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전압조정 측면에서 본 소형 열병합발전 배전계통 도입량 평가

Evaluation of Interconnection Capacity of SCOGNs to the Power Distribution Systems from the Viewpoint of Voltage Regulation

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Abstract - This paper discusses the evaluation of interconnection capacity of small cogeneration (SCOGN) systems to the power distribution systems from the viewpoint of voltage regulation. Power utilities are required to keep the customers' voltage profile over a feeder close to the rated value under all load conditions. However, it is expected that the interconnection of SCOGNs to the power distribution systems impacts on the existing voltage regulation method and customers' voltage variations. Therefore, SCOGNs should be integrated to the automated power distribution systems to prevent interconnection problems and supply high quality electricity to the customers. For these reasons, we should proceed with the evaluation of interconnection capacity of SCOGNs to the power distribution systems. However, it is generally impossible to perform actual testing on the power distribution systems, and standardized methodologies and guidelines are not developed to evaluate it. The criterion indexes for voltage regulation and variations are presented in order to evaluate the interconnection capacity of SCOGNs to the power distribution systems. In addition, the evaluation methodology of interconnection capacity of SCOGNs for power distribution systems is presented. It is expected that the results of this paper are useful for power system planners to determine the interconnection capacity of SCOGNs and dispersed storage and generation (DSG) systems to the power distribution systems.

Key Words : SCOGN, Interconnection Capacity, Voltage Regulation, Interconnection Guideline, Under-Load Tap Changer, LDC

1. Introduction

The interconnection of SCOGNs to the power distribution systems is very attractive for both utilities and customers because of global environmental issues and difficulties in the selection of a site for large thermal and nuclear generating plants. The electric energy of existing thermal power plant is generated in the course of converting mechanical energy produced from steam made by firing fossil fuels. The remaining thermal energy is not used. If the remaining thermal energy is reused for the heating energy, the higher efficiency of energy more than 80% will be possible. It is expected that SCOGNs can meet this requirement.

However, the interconnection of SCOGNs and DSGs to power distribution systems can cause operational problems such as economic dispatch [1-4], voltage variations and regulation [5-7,12-13], harmonic distortion [8-9], protection and safety [8], operation problems of DSGs [9-10], etc.

Power utilities are required to keep the customers' voltage profile over a feeder close to the rated value under all load conditions because voltage quality is an important part of power quality. Therefore, the impacts of SCOGNs and DSGs on existing voltage regulation method and customers' voltage variations should be investigated. In previous research into this issue, in [7] voltage regulation problem with wind generation at the power distribution systems where voltage is regulated by line drop compensation (LDC) method is analyzed. In [6] the relationship between reverse power of DSGs and sending end reference voltage variations in the power distribution systems is analyzed. In [12-13] the voltage regulation method, which maintains the customers' voltages within a permissible voltage limit, for substation main transformer at the power distribution systems with DSGs, is presented.

This paper discusses the evaluation of interconnection capacity of SCOGNs to the power distribution systems from the viewpoint of voltage regulation because the customers' terminal voltages are an important criterion in view of power quality. In section 2, the impacts of SCOGNs on the existing voltage regulation method and the customers' voltage variations are extensively analyzed. In section 3,

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the criterion indexes for voltage regulation and variations are introduced. Also the evaluation methodology of interconnection capacity of SCOGNs is presented. In section 4, the interconnection capacity of SCOGNs for the real distribution system model is evaluated.

2. Voltage Variations with SCOGNs

2.1 LDC Voltage Regulation Method

The modern power distribution systems adopt LDC method as voltage regulation method. The LDC method is employed to compensate the voltage drop (VD) of distribution line and correct the tap position of ULTC transformer from information of the bus voltage and the bank current. The sending end reference voltage (SERV) and the sending end voltage (SEV) in the LDC method are given by [6,12-13]

$$V_{ser}(t) = V_{ce} + Z_{eq} \cdot I(t) \qquad (1)$$

$$V_{se}(t) = V_{tap,k}(t) - Z_{MTR,k}(t) \cdot I(t) \qquad (2)$$

2.2 Sample Distribution System Model

The configuration of a sample distribution system model is shown in Fig. 1. The interconnection node of SCOGNs deals with P-Q node. Specifications of the sample distribution system and the ULTC transformers are as follows

- feeder impedance: 0.0347+j0.0746 [p.u./km]
- number of node per feeder: 10
- node interval: 1 [km]
- peak-load per node: 1 [MVA] (lagging p.f. 0.9)
- light-load per node: 0.25 [MVA] (lagging p.f. 0.9)
- VD of pole transformer at the peak-load: 3[%]
- VD of LV distribution line at the peak-load: 6[%]
- VD of pole transformer at the light-load: 0.75[%]
- VD of LV distribution line at the light-load: 1.5[%]
- upper-permissible voltage limit(V_{max}): 1.06 [p.u.]
- lower-permissible voltage limit(V_{min}): 0.94 [p.u.]
- impedance of main transformer: 0.004+j0.15 [p.u.]
- rated capacity of main transformer: 45/60 [MVA]
- compensating impedance (Z_{eq}): 0.125+j0.065 [p.u.]
- reference voltage (V_{ce}): 1.0 [p.u.]
- total tap of ULTC (K): 17 [steps]
- tap interval: 0.0125 [p.u.]
- dead-band: 0.0125/0.02 [p.u.]

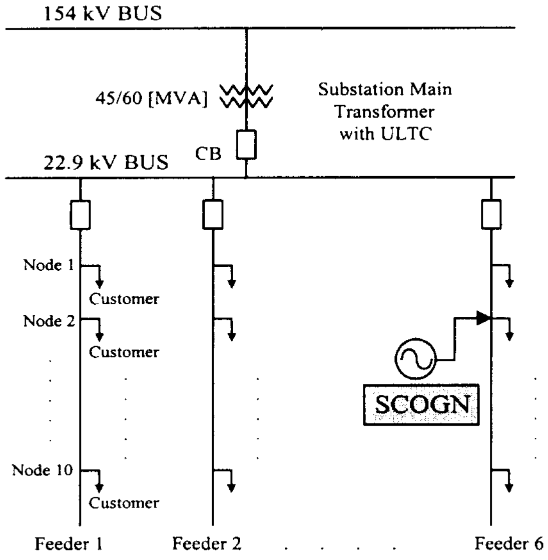


Fig. 1 Sample distribution system model

2.3 Hysterical Behaviors of SEV

ULTC and voltage regulating relay are used to keep the SEV to the SERV in the LDC method. Therefore, the SEV is controlled within SERV ± *db* (dead-band of voltage regulating relay).

To analyze the relationship between SERV and SEV, we simulate the behaviors of the SERV and SEV with load changes from the peak-load to the light-load and vice versa. In Fig. 2, it can be seen that SEV has hysterical behaviors.

2.4 Impacts of SCOGNs on the Voltage Variations

The aforementioned sample distribution system model is used to analyze the customers' voltage variations with SCOGNs. The interconnection node of SCOGNs is the node 10 of feeder 1. The capacity of SCOGNs means reverse power flow of SCOGNs. Loads of the customers' voltage profiles with SCOGNs are considered as the peak-load. From the simulation results of above case studies, the impacts of SCOGNs on the existing voltage regulation method and customers' voltage variations are summarized as follows:

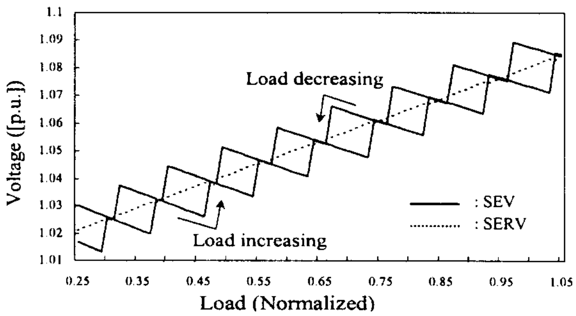
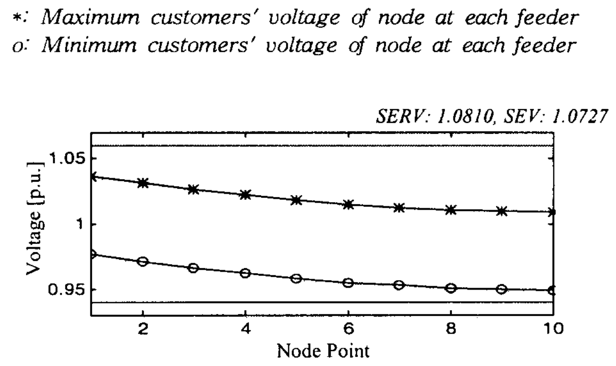
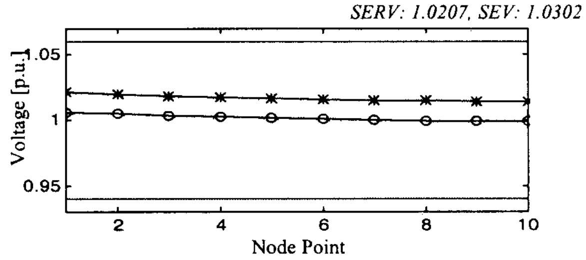


Fig. 2 Hysterical behaviors of SEV

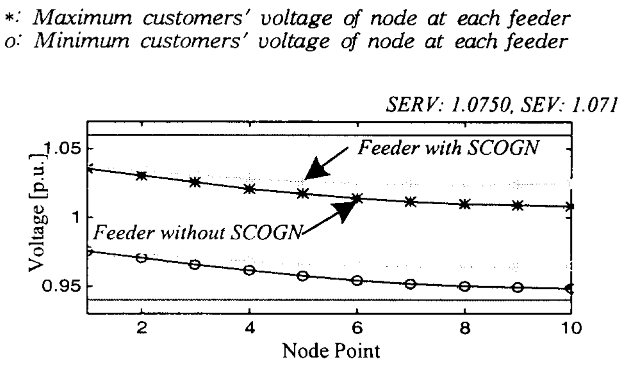


(a) Peak-load

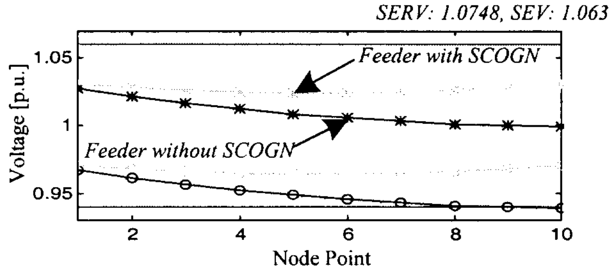


(b) Light-load

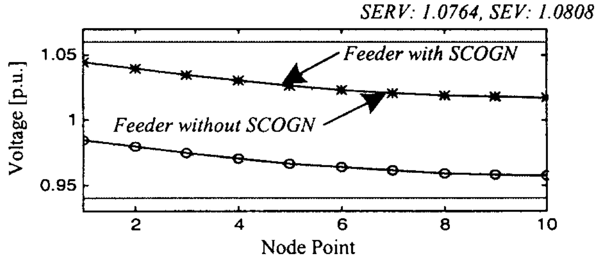
Fig. 3 Customers' voltage profiles



(a) SCOGNs: 5 [MVA], p.f.=1



(b) SCOGNs: 5 [MVA], lagging p.f.=0.9



(c) SCOGNs: 5 [MVA], leading p.f.=0.9

Fig. 4 Customers' voltage profiles with SCOGNs

(1) It is verified that the SERV of the system with SCOGNs gets lower than that of the system without SCOGNs. The reason is that the bank current decreases due to the reverse power of SCOGNs.

(2) It can be seen that the customers' voltage profiles of feeder with SCOGNs are different from those without SCOGNs.

(3) The hysterical behaviors of SEV are obviously shown in the Fig. 3 and 4. Therefore, it is proper that the SEV is used to determine the interconnection capacity of SCOGNs.

(4) The interconnection capacity of SCOGNs to the power distribution systems should be evaluated by system peak-load from the viewpoint of voltage regulation.

3. Evaluation of Interconnection Capacity of SCOGNs

From the above simulation results, the interconnection capacity of SCOGNs should be evaluated by variations of SEV from the viewpoint of voltage regulation since the terminal voltages of customers are mainly dominated by SEV. However, it is very complicate to determine the interconnection capacity of SCOGNs by the variations of SEV due to the hysterical behaviors of SEV.

3.1 Free Margin of Voltage Regulation (V_{fr})

The criterion index for distribution voltage regulation is required to evaluate the interconnection capacity of SCOGNs. In this paper, in a steady state, free margin of voltage regulation in power distribution systems is defined as follows

$$V_{fr}(t)=(V_{max}-V_{min})-(V_{cmax}(t)-V_{cmin}(t))-2db \qquad (3)$$

where

$$V_{cmax}(t)=Max(F(V_{ser}(t)))$$

$$V_{cmin}(t)=Min(F(V_{ser}(t)))$$

In eq. (3), V_{fr} can exclude the effects of hysterical behaviors of SEV contributing to the complexity of evaluating the interconnection capacity of SCOGNs from the viewpoint of voltage regulation.

3.2 Variations of SERV with SCOGNs ($\Delta V_{ser,co}$)

The SERV of system is varied with the reverse power of SCOGNs. Therefore, the $\Delta V_{ser,co}$ should be analyzed to evaluate the interconnection capacity of SCOGNs.

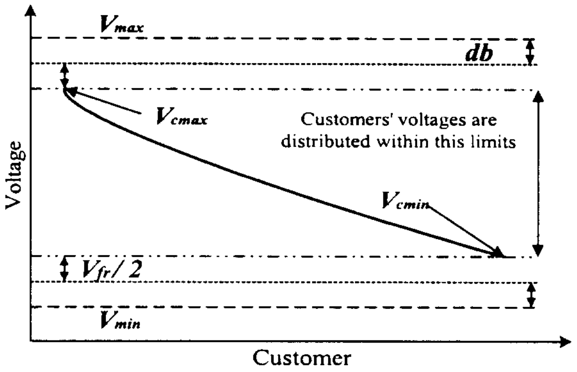


Fig. 5 Illustration of free margin of voltage regulation

Table 1. V_{fr} vs. the length of feeder at the peak-load for different dead-band of sample distribution system model.

Length of feeder [km]	V_{fr} [p.u.]	
	db = 0.0125 [p.u.]	db = 0.02 [p.u.]
1	0.0323	0.0173
2	0.0296	0.0146
3	0.0269	0.0119
4	0.0242	0.0092
5	0.0215	0.0065
6	0.0187	0.0037
7	0.0159	0.0009
8	0.0131	-0.0019
9	0.0102	-0.0048
10	0.0074	-0.0076
11	0.0045	-0.0105
12	0.0016	-0.0134
13	-0.0013	-0.0163

However, it is very difficult to evaluate the interconnection capacity of SCOGNs considering its interconnection site. In this paper, as shown in Fig. 6, the interconnected SCOGNs are integrated to the 22.9 [kV] bus.

The SERV of system is given by eq. (1). In eq(1), V_{ce} and Z_{eq} are constants with reverse power of SCOGNs, but $I(t)$ is variables with reverse power of SCOGNs. From the eq. (1), the SERV of system with reverse power of SCOGNs ($V_{ser,co}$) is given by

$$V_{ser,co}(t) = V_{ce} + Z_{eq} \cdot \Delta I(t) \tag{4}$$

The variation of SERV of power distribution systems with reverse power of SCOGNs ($\Delta V_{ser,co}$) is given by

$$\Delta V_{ser,co}(t) = V_{ser}(t) - V_{ser,co}(t) \tag{5}$$

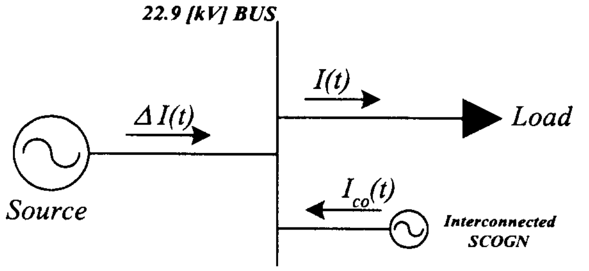


Fig. 6 Equivalent distribution system model with SCOGNs

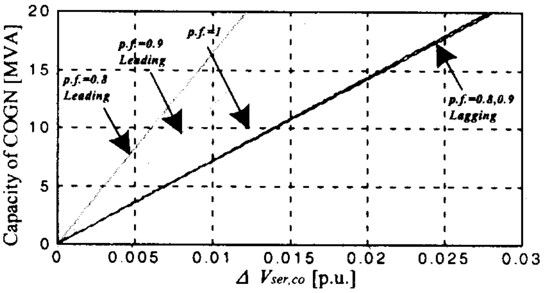


Fig. 7 Changes in $\Delta V_{ser,co}$ vs. power factor of SCOGNs

$$= Z_{eq} \cdot \{I(t) - \Delta I(t)\}$$
$$= Z_{eq} \cdot I_{co}(t)$$

$\Delta V_{ser,co}(t)$ is determined by Z_{eq} and $I_{co}(t)$. For simplicity, the loss variation and the mismatch power of distribution system as the interconnected site and capacity of SCOGNs are ignored. Thus, $I_{co}(t)$ is approximately equal to the reverse current of interconnected SCOGNs, we have

$$I_{co}(t) = (P_{co}(t) + jQ_{co}(t)) / V_{co}^{*}(t) = S_{co}(t) / V_{co}^{*}(t) \tag{6}$$

For simplicity, $V^{*}_{co}(t) \fallingdotseq 1$ [p.u.], $V^{*}_{co}(t)$ can be abbreviated. Then, $\Delta V_{ser,co}(t)$ can be rewritten as follows

$$\Delta V_{ser,co}(t) \cong (R_{eq} \cdot \cos\theta_{co} + X_{eq} \cdot \sin\theta_{co}) \cdot |S_{co}(t)| \tag{7}$$

The $\Delta V_{ser,co}$ is analyzed for sample distribution system model with SCOGNs. From the results, it can be seen that the $\Delta V_{ser,co}$ of system with lagging power factor of SCOGNs is larger than that of system with leading power factor of SCOGNs.

3.3 Evaluation of Interconnection Capacity of SCOGNs

V_{fr} and $\Delta V_{ser,co}$ represent the free margin of voltage regulation and the variations of SERV with SCOGNs at the power distribution systems respectively. In view of distribution voltage regulation, the interconnection capacity of SCOGNs to the power distribution systems can be evaluated from these indexes. If $\Delta V_{ser,co}$ does not deviates from the minimum V_{fr} of power distribution systems, S_{co} of $\Delta V_{ser,co}$ in eq. (7) can be allowably interconnected.

Therefore, the maximum allowable interconnection capacity of SCOGNs can be obtained as follows

$$\Delta V_{ser,co}(t) - Min(V_{fr}(t)) = 0 \tag{8}$$

Thus, we have

$$\left|S_{co}^{max}\right| = \frac{Min(V_{fr}(t))}{(R_{eq}\cdot\cos\theta_{co} + X_{eq}\cdot\sin\theta_{co})} \tag{9}$$

The maximum allowable interconnection capacity of SCOGNs vs. the length of feeder for the sample distribution system model is shown in table 2. The generators for SCOGNs are generally synchronous machines and therefore commonly operate by lagging power factors. The two cases of power factors, that is p.f.=1 and lagging p.f.=0.9, are shown in table 2.

4. Case Study

4.1 Real Distribution System Model

Load values on different feeders are not practically balanced since living styles of the customers are not same. The loads fluctuate because people use different amounts of electricity to support their various activities. Similarly, residential, industrial, and commercial power usage will vary during a day. There are also weekly and seasonal variations in electricity consumption.

Table 2 The Maximum Allowable Interconnection Capacity of SCOGNs vs. the Length of Feeder from the Viewpoint of Voltage Regulation (db=0.0125 [p.u.])

Length of feeder [km]	Capacity of SCOGNs [MVA] p.f.=1	Capacity of SCOGNs [MVA] p.f.=0.9 lagging
1	25.8	22.9
2	23.6	21.0
3	21.5	19.1
4	19.4	17.9
5	17.2	15.2
6	14.9	13.2
7	12.7	11.3
8	10.5	9.3
9	8.2	7.2
10	5.9	5.2
11	3.6	3.2
12	1.3	1.2

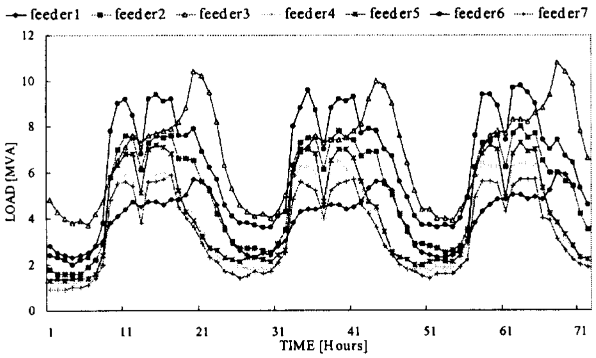


Fig. 8 Assumed daily load diversity

Table 3 The specifications of real distribution system model

Feeder	Underground Line [km] CNCV 325 ㎟	Overhead Line [km] ACSR 160 ㎟
1	1.92	1.58
2	1.49	1.11
3	1.43	2.17
4	1.69	0.41
5	1.40	0.70
6	0.06	1.04
7	1.49	1.41

In Korea, annual peak-load of system occurs in summer season. Hence, it is proper that unbalanced load diversity in summer season is used in order to evaluate the interconnection capacity of SCOGNs to the power distribution systems from the viewpoint of voltage regulation. Fig. 8 illustrates unbalanced load diversity on different feeders, which is taken from the actual load data during three days in a summer season in Korea. It can be seen that not only peak-load of each feeder is different but also load diversity of each feeder has a different type.

The specifications of real distribution system model are shown in table 3. In addition, the load of each feeder is normally distributed in the overhead lines and the other specifications of real distribution system model are identical with the specifications of sample distribution system model.

4.2 Simulation Results

To evaluate the interconnection capacity of SCOGNs, the load diversity is applied to the real distribution system model. The V_{fr} for real distribution system model is shown

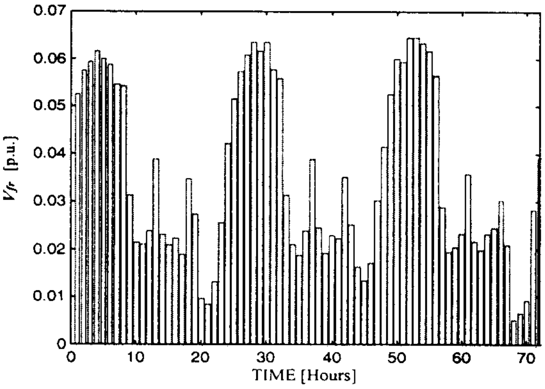


Fig. 9 $V_{fr}(t)$ for real distribution system model (db= 0.0125 [p.u.])

Table 4. Maximum interconnection capacity of SCOGNs for real distribution system model

Capacity of SCOGNs [MVA]	
p.f.=1	p.f.=0.9 lagging
4.4	3.9

in Fig. 9. It can be seen that the load diversity of distribution system has an effect on the V_{fr}. Using eq. (9), the maximum allowable interconnection capacity of SCOGNs for real distribution system model from the viewpoint of voltage regulation is evaluated.

5. Conclusion

This paper discusses the evaluation of interconnection capacity of SCOGNs to the power distribution systems. In view of voltage regulation, the V_{fr} and the $\Delta V_{ser,co}$ are introduced to evaluate the interconnection capacity of SCOGNs to the power distribution systems. The introduced V_{fr} and $\Delta V_{ser,co}$ are expected to be a key index of distribution voltage regulation and voltage variations with reverse power of SCOGNs respectively.

In computer simulation, the maximum allowable interconnection capacity of SCOGNs for the sample and real distribution system model is evaluated. However, the evaluation of interconnection capacity of SCOGNs as their interconnection site is not developed. If advanced voltage regulation method is applied to the power distribution systems, the interconnection capacity of SCOGNs can be increased. Also the various evaluation methodologies for this issue should be developed from the viewpoint of other operational problems such as voltage stability, system reliability, energy saving, etc. In the near future, operational schemes between automated power distribution systems and SCOGNs and DSGs will be studied.

Nomenclature

$V_{se}(t)$	: sending end voltage
$V_{ser}(t)$	: sending end reference voltage
$I(t)$	: bank current
$V_{tap,k}(t)$	: secondary voltage of main transformer when a tap is located in k-th position
$Z_{MTR,k}(t)$	: leakage impedance of main transformer when a tap is located in k-th position.
V_{cmax}	: maximum voltage of customers
V_{cmin}	: minimum voltage of customers
db	: dead-band
$Max(X)$	: maximum value of X
$Min(X)$	: minimum value of X
$F(X)$	: function of load flows
P_{co}	: active power of SCOGNs
Q_{co}	: reactive power of SCOGNs
S_{co}	: apparent power of SCOGNs
V_{co}	: voltage of SCOGNs
I_{co}	: reverse current of SCOGNs
$\cos\theta_{co}$	: power factor of SCOGNs
R_{eq}	: resistance of compensating impedance
X_{eq}	: reactance of compensating impedance
$I(t)$	: bank current
$\Delta I(t)$	: bank current with reverse power of SCOGNs

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