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A Strategy for Balanced Power Regulation of Energy Storage Systems in a Distribution System during Closed-Loop Operation

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Abstract – To resolve overload in a distribution system, a distribution system operator (DSO) often performs a load transfer using normally open tie points and switches in the distribution line. During this process, the distribution system is momentarily operated in closed-loop operation. A closed-loop current in the distribution system can cause a power failure due to excess breaking current in the circuit breakers and reclosers. Therefore, it is necessary to calculate the closed-loop current exactly. However, if there are a large number of distributed generation (DG) systems in the distribution system, such as energy storage systems (ESS), they might obstruct the closed-loop operation based on bidirectional power flow. For quick and precise operation of a closed-loop system, the ESS has to regulate the power generation while satisfying closed-loop operation in the worst cases. We propose a strategy for balanced power regulation of an ESS. Simulations were carried out using PSCAD/EMTDC, and the results were compared with calculation results.

Keywords: Distribution system, Energy storage system, Closed-loop operation

1. Introduction

It is important to secure the reliability of distribution systems against power failures and to minimize the duration of blackouts. Thanks to the development of monitoring and control systems, power system operators can manage the distribution system remotely using a distribution automation system (DAS) [1-3], which helps enhance the power quality. In the case of radial distribution systems, normally open tie points have been set up and operated through the DAS to restore the distribution system in the event of faults or to implement load transfer [4,5]. In such cases, the distribution system will be operated as a closed-loop system [6,7].

A closed-loop system causes a closed-loop current to pass through the normally open tie point. Closed-loop current is determined by two factors: the difference in voltage phase between two distribution systems, and the total impedance of the closed-loop distribution systems [8,9]. However, in the worst case, the current can be high enough to exceed the rated current of some circuit breakers in the distribution system due to the influence of the closed-loop current. In this situation, protective devices can be unexpectedly operated in normal condition so that isolated section cannot receive electricity from distribution system. This malfunction of the protection devices results a wide-area power outage in the distribution system. Hence, a DSO must determine the switching by accurately calculating the closed-loop current passing through the normally open point in the distribution system.

Distribution system with many DGs has a characteristic of bidirectional power flow because the DGs connected to the distribution line inject generating power to substation in reverse [10,11]. Many DG systems can be connected to the distribution system, such as ESS, photovoltaic, and wind turbine. These DG systems have various negative effects on the distribution system due to reverse power flow. The influence of the DG on the closed-loop current during closed-loop operation must be analyzed because the system might be interrupted, even if the closed-loop current is calculated exactly by using a conventional calculation method which is not considered of influence of DG. In this circumstance, the DSO must calculate the accurate closed-loop current while considering the DG systems in the distribution system. However, the DSO must also consider the regulation of the output power of the DG for changing to closed-loop operation without any problems.

We consider the worst case where the power flow in the distribution system must be adjusted for closed-loop operation. The operator must determine what to reduce and how to do so. We could consider adjusting the load demand and output power of the DG. However, compulsory load shedding is completely unacceptable for customers, considering that the closed-loop operation is not an abnormal condition. Regulation of the generated power by the distributed generation could sustain enormous economic damage for the electric utility owner. However, the DSO

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can ask for their understanding in regard to this power regulation based on two reasons: the purpose of the power regulation of the DG systems is stable maintenance of the distribution system, and it will be carried out using a method where all owners can contribute to the work equally. This implies that an algorithm is required for balanced power regulation of the DG systems to contribute to reduction of the closed-loop current. However, complex calculation is required because all DG systems are connected to several other locations in the distribution system.

We propose a strategy for controlling the output power of the DG to prevent the uninterruptible transfer to closed-loop operation. We focused on ESSs because they can produce or absorb active and reactive power. Numerical iteration was applied to calculate the power regulation using the output power of each ESS and the impedance between a substation and the connection point of the ESS. The accuracy of the iterations is determined by the chosen value of permissible error.

2. Calculation of the Closed-Loop Current in the Distribution System

The DSO can devise a plan for load transfer for many reasons, such as inspection of the circuit breakers in the distribution line, as well as various operations for maintenance and the prevention of overload in the distribution system [12-14]. Fig. 1 shows a one-line diagram of the distribution system to explain the closed-loop operation. When a normally open tie point is closed, the distribution is momentarily operated in closed-loop operation. In addition, closed-loop current can pass through the normally open tie point, depending on two factors: the difference in the voltage and phase between the ends of each normally open tie point, and the total impedance of two distribution systems. We can calculate the approximate closed-loop current using Thévenin's equivalent circuit [15], as shown in Fig. 2. In the one-line diagram, the closed-loop current in the distribution system can be calculated as:

$$Z_{TH} = Z_S + Z_{TR} + Z_{DL} \tag{1}$$

$$I_{Loop} = \frac{V_{NO_1}\angle\delta_{NO_1} - V_{NO_2}\angle\delta_{NO_2}}{Z_{TH_1} + Z_{TH_2}} \times \frac{S_{based}}{\sqrt{3}V_{based}} \tag{2}$$

where $V_{NO}\angle\delta_{NO}$ is the voltage and phase at a normally open tie point, and Z_{TH} is the total impedance in the distribution system. In this calculation, the active and reactive power of the load demand can be neglected because they have very low impedances, and the voltage and phase at the normally open tie point are already determined by the total load demand in the distribution system. However, we must consider that there might be many DG systems connected to the distribution systems.

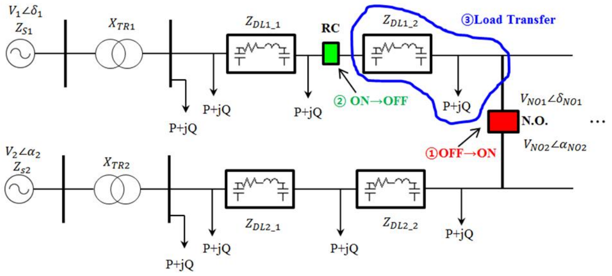

Fig. 1. Load transfer through closed-loop operation

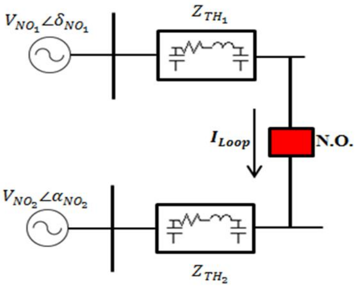

Fig. 2. Thévenin's equivalent circuit from the point of the normally open tie point

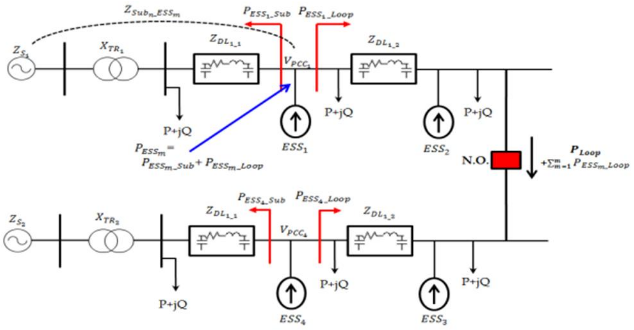

Fig. 3. One-line diagram of the closed-loop operation in a distribution system with ESSs

3. Consideration of the Closed-Loop Current in a Distribution System with Numerous ESSs

When many DG systems are connected to the distribution system, it is more important for the DSO to consider the influence on the DG. Most of the DG systems are controlled in grid-connected mode to produce or absorb active and reactive power [16]. In the near the future, many ESSs will be connected to the distribution system, including electrical vehicles, as shown in Fig. 3. The figure shows the one-line diagram of Thévenin's equivalent circuit of the distribution system with ESSs. Many ESSs are connected at various positions. Before changing to closed-loop operation, ESSs are producing or absorbing power through separate distribution systems. However, all ESSs are producing or absorbing power to both distribution systems based on the rule of current division [17] after changing to closed-loop operation. Grid-connected DG systems can be regarded as current-controlled sources.

Therefore, all ESSs in both distribution systems affect the closed-loop current due to the characteristics of current-controlled sources. Assuming that all ESSs are operated with a factor of unity, the closed-loop current is calculated as:

$$P_{ESS_m} = P_{ESS_m\_Sub} + P_{ESS_m\_Loop} \tag{3}$$

$$P_{ESS_m\_Loop} = \frac{Z_{Sub_n\_ESS_m}}{\left(Z_{TH_1} + Z_{TH_2}\right)} \times P_{ESS_m} \tag{4}$$

$$\begin{aligned} I_{Loop} = {} & \frac{V_{NO_1}\angle\delta_{NO_1} - V_{NO_2}\angle\delta_{NO_2}}{Z_{TH_1} + Z_{TH_2}} \times \frac{S_{based}}{\sqrt{3}V_{based}} \\ & + \sum_{m=1}^{m_f} \frac{Z_{Sub_{n}ESS_{m}}}{\left(Z_{TH_1} + Z_{TH_2}\right)} \times \frac{P_{ESS_m}}{\sqrt{3}V_{PCC_m}} \\ & - \sum_{m=1}^{m_b} \frac{Z_{Sub_n\_ESS_m}}{\left(Z_{TH_1} + Z_{TH_2}\right)} \times \frac{P_{ESS_m}}{\sqrt{3}V_{PCC_m}} \end{aligned} \tag{5}$$

where $Z_{Sub_n\_ESS_m}$ is the total impedance between the ESS and the distribution substation in each system, P_{ESS_m} is the active power currently generated from the ESS, and V_{PCC_m} is the voltage at the point of common coupling (PCC). m_f is the number of ESSs in the distribution system producing closed-loop current according to Eq. (2), and m_b is the number of ESSs in the distribution system absorbing closed-loop current.

The closed-loop current can be increased by ESSs in both distribution systems. In the worst cases, a large reverse current can flow to the other distribution line due to the ESSs. Fig. 4 shows the problem of the closed-loop current in the distribution system. Based on equations (3)-(5), ESS1 and ESS2 provide closed-loop current in the forward direction, and ESS3 and ESS4 provide current in the opposite direction. From the perspective of distribution system 2, the reverse power flow is the sum of $P_{ESS_1\_Loop}$, $P_{ESS_2\_Loop}$, $P_{ESS_3\_Sub}$, and $P_{ESS_4\_Sub}$, including I_{Loop} from Eq. (2). A large current can exceed the rated hosting capacity of the distribution line. In addition, protective devices can be operated incorrectly if the total reverse power flow is larger than the set value of protective devices. Simultaneously, distribution system 1 can be overloaded because the system must provide electricity that includes a separated section in distribution 2. Therefore, accurate calculating the closed-loop current while considering ESSs is very important for reliable operation of the power system.

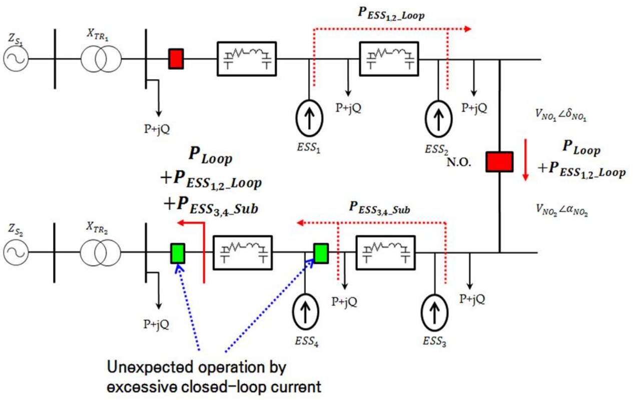

Fig. 4. Influence of reverse power flow including closed-loop current in the distribution system

4. Discussion of Countermeasures of Power Regulation in the Distribution System

When a DSO implements closed-loop operation in this circumstance, it will result in a critical power outage due to an unexpected level of closed-loop current. Let us assume that emergency restoration processes that require uninterruptible load transfer occur in the distribution system. We also assume that many ESSs are generating active power as intended or needed. From the perspective of the DSO, it is necessary to regulate the currently generated active power from ESSs to guarantee electric power to customers. However, the DSO will be faced with difficulties because the process of reasonably regulating active power is very complicated, and there are many considerations with small power producers who are operating ESSs.

After closed-loop operation, the injected active power P_{DL2} is calculated as -14.13 MW. Consider a situation where the DSO needs to reduce P_{DL2} by 4.13 MW in preparation for closed-loop operation. The DSO can accomplish this by implementing an interruptible load shedding [18] or by regulating the currently generated active power of the ESSs. However, the momentary power outage involved in interruptible load shedding can have a negative influence on the reliability of the power supply, so this method must be avoided [19].

Therefore, the DSO has to regulate the active power of the ESSs. The DSO must also determine which ESSs to regulate. There are two options. One is reducing the active power of only one ESS by the desired value (4.13 MW in the case). But in this case, the reduction should actually be more than 4.13 MW because of the current division due to closed-loop operation. However, an electrical utility owner might be dissatisfied with this decision. Even though this circumstance can be solved by giving reparation for the sacrifice, this solution is not ideal in the terms of managing the operating budget. Moreover, this situation can have a negative effect on the voltage profile of the distribution line [20,21].

The economic benefit of the ESSs connected with the distribution system is the reduction of the line losses by generating power near customers [22]. Using more ESSs to supply the distribution system minimizes the losses of the centralized generation source supplied through the transmission and distribution lines. Therefore, measures are needed to minimize losses in situations where the amount

Table 1. Solutions of closed-loop operation considering the momentary limiting of DG output

Solution	Advantages	Disadvantages
Operation is stopped for all DG systems	Closed-loop operation can be implemented easily	Huge loss of power generation must be resolved.
One DG systems reduce their output power	Complex calculation is not needed.	Voltage management problems can occur.
All DG systems reduce their output power equally	All operators can contribute to operation in a balanced and fair way.	Calculation is complicated due to various factors.

of power generated by the ESSs needs to be reduced. However, when the output of a certain ESS is reduced rapidly, the power loss due to the influence of the voltage fluctuation also increases dramatically [23]. In addition, the operation of a voltage regulating device such as a step voltage regulator or on-load tap changer is adversely affected due to the abrupt change of the voltage at PCC. Therefore, it is necessary to consider a reduction of all the distributed power by the same amount so as not to reduce the output of the ESS. Table 1 summarizes the three options of power regulation for closed-loop operation.

For these reasons, it is important for all producers to accommodate each change of active power. Moreover, all producers must agree to the power regulation in an emergency by the rule of provision and use [24]. In this situation, a third option is more reasonable than the above two options based on equity. We contend that balanced power regulation is the most reasonable method, even though it needs more power reduction. Nevertheless, it is hard to control the closed-loop current exactly by simply limiting the output to the ratio between desired output reduction and the number of ESSs. Since the positions of the connection points are all different, the amount of closed-loop current by the ESSs are also different. Therefore, it is necessary to determine an appropriate reduced output considering how much each ESS contributes to the closed-loop current.

5. Balanced Power Regulation of the ESS in the distribution System

Fig. 5 illustrates the proposed algorithm. It uses a kind of iteration method for the reduction of errors for two reasons. First, ESSs are connected at various locations, so they have different line impedances. Second, ESSs generate different active and reactive power. The algorithm consists of the 7 following steps.

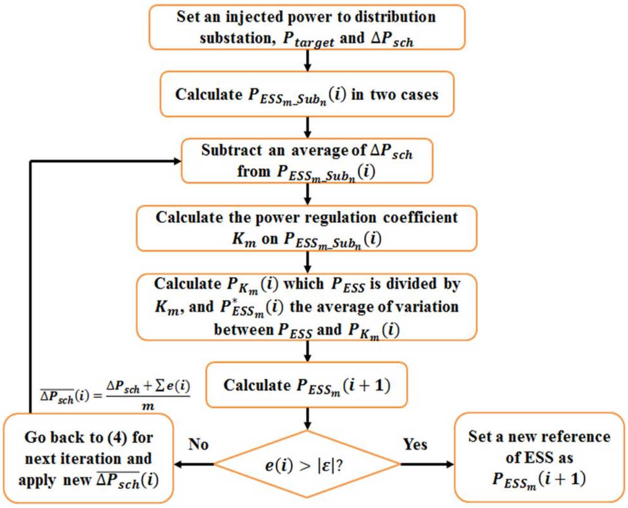

Fig. 5. The proposed algorithm of balanced power regulation of ESSs for closed-loop operation

Step 1: Set an injected power to the distribution substation, P_{target} and ΔP_{sch}

The purpose of this algorithm is to reduce the injected power of the distribution substation. As mentioned in Section 3, the DSO can reduce the injected power by regulating the currently generated power of the ESSs. To determine the reduced power of the ESSs, we must first determine the desired target of injected power $\boldsymbol{P_{target}}$ and the power injected to the distribution substation subtracted from $\boldsymbol{P_{target}}$, $\boldsymbol{\Delta P_{sch}}$.

Step 2: Calculate $P_{ESS_{m\_}Sub_n}(i)$ in two cases

After closed-loop operation, ESSs provide the closed-loop power $P_{ESS_{m\_}Loop}$ and the power injected to the distribution substation $P_{ESS_{m\_}Sub}$ due to the rule of current division. In accordance with section 3, we can calculate the values as follows:

$$P_{ESS_{m\_}Sub_n}(i) = \begin{cases} P_{ESS_{m\_}Loop}(i) = P_{ESS_m}(i) \times \dfrac{Z_{Sub_{n\_}ESS_m}}{Z_{TH_1} + Z_{TH_2}} \\ P_{ESS_{m\_}Sub}(i) = P_{ESS_m}(i) - P_{ESS_{m\_}Loop}(i) \end{cases} \tag{6}$$

In the case of a reduction of the active power injected to substation 2 $P_{ESS_{m\_}Sub_2}(i)$, as shown in Fig. 6. It can be determined based on which ESS is connected to which distribution system. Therefore, classification of the bidirectional power flow of the ESSs is very important in this calculation.

Step 3: Subtract the average of ΔP_{sch} from $P_{ESS_{m\_}Sub_n}(i)$

Based on the purpose of the balanced power regulation, all ESSs should reduce their currently generated active power equally. For n different ESSs, the initial average of the active power reduced by regulation of the ESSs can be calculated as:

$$\overline{\Delta P_{sch}}(i) = \frac{\Delta P_{sch}}{\mathrm{n}} \qquad (i = 0) \tag{7}$$

The new reference of the ESSs for closed-loop operation may be regarded as the difference between P_{ESS} and $\overline{\Delta P_{sch}}$. However, there might be big errors due to the different conditions of the ESSs. Therefore, an iteration method for the correction of errors is required. The correction value will be added to $\overline{\Delta P_{sch}}$, and this process is described in Step 7.

Step 4: Calculate the power regulation coefficient K_m on $P_{ESS_{m\_Sub_n}}(i)$

The coefficient K_m can be regarded as the degree of influence of the closed-loop current. K_m is an indicator of the contribution to the closed-loop current reduction by the power regulation of ESSs in proportion to their output and distance. Therefore, K_m can resolve the problem with different impedances of ESSs. Using the formula of Step 3, K_m can be defined as:

$$K_m(i) = \begin{cases} \dfrac{P_{ESS_{m\_Loop}}(i)}{P_{ESS_{m\_Loop}}(i) - \overline{\Delta P_{sch}}(i)} \\ or \\ \dfrac{P_{ESS_{m\_Sub}}(i)}{P_{ESS_{m\_Sub}}(i) - \overline{\Delta P_{sch}}(i)} \end{cases} \tag{8}$$

Step 5: Calculate $P_{K_m}(i)$ (P_{ESS} divided by K_m) and $P^*_{ESS_m}(i)$ (the average variation between P_{ESS} and $P_{K_m}(i)$)

Compared with Step 2, the difference in Step 5 is that the power regulation level in proportion to the distance is considered for the calculation. We can define $P_{ESS}(0)$ divided by $K_m(i)$ as $P_{K_m}(i)$, and the reference of active power of the ESSs is the average variation between $P_{ESS}(0)$ and $P_{K_m}(i)$, which are calculated as

$$P_{K_m}(i) = \frac{P_{ESS_m}(i)}{K_m(i)} \tag{9}$$

$$\overline{P^*_{ESS}}(i+1) = \frac{\sum_{m=1}^{n}(P_{ESS_m}(i) - P_{K_m}(i))}{\mathrm{n}} \tag{10}$$

Step 6: Calculate $P_{ESS_m}(i+1)$

The balanced reference of ESSs is finally calculated by the previous steps. The newly calculated active output power of ESSs for balanced power regulation can be calculated as:

$$P_{ESS_m}(i+1) = P_{ESS_m}(0) - \overline{P^*_{ESS}}(i+1) \tag{11}$$

If the currently generated active power of ESSs is changed to $P_{ESS_m}(i+1)$, we can expect $P_{DL_n}(i+1)$ to be approximately P_{target}. However, we must also consider the range of permissible error ε.

Step 7: Compare $e(i)$ with |ε|

Step 7 must be performed precisely because the new reference of ESS is determined in that step for closed-loop operation. Otherwise, closed-loop current can be increased in the worst case. Reclosers in the distribution system can be tripped at currents higher than their rated breaking current. Therefore, it is necessary to revise the reference value if the calculated reference of ESSs is inaccurate outside the rated range. Before starting this algorithm, we must specify the permissible error |ε|. If $e(i)$ is smaller than |ε|, $P_{ESS_m}(i+1)$ can be used as the new reference of ESSs. However, if it is larger than |ε|, $\overline{\Delta P_{sch}}(i)$ is changed to Eq. (13), and the algorithm is repeated from Step 3:

$$e(i) = P_{target} - (P_{DL_n}(i+1) + P_{Loss,n}) \tag{12}$$

$$\overline{\Delta P_{sch}}(i) = \frac{\Delta P_{sch} + \sum e(i)}{\mathrm{n}} \quad (i = 1,2,\ldots,n) \tag{13}$$

If Step 7 satisfies these conditions, the algorithm will be terminated, and the reference of all ESSs will be changed to $P_{ESS_m}(i+1)$. Therefore, all ESSs will reduce their currently generated power by the same amount, and closed-loop operation can be done without worrying about power outages due to excess current.

6. Simulation Results and Analysis

To demonstrate the balanced power regulation strategy, we carried out some verification tests, simulations, and calculations. First of all, we proved that the equation and Thévenin's equivalent circuit for calculation of the closed-loop current is accurate. Second, we designed two distribution systems using PSCAD/EMTDC to analyze the influence of ESSs during closed-loop operation. In addition, the closed-loop current with ESSs was calculated using the proposed equations. Third, the strategy of balanced power regulation is demonstrated by comparing the simulation results with the calculation results. The tested distribution systems are based on actual systems in Korea except for the information about the ESSs.

Fig. 6. Verification results of closed-loop operation in Taeseong D/L

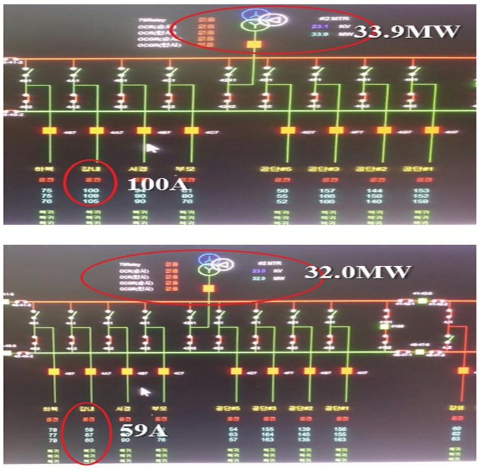

Fig. 7. Verification results of closed-loop operation in Kangnae D/L

Table 2. The specifications of distribution systems

	Distribution System 1	Distribution System 2
S_{based}	100 MVA	
V_{based}	22.9 kV	
P_{DL} (before)	22.8 MW	33.9 MW
P_{DL} (after)	24.8 MW	32 MW
$V_{N.O.}$(p.u.)	$0.907-j0.432$	$0.898-j0.455$
Z_{TH_DS}(p.u.)	$0.218+j0.785$	$0.077+j0.478$

Table 3. Comparison of power flow between simulation and experiment results

	Simulation result	Experimental result
P_{Sub1} (Before)	22.8 MW	
P_{Sub2} (Before)	33.9 MW	
P_{Sub1} (After)	24.64 MW	24.8 MW
P_{Sub2} (After)	32.04 MW	32 MW

6.1 Calculation of closed-loop current

Figs. 6 and 7 show the verification results of closed-loop operation at Taeseong D/L in Juklim substation and Kangnae D/L in Seocheongju substation in Cheong-ju, Korea. The changes in power flow between the two distribution systems are shown in Table 3. The closed-loop current in the distribution system is show in Table 4. The result of closed-loop current in Thévenin's circuit nearly matches the full-scale modeling of the distribution system. Moreover, the results are similar to the experimental results, even though the reactive power is neglected in the verification test. The closed-loop current can be calculated easily using this theory, so we can determine whether to change to closed-loop operation.

Table 4. Comparison of closed-loop current between simulation and experimental results

	Simulation result		Experimental result
	Full modeling	Thévenin's circuit	
P_{Loop}	1.84 MW	1.787 MW	1.9 MW
Q_{Loop}	0.688 Mvar	0.683 Mvar	-
I_{Loop}	47 A	48 A	44 A

Note : $I_{Loop}=\frac{(0.907-j0.432)-(0.898-j0.455)}{0.218+j0.785+0.077+j0.478}\times\frac{100MVA}{\sqrt{3}\times 22.9kV}$
$=47.97\angle-8.19$ A

Table 5. Output information of ESSs

	ESS_1	ESS_2	ESS_3	ESS_4
$Z_{Sub_n\_ESS_m}$	0.021 +j0.403	0.151 +j0.693	0.057 +j0.435	0.03 +j0.392
P_{ESS}	8 MW	7 MW	5 MW	5 MW
Q_{ESS}	0 Mvar			

Table 6. Simulation results of closed-loop current

	Simulation results	
	Before operation	After operation
P_{DL_1}	-8.384 MW	-0.117 MW
P_{DL_2}	-5.959 MW	-14.13 MW
P_{Loop}	0 MW	5.15 MW (DS)+ 3.33 MW(ESS)
I_{Loop}	0 A	129.92 A (DS)+ 84.11 A(ESS)

6.2 Calculation of closed-loop current considering esss in distribution systems

We assume that ESSs are operating in a closed-loop distribution system, as shown in Fig. 3. The specifications of the distribution system are given in the appendix. Table 5 shows the simulation conditions of ESSs connected to each distribution system. The ESSs are producing only active power in the distribution system. When the normally open tied point is closed, the distribution systems will be operated as a closed-loop system. After closing the point, ESSs will produce active power to both the distribution systems due to rule of current division. Table 6 summarizes the simulation results with closed-loop current. Comparing the closed-loop current between these results and the verification test in Section 6.1 shows that the ESSs can have an influence on the closed-loop current [25].

6.3 Demonstration of balanced power regulation strategy during closed-loop operation

We demonstrate the balanced power regulation of ESSs in a distribution system. We assume that a DSO should reduce P_{DL_2} by 4.13 MW for prompt closed-loop operation, and ε is set as 0.05 MW. The losses of the distribution lines are set as 0.25 MW for $P_{Loss,1}$ and 0.1 MW for $P_{Loss,2}$ based on the total length of the distribution lines [26].

6.3.1 First iteration

According to the schedules in the simulation, $\overline{\Delta P_{sch}}(0)$ can be calculated as 1.032 MW, as shown in Table 7. It will be subtracted from the corresponding $P_{ESS_m\_Loop}$ or

$P_{ESS_m\_Sub}$. Table 8 shows the result of Step 4, which can be used to check the proportion between distances and $K_m(i)$. Table 9 shows the result of Step 5 in the simulation, $P_{K_m}(i)$ and $\overline{P_{ESS}^*}(i)$. We can calculate $P_{ESS_m}(1)$, $P_{ESS_m\_Loop}$, and $P_{ESS_m\_Sub}$, as shown in Table 10. This table shows the active power flow of ESSs injected to substation 2 after changing the reference of the ESSs.

Finally, we can calculate P_{DL_1} and P_{DL_2} before and after closed-loop operation with balanced power regulation of ESSs, as shown in Table 11. However, the first iteration, $e(1)$, fails to meet the permissible error ε according to the results shown in Table 12. Therefore, this case should repeat again from Step 3 with a modified $\overline{\Delta P_{sch}}(i)$. The process will continue until the error meets is in the permissible range error.

Table 7. Active power flow of ESSs injected to substation 2 in the first iteration of the simulation

	$P_{ESS_m}(0)$ injected to DS_2	$\overline{\Delta P_{sch}}(0)$	Note
ESS_1	2.452 MW	1.032 MW	$P_{ESS_m\_Loop}$: ESS_1, ESS_2 $P_{ESS_m\_Sub}$: ESS_3, ESS_4
ESS_2	3.828 MW		
ESS_3	1.685 MW		
ESS_4	1.508 MW		

Table 8. Result of $K_m(i)$ of Step 4 in the first iteration

	P_{ESS}-$\overline{\Delta P_{sch}}(0)$	$K_m(0)$	Note
ESS_1	1.420 MW	1.727	$P_{ESS_m\_Loop}$: ESS_1, ESS_2 $P_{ESS_m\_Sub}$: ESS_3, ESS_4
ESS_2	2.796 MW	1.369	
ESS_3	0.653 MW	2.582	
ESS_4	0.476 MW	3.171	

Table 9. Result of $P_{K_m}(0)$ and $\overline{P_{ESS}^*}(i)$ of Step 4 in the first iteration

	$P_{K_m}(0)$	$P_{ESS_m}(0) - P_{K_m}(0)$	$\overline{P_{ESS}^*}(1)$
ESS_1	4.631 MW	3.369 MW	2.936 MW
ESS_2	5.112 MW	1.888 MW	
ESS_3	1.936 MW	3.064 MW	
ESS_4	1.577 MW	3.423 MW	

Table 10. Active power of ESS injected to substation 2 after changing the reference of ESSs in the first iteration

	$P_{ESS_m}(1)$	$P_{ESS_m}(1)$ injected to DS_2	Note
ESS_1	5.064 MW	1.577 MW	$P_{ESS_m\_Loop}$: ESS_1,ESS_2 $P_{ESS_m\_Sub}$: ESS_3,ESS_4
ESS_2	4.064 MW	2.223 MW	
ESS_3	2.064 MW	0.699 MW	
ESS_4	2.064 MW	0.628 MW	

Table 11. Comparison between before and after closed-loop operation in the first iteration

	$P_{DL1}(1)$	$P_{DL2}(1)$
Simulation result (before)	-0.117 MW	-14.13 MW
Calculation result (after)	5.040 MW	-7.761 MW
Simulation result (after)	5.115 MW	-7.662 MW

6.3.2 Second Iteration

In the second iteration, there is no difference in any steps except Step 3. $\overline{\Delta P_{sch}}(i)$ is changed from Eq. (7) to Eq. (13), and the next results after Step 3 are corrected as the error is minimized. Table 13 shows the result of Step 4 after applying the modified $\overline{\Delta P_{sch}}(i)$. As in the first iteration, this process lastly calculates $P_{ESS_m}(2)$ and compares $e(i)$ with $|\varepsilon|$. If the stop condition is not satisfied, the iterations continue. This iteration can converge faster when ε is larger, but the accuracy of the calculation might be reduced. As the iteration progresses, the calculation results finally approach the target value.

6.3.3 Final iteration

This simulation condition finishes in the eighth iteration. Table 14 shows the total results of iterations. Through the final iteration, the DSO can check the new reference of ESSs and predict the power flow of distribution lines after closed-loop operation. If ε is set to a low value, more iterations might be needed. However, the accuracy of the algorithm will be increased as well. This algorithm can present a reasonable reference result of balanced power regulation by numerous iterations. Fig. 9 shows graphs of the results.

6.3.4 Simulation results and comparison

Fig. 10 shows the simulation results of the proposed algorithm, and Table 15 compares the simulation results

Table 12. Permissible error of Step 7 in the first iteration

Calculation results		Note
$e(1)$	-10 - (-7.761) = **-2.239**	Not satisfied with $\lvert\varepsilon\rvert$ (0.05)
$\overline{\Delta P_{sch}}(1)$	$\frac{4.13+(-2.239)}{4}$ =**0.473 MW**	This value will be applied to the 2nd iteration

Table 13. Result of $K_m(i)$ of Step 4 in the second iteration

	$P_{ESS_m}(0)$ injected to DS_2	$\overline{\Delta P_{sch}}(1)$	$K_m(1)$
ESS_1	2.452 MW	**0.473 MW**	**1.239**
ESS_2	3.828 MW		**1.141**
ESS_3	1.685 MW		**1.390**
ESS_4	1.508 MW		**1.457**

Table 14. Final result of iteration (8th)

	$\overline{\Delta P_{sch}}(i)$	$\overline{P_{ESS}^*}(i)$	$P_{DL2}(i)$	$e(i)$
1st	1.033 MW	2.936 MW	-7.761 MW	-2.239
2nd	0.475 MW	1.344 MW	-11.288 MW	1.288
3rd	0.785 MW	2.260 MW	-9.259 MW	-0.741
4th	0.610 MW	1.733 MW	-10.426 MW	0.426
5th	0.716 MW	2.036 MW	-9.755 MW	-0.245
6th	0.655 MW	1.862 MW	-10.140 MW	0.140
7th	0.690 MW	1.961 MW	-9.921 MW	-0.079
8th	**0.670 MW**	**1.905 MW**	**-10.045 MW**	**0.045**

with the calculations. Closed-loop operation starts at 0.5 s, and the references of ESSs are changed by the result of iteration every 1 second. The simulation was also performed using PSCAD/EMTDC. In both cases, there is close correspondence between the simulation and calculation results because the power loss of distribution lines is also applied in the calculation of Eq. (10).

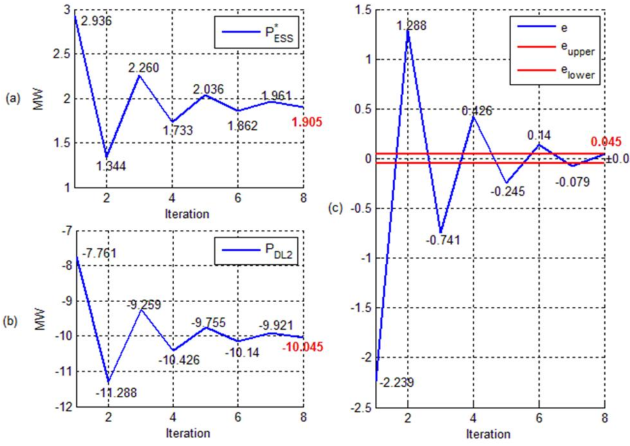

Fig. 9. Calculation result of convergence : $\overline{P^*_{ESS}(i)}$ (b) : P_{DL_2} (c) : $e(i)$

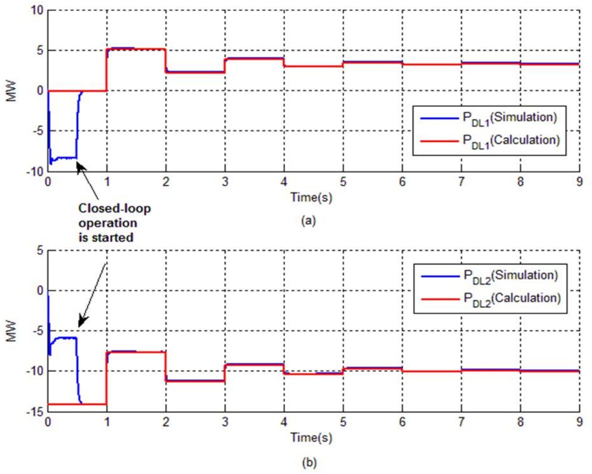

Fig. 10. Simulation and calculation results of balanced power regulation: (a) Substation 1; (b) Substation 2

Table 15. Simulation results of $P_{DL2}(i)$ and $P_{DL2}(i)$

	$P_{DL1}(i)$ (MW)		$P_{DL2}(i)$ (MW)	
Time	Simulation	Calculation	Simulation	Calculation
0-0.5	-8.492		-5.959	
0.5-1	-0.117		-14.13	
1-2	5.115	5.040	-7.662	-7.761
2-3	2.277	2.199	-11.242	-11.288
3-4	3.929	3.834	-9.180	-9.259
4-5	2.967	2.893	-10.365	-10.426
5-6	3.503	3.434	-9.681	-9.755
6-7	3.195	3.123	-10.079	-10.140
7-8	3.380	3.300	-9.856	-9.921
8-9	3.280	3.200	-9.982	-10.045

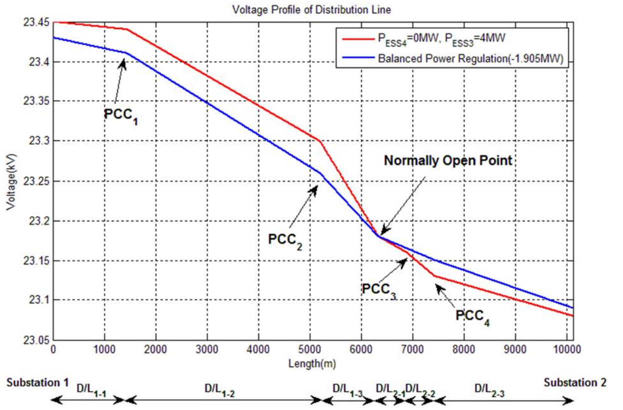

Fig. 11. Simulated voltage profile of distribution lines between two strategies

The advantage of balanced power regulation is the effective management of the voltage profile in distribution lines. In general, a voltage rise caused by reverse power flow from DG is one type of disturbance in the maintenance of distribution power quality [27]. In a bi-directional power flow system, the voltage can be maintained within a narrower range through balanced power regulation.

Fig. 11 shows the voltage profile of distribution lines in two cases of power regulation of ESSs. The red line in figure 11 is the result of power reduction for particular ESSs (P_{DG4} =0 MW and P_{DG3} =4 MW in this case). However, the total power generation of ESSs in distribution line 1 is much larger than the opposite line, so the range of the voltage profile is wider than the result of balanced power regulation of ESSs. Although the total reduced power is larger than in the former case, this algorithm can also be effective at voltage regulation.

7. Conclusion

In order to ensure the consistent and reliable maintenance of a distribution system, precise closed-loop operation is required. In emergency situations during the operation of numerous DG systems, it is necessary for a DSO to forcibly adjust the output of the DG systems. However, discretion is required because it is very sensitive issue to determine the targets and amounts of adjustments. We have proposed a strategy for balanced power regulation of all ESSs to resolve these problems. The performance of the algorithm was demonstrated through simulations and calculations. The strategy has three main advantages:

1. There is no reason not to cooperate with the DSO for all electrical utility owners who are using the distribution system because there is a definite purpose for the management of the distribution system.
2. Since the initial conditions are all known values and a correction value is added to the iteration method, the calculation result based on the algorithm has a high

possibility of convergence. This means that the accuracy of the algorithm is very high.
3. There can be a significant problem of voltage regulation at PCC in the case of a distribution system that is greatly affected by many DG systems. However, thanks to the balanced power regulation, the DSO can maintain similar levels of the voltage profile on the distribution lines.

This paper analyzed the reasonable solution of output power regulation of ESS. On the other hand, we should consider that ESS can be charging or discharging active and reactive power. Therefore, other improved studies such as active and reactive power control at the normally-tied open point will be also required.

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Nomenclature

m	Number of ESSs
m_f	Number of ESSs in distribution system producing closed-loop current (forward direction)
m_b	Number of ESSs in distribution system absorbing closed-loop current (backward direction)
n	Number of distribution substations (generally 2)
Z_{TH}	Total impedance of Thévenin’s equivalent circuit
Z_S	Source impedance
Z_{TR}	Transformer impedance
Z_{DL}	Distribution line impedance
P_{Loop}	Closed-loop active power
Q_{Loop}	Closed-loop reactive power
I_{Loop}	Closed-loop current
V_{NO}	Voltage at normally open tie point before closed-loop operation
δ_{NO}	Phase at normally open tie point before closed-loop operation
S_{based}	Based complex power
V_{based}	Based voltage
P_{DL}	Active power of distribution line
P_{Sub}	Active power of distribution substation
V_{Sub}	Voltage at distribution substation
V_{PCC_m}	Voltage at point of common coupling of ESS_m
$Z_{Sub_n\_ESS_m}$	Distribution line impedance between $\mathrm{substation}_n$ and ESS_m
P_{ESS_m}	Active power of ESS_m
P_{target}	Target active power injected to substation
ΔP_{sch}	Active power fluctuation between P_{target} and P_{DL}
$P_{ESS_m\_Sub_n}$	Active power of ESS_m injected to $\mathrm{substation}_n$
$P_{ESS_m\_Loop}$	Active power of ESS_m passing through normally open tie point
$P_{ESS_m\_Sub}$	Active power of ESS_m injected to substation
$\overline{\Delta P_{sch}}$	Average of active power variation
K_m	Power regulation coefficient
P_{K_m}	Active power of ESS_m divided by K_m
P_{ESS}^*	Reference output power of ESS
e	Permissible error of iteration

Appendix

The following two tables show the actual parameters of distribution systems in Cheongju, Korea. These data were applied in the simulation analysis.

Substation 1 (Juklim S/S Taeseong D/L)			
$V_{S1}\angle\delta_{S1}$	154 kV$\angle -17.4^{\circ}$	$P_{Sub1} + jQ_{Sub1}$	22.8 MW +1.571 Mvar
Z_{S1}	0.083+j0.995	$P_{DL1\_1} + jQ_{DL1\_1}$	2.847 MW +0.938 Mvar
X_{TR1}	j0.359	$P_{DL1\_1} + jQ_{DL1\_2}$	2.847 MW +0.938 Mvar
V_{Sub1}	23.36 kV	$P_{DL1\_3} + jQ_{DL1\_3}$	0.595 MW +0.195 Mvar
Z_{DL1_1}	0.0208+j0.03459	V_{PCC1}	23.39 KV
Z_{DL1_2}	0.1307+j0.2896	V_{PCC2}	23.41 KV
Z_{DL1_3}	0.0657+j0.0922	$V_{NO_1}\angle\delta_{NO_1}$	23.4 kV$\angle -18.29^{\circ}$

Substation 2 (Seocheongju S/S Kangnae D/L)			
$V_{S1}\angle\delta_{S1}$	154 kV$\angle -20.3^{\circ}$	$P_{Sub1} + jQ_{Sub1}$	33.9 MW +6.657 Mvar
Z_{S1}	0.083+j1.02	$P_{DL1\_1} + jQ_{DL1\_1}$	1.755 MW +0.157 Mvar
X_{TR1}	j0.319	$P_{DL1\_1} + jQ_{DL1\_2}$	1.755 MW +0.157 Mvar
V_{Sub1}	23.15 kV	$P_{DL1\_3} + jQ_{DL1\_3}$	0.386 MW +0.0346 Mvar
Z_{DL1_1}	0.0383+j0.0636	V_{PCC1}	23.16 KV
Z_{DL1_2}	0.01924+j0.04262	V_{PCC2}	23.15 KV
Z_{DL1_3}	0.01924+j0.04262	$V_{NO_1}\angle\delta_{NO_1}$	23.2 kV $\angle -24.53^{\circ}$

References

[1] D. Gruenemeyer, “Distribution Automation: How Should It Be Evaluated?”, *Rural Electric Power Conference at the 35th Annual Conference,* pp.D3/1-D3/10, Apr. 1991.

[2] A. Pahwa, “Planning and Analysis Tools to Evaluate Distribution Automation Implementation and Benefits”, *IEEE Power Engineering Society General Meeting,* pp. 2622-2623, Jun. 2005.

[3] R. Greer et al, “Distribution Automation Systems with Advanced Features”, *Rural Electric Power Conference (REPC) 2011 IEEE,* pp. C4/1-C4/15, Apr. 2011.

[4] Miroslav M. Begovic, “*Electrical Transmission Systems and Smart Grids: Selected Entries from the Encyclopedia of Sustainability Science and Technology*”, Springer Science & Business Media, NY, USA, pp. 7-68, 2012.

[5] Mesut. E. Baran et al, Network Reconfiguration in Distribution Systems for Loss Reduction and Load Balancing, *IEEE Trans. Power Delivery,* vol. 4, no. 2, pp. 1401-1407, Apr. 1989.

[6] T.H. Chen et al, “Feasibility Study of Upgrading Primary Feeders from Radial and Open-Loop to Normally Closed-Loop Arrangement”, *IEEE Trans. Power Systems,* vol. 19, no. 3, pp. 1308-1316, Aug. 2004.

[7] W.T. Huang et al, “Nature and Operation Schemes of Normally Closed-Loop Distribution Systems”, *10th International Conference on Control, Automation, Robotics and Vision,* Hanoi, Vietnam, pp. 1718-1723, Dec. 2008.

[8] Z.H. Zhang et al, “Research on the Optimal Power Flow Control Method of the Closed-Loop Distribution Network with UPFC”, *IEEE PES Innovative Smart Grid Technologies,* Tianjin, China, pp. 1-3, May 2012.

[9] Ke Xuan et al, “Analysis of Current Due to Closing Loop in Distribution Network Based on Angle Changing”, *2010 Asia-Pacific Power and Energy Engineering Conference,* Chengdu, China, pp. 1-4, March 2010.

[10] N. Jenkins et al, “*Distributed Generation*”, The Institution of Engineering and Technology: London, UK, pp. 1-20, 2010.

[11] R. Teodorescu et al, “*Grid Converters for Photovoltaic and Wind Power Systems*”, John Wiley & Sons: Chichester, West Sussex, UK, pp. 123-142, 2011.

[11] Thomas A. Short, “*Electric Power Distribution Handbook*”, CRC Press, pp. 123-142, 2014.

[12] William H. Kersting, “*Distribution System Modeling and Analysis*”, CRC Press: Boca Raton, FL, USA, pp. 1-9, 2001.

[13] Juan M. Gers, “*Distribution System Analysis and Automation*”, Institution of Engineering and Technology, 2013.

[14] Thomas Allen Short, “*Electric Power Distribution Handbook*”, CRC Press, 2014.

[15] Zhelin Deng et al, “Closed-loop Current Adjustment Strategy in Distribution Network Based on Sensitivity Analysis”, *Power Engineering and Automation Conference* (*PEAM*), *2011 IEEE,* Wuhan, China, pp. 55-58, Sep. 2011.

[16] Joan Rocabert et al, “Control of Power Converters in AC Microgrid” *IEEE Trans. Power Electronics*, vol. 27, no. 11, pp. 4734-4749, Nov. 2012.

[17] Charles K. Alexander and Matthew N. O. Sadiku, “*Fundamentals of Electric Circuits*”, McGraw-Hill Higher Education, 2009.

[18] A.M. Leite da Silva et al, “Optimum Load Shedding Strategies in Distribution Systems”*, 2001 IEEE Power Tech Proceedings,* Porto, Portugal, Sept. 2001.

[19] P. Wang et al, “Optimum load-shedding technique to reduce the total customer interruption cost in a distribution system”, *IEE Proceedings - Generation, Transmission and Distribution,* vol. 147, no. 1, pp. 51-56, Jan. 2000.

[20] B. Renders et al, “Distributed generation and the voltage profile on distribution feeders during voltage dips”, *Electric Power Systems Research*, Volume 80, no. 12, pp. 1452-1458, Dec. 2010.

[21] A. Casavola et al, “Voltage Regulation in Distribution Networks in the Presence of Distributed Generation: a Voltage Set-Point Reconfiguration Approach”, *Electric Power Systems Research,* vol. 81, no. 1, pp. 25-34, Jan. 2011.

[22] U.S. Department of Energy, “*The Potential Benefits of May Impede Their Expansion*”, U.S. Department of Energy, 2007.

[23] I. Lepadat et al, “Impact of Distributed Generation on Voltage Profile and Power Losses in a Test Power Grid”, *Control Conference (CCC), 2013 32nd Chinese*, Xian, China, July 2013.

[24] Korea Electric Power Corporation, “*Provision and Use of Electric Transmission & Distribution Facilities*”, Korea Electric Power Corporation, 2017.

[25] Xingquan Ji et al, “Optimal Regulation for Loop-closing Operation in a Distributed Generation Integrated System”, *Journal of Electrical Systems,* vol. 11, no. 3, pp. 296-307, Sep. 2015.

[26] Anguan Wu et al, “*Line Loss Analysis and Calculation of Electric Power Systems*”, John Wiley & Sons, 2016.

[27] Pedro M. S. Carvalho et al, “Distributed Reactive Power Generation Control for Voltage Rise Mitigation in Distribution Networks”, *IEEE Trans. Power Systems*, vol. 23, no. 2, pp. 766-772, May, 2008.

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