because it is difficult to maintain customer voltage within the allowable limit during delay time of SVR, this paper proposes the coordination control algorithm between SVR and BESS as shown in Fig. 6, which is combined by Fig. 4 and Fig. 5 during the delay time of SVR. In other words, tap operation of SVR is basically decided by conventional LDC method and a modified tap control mode is adapted only during delay time of SVR and the operation of BESS, which is excluding BESS current from passing current of SVR when customer voltage violates the allowable limit. And also, BESS should be operated only when customer voltage violates the allowable limit during the delay time of SVR, and as a discharging mode when customer voltages are lower than the allowable limit and as a charging mode when customer voltage is upper than the

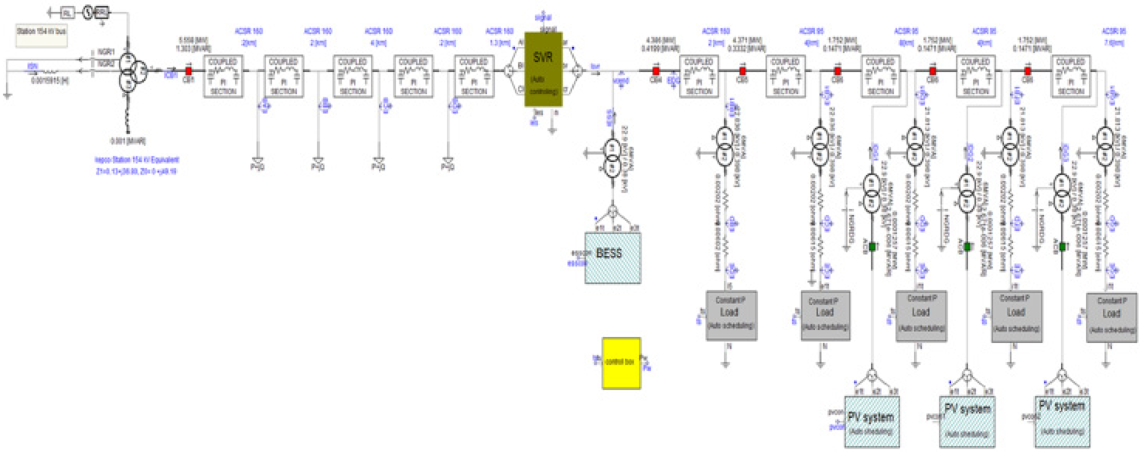


Fig. 7. Modeling of distribution system using the PSCAD/ EMTDC

allowable limit, based on the operation algorithm of BESS as mentioned section 3.2.

4. Modeling of SVR and BESS using the PSCAD/EMTDC

4.1 Modeling of distribution system

In order to analyze characteristic of customer voltage based on the proposed coordination algorithm between BESS and SVR, this paper presents a modeling of distribution system including SVR and BESS by using the PSCAD/EMTDC as shown in Fig. 7. Where, primary feeder (D/L) is composed of a total of 9 sections and PV system is located at the end section. And also, BESS and SVR to control voltage of the primary feeder are installed at the section 4 which is decided by voltage profile in primary feeder.

4.2 Modeling of SVR

Based on the concept of modified control mode in Eq. (2), the LDC method of SVR can be illustrated as shown in Fig. 8. Where, the optimal sending voltage is decided by load center voltage(Vce) and equivalent impedance(Zeq) according to variation of passing current in SVR(Ipass(t)) at each time interval.

Using the LDC method of SVR as mentioned earlier, the tap operation can be expressed as shown in Fig. 9, considering with the bandwidth of 50% and predesigned delay time of 30 seconds. It is composed of tap up (a) and tap down(b) operation. Where, tap operation logic is decided by voltage variation(*Er*), integration element and comparator during the delay time(*Td*)

4.3 Modeling of BESS

In order to obtain the desired active and reactive powers of BESS, this paper adapts current control algorithm as shown in Eq. (6) and Eq. (7). In this process, the decoupling control algorithm of active and reactive power of PV system is introduced [10]. Here, to obtain the reference value for desired current, the DC voltage is controlled by the PI(Proportional Integral) controller. Where, the 3-phase voltage of distribution system is converted into 2-phase current of the d-q stationary coordinate by using the d-q transformation method. And then 2-phase current are transformed into DC current of the d-q synchronizing coordinate to easily control the desired voltage and current.

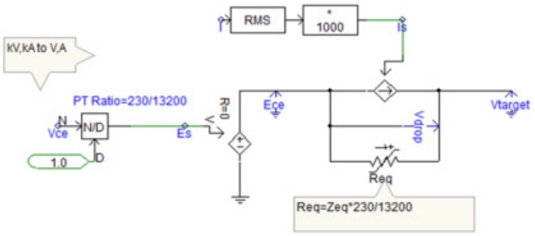
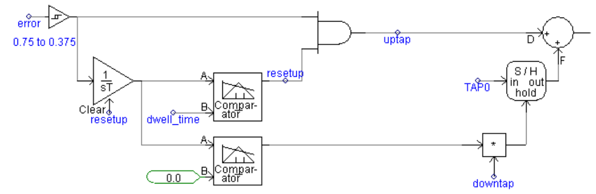
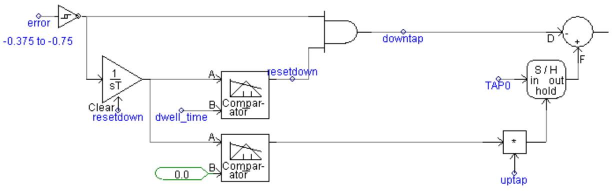


Fig. 8. Modeling of LDC method



(a) Tap Up logic



(b) Tap down logic

Fig. 9. Tap up and down logic of SVR

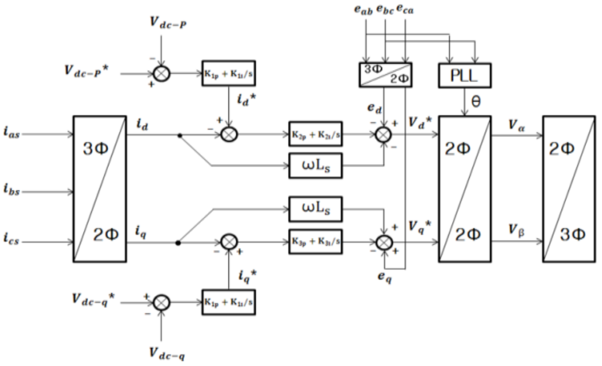


Fig. 10. Modeling of BESS

$$V_d = \left(I_{dref} - I_d\right) \cdot \left(k_p + \frac{k_i}{s}\right) - I_q \cdot \omega Ls + e_d \qquad (6)$$

$$V_q = \left(I_{qref} - I_q\right) \cdot \left(k_p + \frac{k_i}{s}\right) - I_d \cdot \omega Ls + \mathrm{e_q} \qquad (7)$$

where, V_d is voltage of d axis, V_q is voltage of q axis, $\mathrm{k_p} + \frac{\mathrm{k_i}}{\mathrm{s}}$ is PI controller I_{dref} and I_{qref} are the desired active and reactive current, ωL is internal reactance for feed-forward Compensation and e_d and e_q are instantaneous voltage d axis and q axis.

In general, instantaneous active power (P) and reactive power (Q) in balanced 3-phase system can be expressed as shown in Eq. (8) with the concept of the d-q axis variables.

$$P = \tfrac{3}{2}\left(V_d I_d - V_q I_q\right), \quad Q = \tfrac{3}{2}\left(V_q I_d - V_d I_q\right) \qquad (8)$$

where, $|\mathrm{V_0}|$ is the magnitude of instantaneous voltage.

Because, the $\mathrm{V_q}$ with synchronous speed (ω) in the d-q coordinate method is equal to the magnitude of instantaneous voltage and $\mathrm{V_d}$ is zero, reference current of d-q axis as shown in Eq. (9) can be obtained from Eq. (8).

$$P = \tfrac{3}{2}|V_0| I_{qref}, \quad Q = -\tfrac{3}{2}|V_0| I_{dref} \qquad (9)$$

Based on the current control algorithm in Eq. (6) and Eq. (7), modeling of BESS to enable control for changing and discharging is carried out by PSCAD/EMTDC as shown in Fig. 10.

5. Case Studies

5.1 Characteristics of BESS modeling

In order to control the desired charge and discharge output of the BESS modeling using the PSCAD/EMTDC, it is critical to obtain the value of reference current in current control mode. Based on the Eq. (8) and Eq. (9), the relationship between reference current and output of BESS can be expressed by Eq. (10). Where, BESS is operated as a charging mode related with (-) value to reference current, and BESS is operated as a discharging mode related with (+) value to reference current.

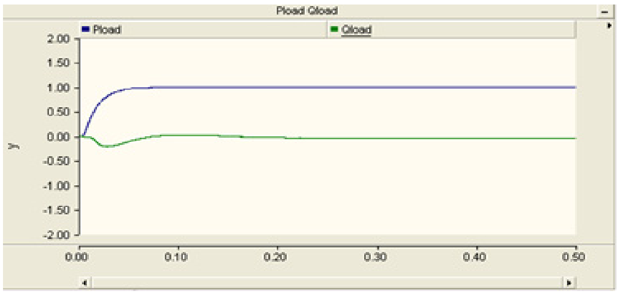


Fig. 11. Characteristic of 1MW charging output

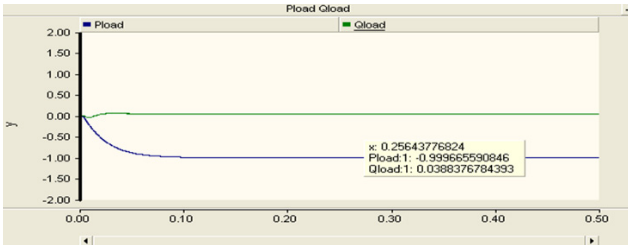


Fig. 12. Characteristic of 1MW discharging output

$$I_{qref} = \frac{2}{3} \times \left|\frac{P}{V_q}\right| \qquad (10)$$

where, $\mathrm{I_{ref-q}}$ is reference current of q-axis, P is desired active power, and V_q is voltages of q-axis.

For example, to obtain the charging capacity of 1 [MW], the reference current (I_{qref}) can be calculated by Eq. (8), where the q-axis power system voltage of $\mathrm{V_q}$ is assumed as nominal voltage (0.31kV). By applying calculated reference value to BESS modeling, it is verified that the charging capacity of BESS can be obtained as desired value of 1 [MW] as shown in Fig. 11.

On the other hand, to obtain the discharging capacity of 1 [MW], the reference current (I_{qref}) is calculated by Eq. (7).

By applying calculated reference value to BESS modeling, it is confirmed that the discharging capacity of BESS can be obtained as desired value of -1 [MW] as shown in Fig. 12.

5.2 Characteristic of voltage stabilization by BESS and SVR

5.2.1 Simulation Conditions

In order to analyze the characteristics of voltage stabilization using the proposed coordination method between BESS and SVR, this paper assumes a model distribution system of 22.9kV as shown in Fig. 13 and distribution system parameter with total of 9 section and 36.9km line length as shown in Table 1. And also, SVR and BESS are located at the middle point of primary feeder and

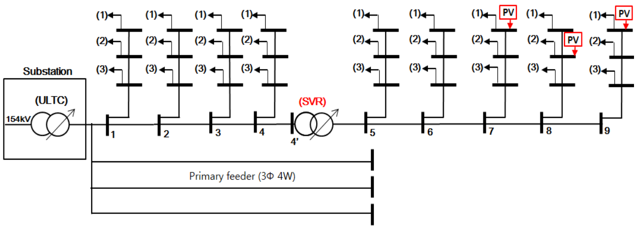


Fig. 13. Model distribution system of 22.9KV

Table 1. Distribution parameter and section data of primary feeder

[1PU: 10MVA]

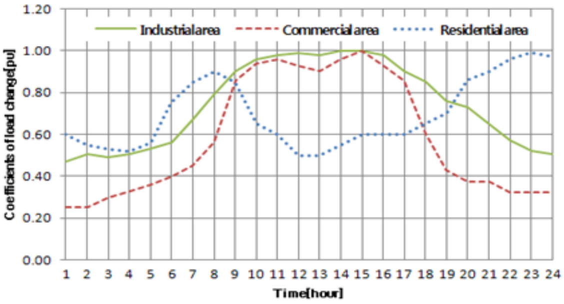
Section Number	Section Impedance R (Ω/km)	Section Impedance X (Ω/km)	Length (km)	Branch Number	Branch Length (km)	Section Impedance R (Ω/km)	Section Impedance X (Ω/km)	Load(PU)	PV system (MW)
1	0.182	0.391	2	1	0.5	0.403	0.408	0.0032+j0.0015	0
				2	0.5	0.403	0.408	0.0032+j0.0015	0
				3	0.5	0.403	0.408	0.0032+j0.0015	0
2	0.182	0.391	2	1	0.5	0.403	0.408	0.0063+j0.0031	0
				2	0.5	0.403	0.408	0.0063+j0.0031	0
				3	0.5	0.403	0.408	0.0063+j0.0031	0
3	0.182	0.391	4	1	0.5	0.403	0.408	0.0032+j0.0015	0
				2	0.5	0.403	0.408	0.0032+j0.0015	0
				3	0.5	0.403	0.408	0.0032+j0.0015	0
4	0.182	0.391	2	1	0.5	0.403	0.408	0.0063+j0.0031	0
				2	0.5	0.403	0.408	0.0063+j0.0031	0
				3	0.5	0.403	0.408	0.0063+j0.0031	0
5	0.182	0.391	3.3	1	1	0.403	0.408	0.0241+j0.0114	0
				2	1	0.403	0.408	0.0241+j0.0114	0
				3	1	0.403	0.408	0.0241+j0.0114	0
6	0.182	0.391	4	1	0.8	0.403	0.408	0.0202+j0.0101	0
				2	0.8	0.403	0.408	0.0202+j0.0101	0
				3	0.8	0.403	0.408	0.0202+j0.0101	0
7	0.403	0.408	8	1	0.8	0.403	0.408	0.0111+j0.0054	0
				2	0.8	0.403	0.408	0.0111+j0.0054	0
				3	0.8	0.403	0.408	0.0111+j0.0054	0~2.6
8	0.403	0.408	4	1	0.8	0.403	0.408	0.0111+j0.0054	0
				2	0.8	0.403	0.408	0.0111+j0.0054	00~0.8
				3	0.8	0.403	0.408	0.0111+j0.0054	0
9	0.403	0.408	7.6	1	0.8	0.403	0.408	0.0221+j0.0107	
				2	0.8	0.403	0.408	0.0221+j0.0107	0
				3	0.8	0.403	0.408	0.0221+j0.0107	0~0.5

PV systems are installed at the end of primary feeder. The tap ratio of pole transformer (P.tr) is considered as 13,200V/230V and also voltage drops at the first and last customers of secondary feeder are considered as 2% and 8% of rated voltage (220V) respectively. Furthermore, a daily load pattern depending on the customer type such as residential, commercial and industrial area and daily output pattern of PV system are assumed as shown in Fig. 14.

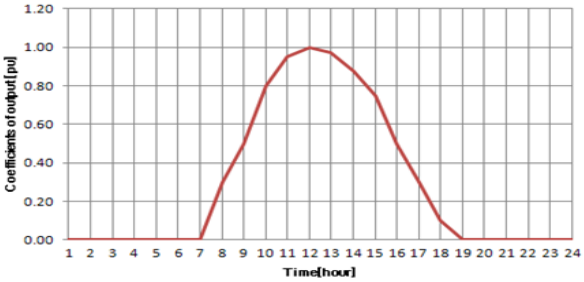
5.2.2 Characteristic of customer voltage variation

(1) Customer voltage without SVR

Before SVR is installed at primary feeder, customer voltage profiles of secondary feeder at the end sections (6-9th) in primary feeder interconnected with PV system can be obtained as shown in Fig. 15. It is found that some customer voltages cannot be maintained within the allowable limits, because the over voltage and under voltage phenomena is caused by the reverse power flow of PV system. Therefore, it is clearly expected that some severe voltage quality problems may be occurred and some countermeasures will be required, if the large scale PV systems are introduced at the primary feeder.



(a) Daily load pattern depending on customer type



(b) Daily output pattern of PV system

Fig. 14. Daily pattern of PV output and customer load

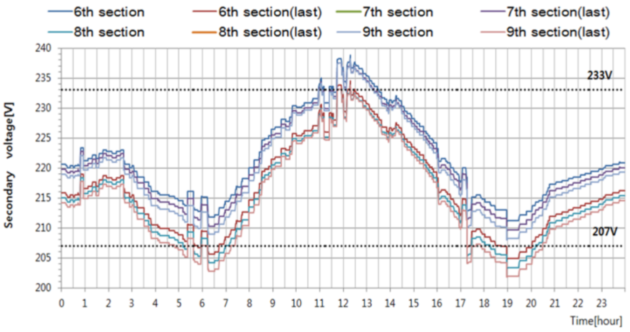


Fig. 15. Customer voltage characteristic without SVR

(2) Customer voltage with only SVR

If SVR is installed at section 4, customer voltage profiles of secondary feeder at the end sections (6-9th) in primary feeder interconnected with PV system, can be obtained as shown in Fig. 16. Even though SVR is introduced, it is clear that customer voltages cannot be shortly and partly maintained within the allowable limit because customer voltages can violate the allowable limits during delay time of SVR.

(3) Customer voltage with coordination method between SVR and BESS

When SVR and BESS are installed at section 4 of middle point in primary feeder, customer voltage profiles of secondary feeder in primary feeder can be obtained as shown in Fig. 17. Fig. 17(a) represents customer voltage

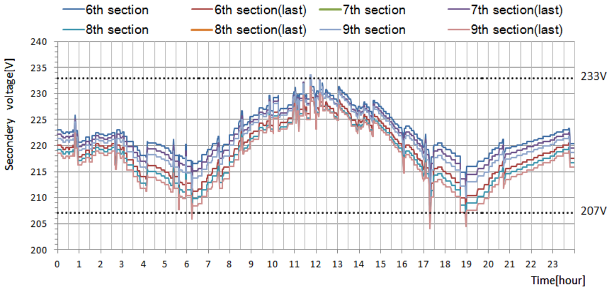
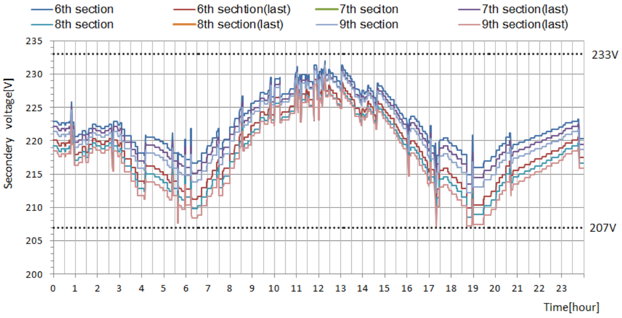
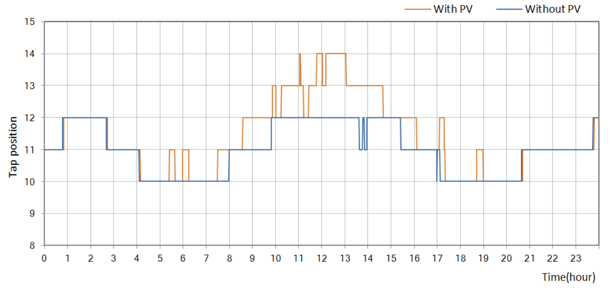


Fig. 16. Customer voltage characteristic with SVR operation



(a) Customer voltage characteristic by BESS and SVR operation



(b) Control characteristic of SVR by BESS operation

Fig. 17. Analysis of customer voltage characteristic by BESS and SVR operation

profiles at sections from 6th to 9th during a day and Fig 17(b) shows tap operation characteristic of SVR in case of with and without PV. Regarding the coordination control between SVR and BESS, it is clear that customer voltages do not violate the allowable limit and can be kept as reasonable conditions even during the delay time of SVR. Therefore, it is confirmed that the coordination operation between SVR and BESS can make the customer voltages in distribution system with PV system keep better voltage conditions.

6. Conclusion

This paper presents an optimal coordination operation algorithm between BESS and SVR using the proposed LDC method in real distribution system interconnected with the PV systems. The main results are summarized as follows.

(1) Before SVR is introduced at primary feeder, it is found that some customer voltages violate the allowable limits, because the over voltage and under voltage phenomena is caused by the reverse power flow of PV system. If the large scale PV systems are introduced to distribution system, it is clearly expected that some severe voltage quality problems may be occurred and some countermeasures will be required.

(2) Even though SVR is introduced at primary feeder, it is clear that customer voltages cannot be shortly and partly maintained within the allowable limit during the delay time of SVR.

(3) With the coordination voltage control of SVR and BESS comparing with existing method like without SVR and only SVR, it is clear that customer voltage can be maintained as reasonable conditions during delay time of SVR. Therefore, it is confirmed that the coordination operation of SVR and BESS can make the customer voltages of distribution system with PV system keep better voltage conditions.

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