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# Clustered Effective Reactive Reserve to Secure Dynamic Voltage Stability in Power System Operation

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***Abstract*—Reactive power reserves are important for grid stability and have a variety patterns depending on fault location as power systems become larger and complex. This paper presents the clustered effective reactive reserve (CEQR), an indicator that is suitable for identifying the risk of dynamic voltage stabitlity in terms of power system operation. This indicator provides the following features: i) It calculate the local realistic reactive reserve to recognize dynamically changing system conditions; ii)it derive clustered areas to identify valid regions for system control. The proposed method uses the sensitivity between dynamic reactive resources or load buses and a particular bus to obtain the correlation. And since this indicator is calculated using only the system topology, current and maximum outputs of the generators, there is less computational burden. This study verified the features of clustered effective reactive reserve (CEQR) by analyzing the practicable dynamic voltage collapse scenarios in the Korean electric power (KEPCO) system. In addition, as a countermeasure against the dynamic voltage collapse, the control performance of blocking tap changer scheme using the proposed indicator is described.**

***Index Terms*—Power system stability, Reactive power reserve, Power system protection, Clustering, Blocking tap changer, Sensitivity**

## I. Introduction

In recent years, renewable energy sources are increasingly being integrated into power systems to address climate change worldwide. Because the margin of stability of system operation is insufficient because of the increased demand and the constraints on the construction of transmission facilities, additional compensation facilities are installed to maintain voltage stability, such as SVC, Shunt devices, and FACTS. As this trend continues, the probability of unexpected voltage collapse in a stressed system may increase, thus requiring improved system operation efficiency and more accurate and intuitive system condition identification in online or real time periods. Various blackout cases and previous studies indicate that the high correlation of reactive power reserves to voltage instability and that proper management of reactive power reserves in power system operation are very important for stable system operation [1]–[3].

The NERC provides guidelines for reactive power reserves in terms of planning and requires appropriate monitoring and control of reactive power sources from transmission operators to ensure reliable operation [4]. For proper planning of reactive power sources, each ISO (PJM, ERCOT, ISO-NE, MISO, etc.) in North America also determines the stability of the system via the method proposed by the guidelines and attempts to establish a real-time contingency analysis environment to improve operational efficiency [5]. Because of the importance of reactive power reserve as an indicator, various approaches have been studied to monitor and control the reactive power reserve to maintain the stability of the system.

Reference [6] investigated several definitions of generator reactive power reserves related to voltage stability margin and voltage violations. Reference [7] determined the most effective control actions such as management of generators and shunt capacitors and load shedding to boost reactive power reserves while maintaining a minimum amount of voltage stability margin using sensitivity with respect to control actions. [8] proposed an operational reactive power management tool that minimizes the operating cost of the disturbances while ensuring the level of VAR reserves without violating system security using a hybrid solution technique based on PSO and classical methods. Online voltage stability monitoring using reactive power reserve has been discussed an optimization procedure to estimate the VMS using the correlation between the reserves [9]. [10] proposed a management solution that maximizes the reactive power reserve to improve the voltage stability margin through one-and two-stage optimization approaches from generator perspective. [11] discussed the optimal reactive power dispatch to enhance voltage stability margin through optimization approaches. Reference [12], [13] introduced an approach to effectively evaluate reactive power reserve using linear sensitivity between generators and loads. In addition, secondary and tertiary voltage regulation (SVR and TVR), which has been applied to grid operations since Europe, directly coordinates the each area's reactive power output of the generators to control local voltages [14]. This hierarchical voltage regulation system is widely used in Europe and several countries, mainly in Italy and France [15]–[21].

Blackout cases, such as those in 2003 and 1996 in North America and in 2003 and 2006 in Europe were caused by voltage instability due to effects of stress conditions, unex-

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pected failures, and continuous mutual action of the protection system [22]–[25]. Among them, the reciprocal actions of over excitation limiter (OEL) and on-load tap changer (OLTC) accelerated the lack of reactive power, significantly affecting dynamic voltage instability. The defense plan for dynamic voltage stability typically includes load shedding, switching shunt, tap changing, and blocking OLTC [26]–[28]. The KEPCO system has only managed stability in the transient time period in which the rotor angle stability. However, with changes in the system, the possibility of long-term voltage instability is recognized, and the KEPCO system operator (KPX; Korea power exchange) conducted a study to derived practical scenarios [29], [30]. After these projects were completed, operator needed monitoring and decision-making method for preventing voltage instability at the EMS network analysis.

In this study, the clustered effective reactive reserve (CEQR) is proposed that improves the concept of effective reactive power reserve (EQR) which was developed by Korea University [12]. This proposed method calculated regional effective reactive power reserves from bus perspective to improve indicator accuracy in large systems. And assuming functions in an online environment such as the Energy Management System (EMS) network analysis system, a nonlinear analysis (time-domain analysis) was performed to complement the limit of linear analysis approaches in terms of long-term voltage stability. It also determines the area with similar voltage patterns and utilizes the CEQR value as an operation criterion of the control action such as blocking tap changer to secure dynamic voltage stability.

The remainder of this paper is organized as follows. The concept of CEQR and the characteristics are introduced in Section II. The practical scenario derived from the KEPCO system to be used in subsequent sections is described in Section III. The results of the CEQR calculated in the practical scenarios are analyzed in Section IV. Section V discusses the utilization strategy and results of CEQR to secure dynamic voltage stability. Finally, Section VI concludes the main observation of the proposed method and mentions future directions.

## II. Clustered Effective Reactive Reserve (CEQR)

### A. Concept of Effective Reactive Power Reserve (EQR)

Generally, dynamic reactive reserves are analyzed based on the reactive power reserve of the generator. [6] provided the generator reactive power reserve of four types. The four types depend on constant maximum reactive power, capability curve, minimum voltage limit, and voltage collapse limit. The conventional reactive reserve (CQR) can be defined as the sum of the reactive power reserves of each generator as (2).

$$Q_{i,CGR} = Q_{i,max,rated} - Q_{i,cur} \tag{1}$$

$$CQR_j = \sum_{i=0}^{n} Q_{i,CGR} = \sum_{i=0}^{n} Q_{i,max,rated} - Q_{i,cur} \tag{2}$$

where:

$Q_{i,CGR}$ is the conventional reactive reserve of the generator $i$;

$Q_{i,max,rated}$ is the rated maximum reactive power of the generator $i$;

$Q_{i,cur}$ is the current reactive output of the generator $i$;

The EQR reflects that the effects on the system are not equal because the reactive power output of each generator cannot be completely delivered by the path impedances. As shown in Fig. 1, the real reactive power reserve is less than the CQR because each generator has a different reactive power capacity that can actually transmit on a particular bus.

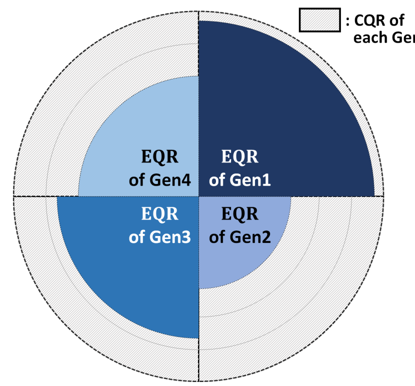


Fig. 1: Concept of the EQR compared to CQR

The EQR is calculated by the weight factor ($\omega_{ij}$) of the sensitivity between the reactive resources and the particular buses and is expressed as (3). This linear method of using sensitivity does not require a PV curve, requiring only a small burden.

$$\begin{aligned} EQR_j &= \sum_{i=0}^{n} \omega_{ij} \cdot (Q_{i,CMR}) \\ &= \sum_{i=0}^{n} \omega_{ij} \cdot (Q_{i,max,rated} - Q_{i,cur}) \end{aligned} \tag{3}$$

The weight factor is mathematically calculated from the B matrix derived from the jacobian matrix.

### B. Definition of Clustered Effective Reactive Reserve (CEQR)

The CEQR is an extension of the concept that the effective reactive reserve (EQR), used for system planning by offline studies, is available for the operation of the online mode. On larger power systems, it is difficult to evaluate reserves with a single system EQR. Therefore, the CEQR need to be monitored in multiple buses to reflect the regional characteristics of reactive power. The CEQR is a method to monitor the regional reactive power reserve in a large system and to use them as a criterion for blocking tap changer for preventing long-term voltage instability.

For example, suppose four areas and pilot buses are selected in a transmission system with relevant generators, as shown in Fig. 3. The clustered areas and resources can share the same generator or bus based on sensitivity, such as area of pilot bus 1 and 2. The shared resources are affected by reactive power changes of related buses that more than a certain sensitivity. And the CEQR is based on a time-variant indicator that is

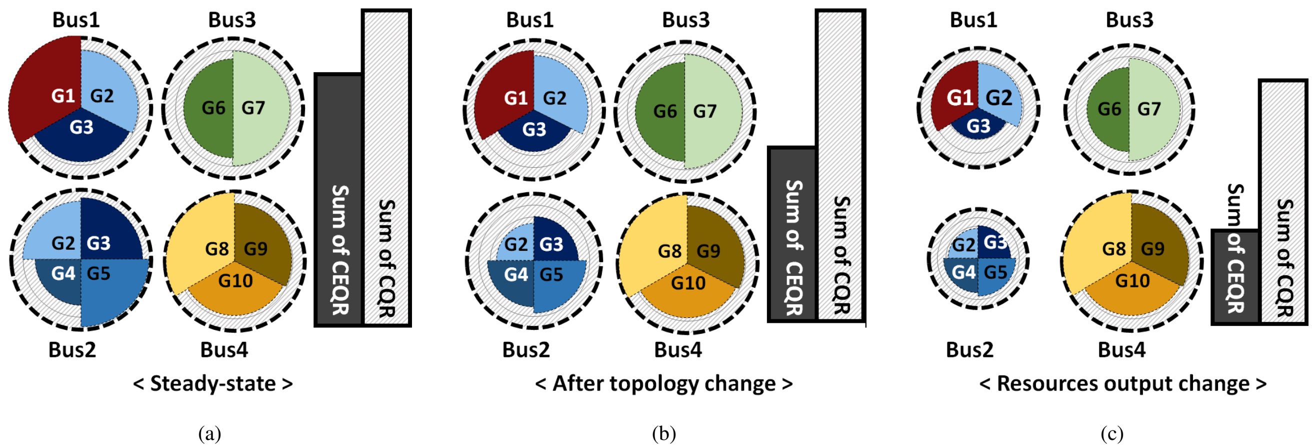


Fig. 2: Illustration of the CEQR changes according to system state: (a) Steady-state; (b) after topology change; and (c) resource output change

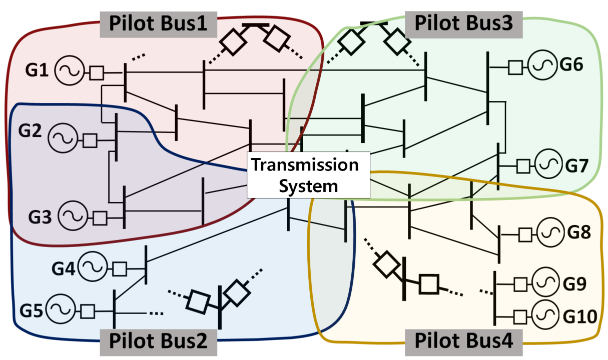


Fig. 3: System topology example for explaning CEQR

calculated to reflect the changing system conditions. In Fig. 2a, the CEQR calculated for each pilot bus differs from the CQR depending on the topological characteristics. If system topology changes because of contingency or generator trip, the CEQR value of each area is changed, as shown in Fig. 2b. The CQR value does not change unless the generator trips. If the reactive power output of a resource changes because of the operation of dynamic devices such as OEL, OLTC, or FACTS in the system, the change of the CEQR is differ regionally. On large systems, the difference between CQR and CEQR values by region is significantly different than that described above, because the resources involved in the CEQR calculation of each clustered area are filtered by sensitivity.

To use the CEQR as an appropriate indicator for operation, proper selection of pilot buses is required. A conservatively suitable bus as a pilot bus is that the voltage changes due to reactive power changes is small. Since this suitable bus has a smaller voltage variation than a nearby buses, conservatively recognizes the effect of voltage problem. In addition to the theoretical approaches, the system operator can select these pilot buses considering the size and characteristics of the system such as important operational nodes.

The configuration of the pilot bus and voltage control area is used for voltage control purposes, such as the SVR system mentioned above. In [18], [31], the voltage control area is divided by the electrical distance, and the buses with similar reactive power margin at the nose point of the V-Q curve is determined as the area [32]. Alternatively, the area is determined by the participation factor through the eigenvalue analysis of Jacobian [33]. In the proposed method, the purpose of pilot buses and clustered area is to monitor the regional reactive power reserve in a large system, and to use them as a decision-making method for control action such as blocking tap changer.

Assuming that the appropriate pilot buses have been selected, the CEQR is applied in two stages. The first step is to determine the relevant clustered areas. The formula for determining the clustered area is as follows. From a Jacobian matrix of power flow equation

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial v}\\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial v}\end{bmatrix} \begin{bmatrix}\Delta \delta\\ \Delta v\end{bmatrix} \tag{4}$$

Stott's simplification is applied to the above equation to quickly calculate the sensitivity of the reactive power variation between bus and bus or bus and resource. The power system equations are linearized and expressed as follows:

$$\left[\Delta Q\right] = -\left[B\right]\left[\Delta v\right] \tag{5}$$

$\Delta Q$ is a vector of reactive power variation, and $\Delta v$ denotes a vector of bus voltage variation. The matrix $B$ is a N by N matrix of the susceptances of the system. The equation expressed by rearranging the B matrix to distinguish the power generation bus and the load bus is as follows:

$$\begin{bmatrix}\Delta Q_G\\ \Delta Q_L\end{bmatrix} = \begin{bmatrix}B_{GG} & B_{GL}\\ B_{LG} & B_{LL}\end{bmatrix} \begin{bmatrix}\Delta v_G\\ \Delta v_L\end{bmatrix} \tag{6}$$

$B_{GG}, B_{GL}, B_{LG}, B_{LL}$ are the submatrices of $B$ composed of $G\times G$, $G\times L$, $L\times G$, and $L\times L$, respectively. The formula to express $\Delta v_L$ from (6) to obtain the sensitivity of reactive power as the voltage between the load buses is as follows.

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$$\begin{aligned}\left[\Delta v_L\right] = &-\left[B_{LL}\right]^{-1}\cdot\left[\Delta Q_L\right]\\ &-\{\left[B_{LL}\right]^{-1}\left[B_{LG}\right]\}\cdot\left[\Delta v_G\right]\end{aligned} \tag{7}$$

Assuming a steady state fluctuation in the generator voltage close to zero($\Delta v_G \simeq 0$), (7) can be simplified.

$$\left[\Delta v_L\right] = -\left[B_{LL}\right]^{-1}\cdot\left[\Delta Q_L\right] \tag{8}$$

(8) represents the relation between the buses and can be used for clustering because it is valid even if $\Delta v_G$ is not zero. From (8), sensitivity normalization is performed to determine the clustered areas of buses with sensitivity above a certain level near the pilot bus. In $-\left[B_{LL}\right]^{-1}$ matrix defined as L by L, the weight factor is calculated by normalizing the submatrix of the pilot bus ($j_{th}$ column) to the maximum of the components except for self-sensitivity in the submatrix. $\omega_{ij}^{LL}$ is expressed as follows:

$$\omega_{ij}^{LL} = \left[\frac{m_i}{Max(M_j)}\right] \quad (i = 1\ldots n, i \neq j) \tag{9}$$

where:

$\omega_{ij}^{LL}$ is the weighting factor of the $i_{th}$ load bus with respect to the $j_{th}$ pilot bus;
$m_i$ is the sensitivity value of the $i_{th}$ load bus with respect to the $j_{th}$ pilot bus;
$M_j$ is the submatrix of the $j_{th}$ column in the sensitivity matrix;
$Max(M_j)$ is the maximum value of the $M_j$ matrix;

The second step is to calculate the CEQR. From (6), (7), and the assumptions for simplifying (7) to (8), the sensitivity between the reactive power generation of each resources and reactive power of load buses is derived as followed:

$$\left[\Delta Q_G\right] = \left[B_{GL}\right]\left[B_{LL}\right]^{-1}\cdot\left[\Delta Q_L\right] \tag{10}$$

Similar to (9), the weighting factors between the resources and pilot buses for calculating CEQR can be obtained as follows:

$$\omega_{ij}^{GL} = \left[\frac{g_i}{Max(G_j)}\right] \quad (i = 1\ldots n, i \neq j) \tag{11}$$

where:

$\omega_{ij}^{GL}$ is the weighting factor of the $i_{th}$ resource with respect to the $j_{th}$ pilot bus;
$g_i$ is the sensitivity value of the $i_{th}$ resource with respect to the $j_{th}$ pilot bus;
$G_j$ is the submatrix of the $j_{th}$ column in the sensitivity matrix;
$Max(G_j)$ is the maximum value of the $G_j$ matrix;

The formula for calculating CEQR considering the weighting factor adjustment is described as follows:

$$CEQR_j = \sum_{i=1}^{n}\omega_{ij}^{GL}\cdot(Q_{i,max,rated} - Q_{i,cur} \tag{12}$$

$$\begin{cases}\omega_{ij}^{GL} = \omega_{ij}^{GL}, & if \quad \omega_{ij}^{GL} > \omega^{beset}\\ \omega_{ij}^{GL} = 0, & if \quad \omega_{ij}^{GL} < \omega^{beset}\end{cases}$$

$\omega^{beset}$ is the sensitivity level set by the operator.

$\omega_{ij}^{LL}$ and $\omega_{ij}^{GL}$ are parameters that determine the monitoring range by selecting resources and buses that have high correlation with the pilot bus.

### C. Features of Clustered Effective Reactive Reserve(CEQR)

From the viewpoint of power system operation, the CEQR has the following characteristics:

1) Sensitivity changes according to system contingencies. This means that changes in the system topology are reflected in the dynamic reactive reserve calculation between pre- and post-contingency. This makes it possible to use it as an indicator to represent various systems of changing.

2) Reflect the regional characteristics of reactive power. Because the CEQR uses sensitivity to calculates the reactive power reserve for each clustered area, can be obtained a more realistic regional value. The variation in the CEQR in the buses nearby the contingency will be greater and more rapid than the far buses. And the clustered areas are also used as a proper operating range of the control action such as blocking tap changer scheme.

3) Only matrix B and the maximum rated reactive power and current reactive power output information of each resource are needed. This means that converged system data are not required for the CEQR calculation, and the computational burden is small.

The above characteristics are useful for operators monitoring reactive power reserve in online. The cycle and accuracy of the updated values depends on the operator's system configuration and the instrument specifications. For example, operators in the KEPCO system basically use SCADA/EMS for system operation and install more than 40 PMUs to improve the operational efficiency. The topology information of the power system by the state estimation of SACDA/EMS is generated every 2 min, and the generator data can be collected every 2 s. In this case, the CEQR reflects the change in dynamic reactive power reserve of post-contingency before the sensitivity change through data obtained every 2 s, and more accurate indices are obtained after the topology information is updated in 2 min.

## III. Practicable Voltage instability Scenarios in KEPCO system

### A. Response based Simulation and Modeling

Because long-term voltage collapse is caused by the mutual automatic operation of various dynamic devices in the system, this phenomenon cannot be observed by a simulation environment by inputting each expected device's operation one by one. Therefore, long-term voltage instability scenarios were derived by a response-based simulation that reflected the unique characteristics of each power system. The response-based simulation can observe the mutual influence of modeled devices through automatic operation. This simulation environment includes models such as generator governor, exciter and power system stabilizer (PSS), and FACTS devices as well as voltage-stability-related models provided in Table I. These models used the general model of PSS/E.

TABLE I: Detail model reflected in response-based simulation

| Types | Model Name | Remarks |
|---|---|---|
| OEL | MAXEX2 | Installed all generators |
| OLTC | OLTC1T | Installed all distribution transformers (154-22.9kV) |
| Induction motor load | CIM5BL | Ratio adjustment |
| Quadrilateral distance relay | RXR1 | Installed transmission lines (154,345kV) |
| Power swing block | SLNOS1 | With quadrilateral distance relay |

TABLE II: Numerical data of KEPCO system using simulation

| System characteristics | Number |
|---|---|
| Number of buses | 3546 |
| Number of transmission lines | 5670 |
| Number of transformers | 2100 |
| Number of Generators (In services / Out services) | 231 / 356 |
| Total load (peak) / Total power generation | 80275 / 81558 (MW) |

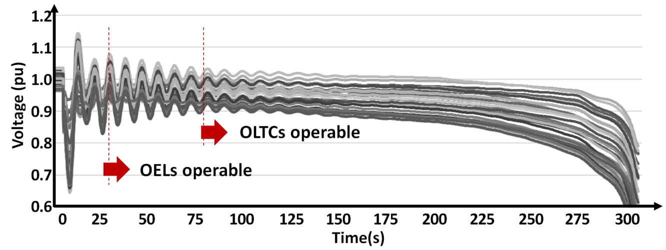



Fig. 4: [Case1] Voltages at 154 kV buses in Chungchung

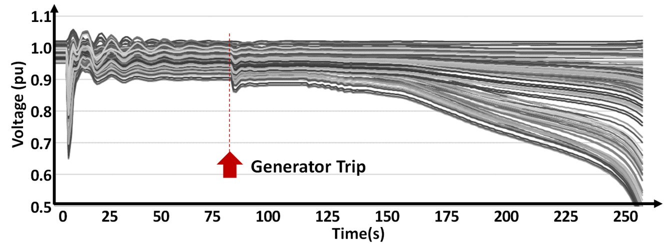



Fig. 5: [Case2] Voltages at 154 kV buses in Yeongnam

### B. Description of Study Cases

As shown in Fig. 6, the loads of the KEPCO system are concentrated in the metropolitan area, whereas large-scale generators are mostly located in the other areas. Therefore, the lacking power in the metropolitan area is supplied from nonmetropolitan areas via six long distance interconnected transmission lines. These study cases were derived from projects to find practical long-term voltage instability scenarios that can occur in the KEPCO system [29], [30]. To increase the accuracy of simulation, we applied realistic parameters of voltage-stability-related from the plant utilities and the KEPCO system operator. We comprehensively included the parameters in appendix. The transmission system is composed of a 765 kV, 345 kV, 154 kV, and 22.9 kV voltage level hierarchy. And the numerical information of the data shows in Table II.

*1) Case 1:* 765 kV one route outage

The contingency considered in case 1 is the route outage of the Shinanseong-Shinseosan 765 kV transmission line, one of six interconnected lines. This transmission line is the most severe contingency in terms of voltage stability in the KEPCO system. Generator trip SPS is installed to secure rotor angle stability, but long-term voltage instability is observed in the response-based simulations. Fig. 4 shows the dynamic voltage collapse after contingency by the voltage trajectory of the 154 kV buses in Chungchung.

*2) Case 2:* 345 kV one route outage and one generator trip

The contingency considered in case 2 is the route outage of the Bukbusan-Shinkimhae 345 kV transmission line, which includes an additional trip of one generator. This contingency assumes an unexpected failure of one generator because the reactive power output of an adjacent large-scale power plant is nearing its limit after transmission outage. In Fig. 5, the voltage drops rapidly after the generator is tripped, resulting in voltage collapse.

## IV. Observation of CEQR during Voltage Collapse

The pilot buses were selected from among the buses monitored by the KEPCO system operator. The values of $\omega_{ij}^{LL}$ and $\omega_{ij}^{GL}$ for clustering are greater than 0.15. The value of the CEQR was calculated at 25-s intervals during propagation of the scenarios.

*1) Case 1:* 765kV one route outage

The CEQR changes during voltage instability are shown in Fig. 7b The contingency in Case 1 is trip of the transmission line that supplies power from Area 2 to Area 1 and the generator in Area 2. Therefore, the reactive power reserve of Area 1, the sink area, and Area 2 with reduced dynamic

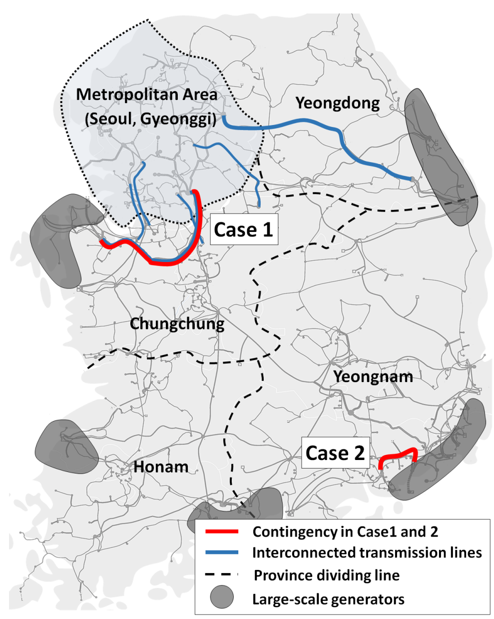
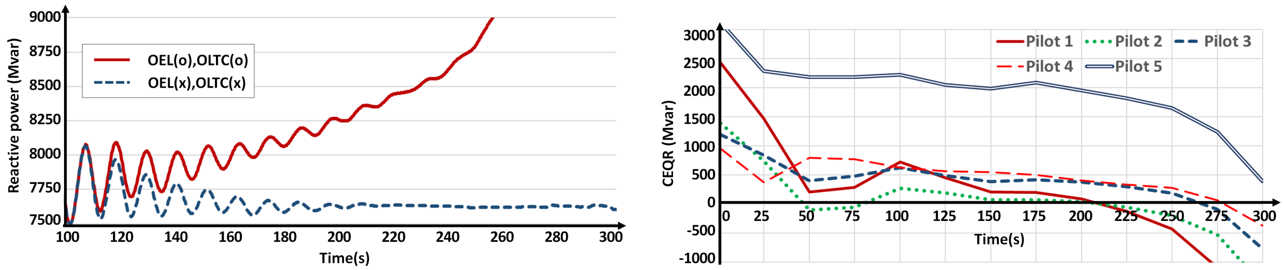
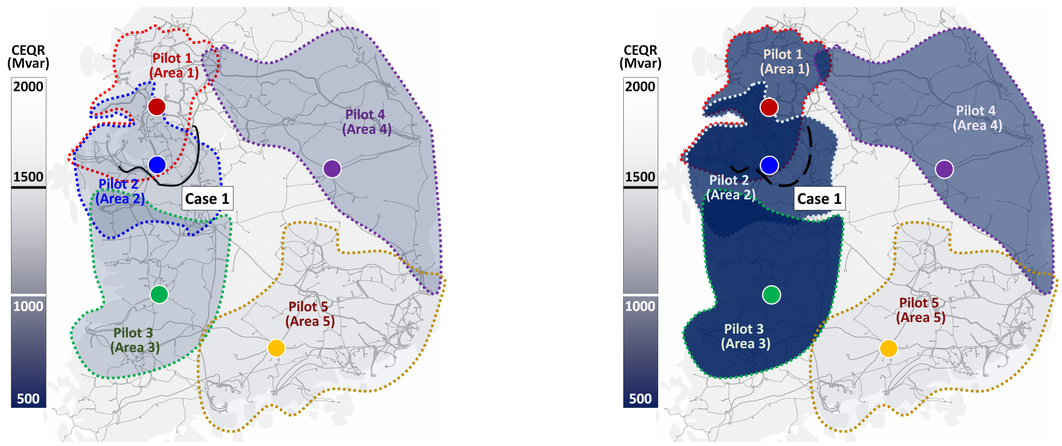



Fig. 6: Location of contingency cases in KEPCO system




(a) (b)

Fig. 7: [Case1] (a) Sum of reactive outputs in Area 1 and 2. (b) CEQR trajectory in pilot buses




(a) (b)

Fig. 8: [Case1] (a) Regional CEQR contour chart at 1 s. (b) Regional CEQR contour chart at 100 s.

reactive resources are rapidly changed in Fig. 8a and 8b. Because this fault is the most serious fault in the system, Area 1 and 2, which were directly related, were considerably affected. In addition, the CEQR value of Area 3 and 4 also changed significantly after the contingency because this area also supplied the current to Area 1. The summation of reactive power outputs in Area 1 and 2, which increase after 100 s when OLTC is operated, is expressed in Fig. 7a. Fig. 7b shows that the CEQR value close to zero after approximately 275 s when the dynamic voltage collapse starts even though the CEQR value is maintained at about 500 to 1000 MVar after failure. The CEQR value is negative because the reactive power output of the resources exceeds the maximum, and if OEL is operated, the CEQR could rise.

*2) Case 2:* 345 kV one route outage and one generator trip

Case 2, which is an outage of a power transmission line and generator in the Area 5 system, has relatively lower severity than case 1. In Fig. 5, the impact of contingency is regional and does not include all buses in Area 5, compared to case 1, in which the impact was nationwide. CEQRs represent these local characteristics, as confirmed in Fig. 9b. Initial condition is similar to case 1, but in case 2, only the CEQR value of Area 5 changes rapidly after contingency as shown in Fig. 10a, 10b. The results of this case 2 show that the CEQR reflects regional reactive power changes well. Fig. 9b shows that the CEQR value of Area 5 is close to zero from around 200 s when the system starts to become unstable.

## V. Utilization Strategy of the CEQR for Securing Dynamic Voltage Stability

### *A. CEQR as an indicator for Blocking Tap Changer Scheme*

As mentioned earlier, the KEPCO system has no countermeasures against risk of long-term voltage instability. In such circumstances, the blocking tap changer scheme has the advantage in terms of implementation for delaying or preventing voltage instability. Methodologies for determining the proper operating time of blocking tap changer have been studied and proposed [34]–[36]. To effectively prevent voltage instability with blocking schemes, the initial response capability and proper operation in various system conditions are required.

As shown in the above results, the CEQR indicates the dynamic voltage stability condition regionally. There are several thresholds that can be considered as a criterion of the blocking tap changer schema through the CEQR. Among them, this study used the rate of change of the CEQR value to the criterion. Thus, two consecutive violations of 30%, 50%, and 70% are applied as a threshold for CEQR rate of change, and results are observed.

Table III shows the calculation of the CEQR change rate to apply the blocking tap changer scheme. If the threshold is 30%, the taps of Areas 1, 2, and 3 blocked in 50 s, and 75 s when the threshold is 50%. If the threshold is 70%, only Areas 1 and 2 are blocked in 75 s. Similarly in Case 2, if the

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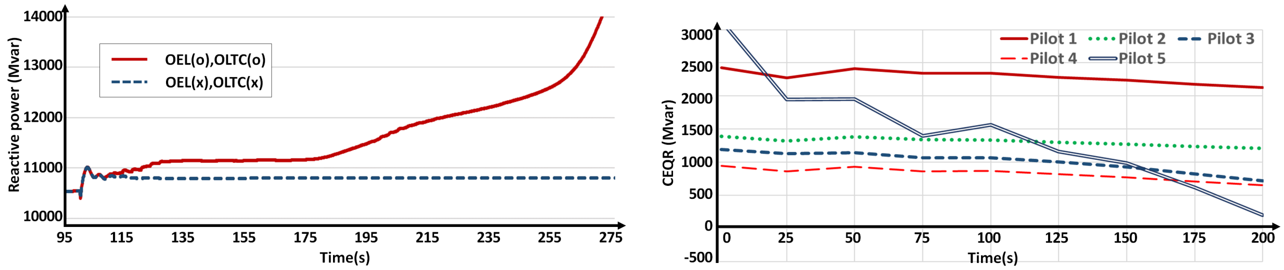
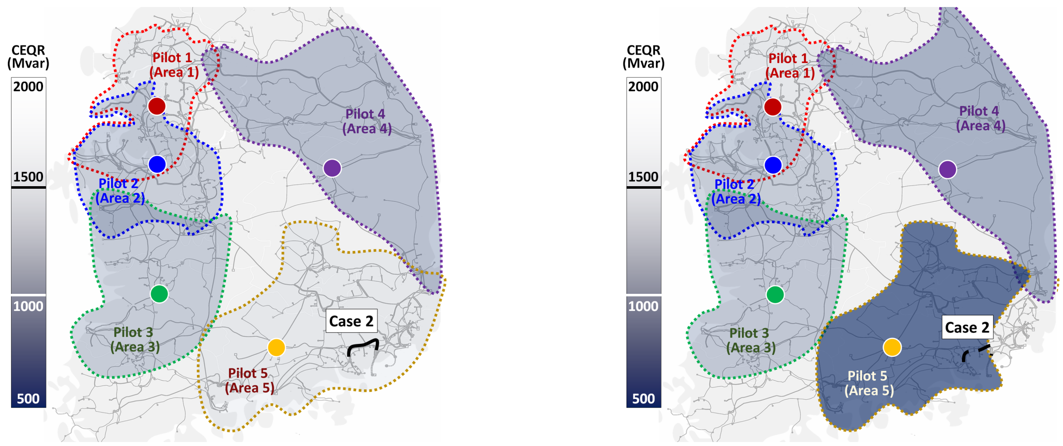



(a) (b)

Fig. 9: [Case2] (a) Sum of reactive outputs in Area 5. (b) CEQR trajectory in pilot buses




(a) (b)

Fig. 10: [Case2] (a) Regional CEQR contour chart at 1 s. (b) Regional CEQR contour chart at 125 s.

threshold is 30%, the Area 5 blocked in 50 s, and in 100 s at 50%. If the threshold is 70%, Area 5 is blocked in 200 s.

### B. Performance of Blocking Tap changer by CEQR

*1) Case 1:* 765 kV one route outage

Fig. 11 shows the voltage trajectory of pilot bus 2 for each criterion. If the criterion of the blocking tap changer is the CEQR rate of change over two steps at 30% or 50%, dynamic voltage stability is ensured. In both cases, tap changers in Areas 1, 2, and 3 are blocked before the first operation to prevent reactive power imbalances early enough to ensure stability. If the criterion threshold was 70%, voltage collapse occurred at about 1600 s. However, the tap changer of Area 3 is not blocked, although the blocking time of the scheme is the same as that of the above cases. A criterion of 70% is considered insufficient to eliminate the factors that accelerate the propagation of voltage collapse.

TABLE III: Rate of change of CEQR on pilot buses at Case1

| Time(sec) | Pilot 1 | Pilot 2 | Pilot 3 | Pilot 4 | Pilot 5 |
|---|---|---|---|---|---|
| 1 | Normal condition | | | | |
| 25 | 40% | 47% | 30% | 61% | 27% |
| 50 | 91% | 108% | 67% | 16% | 30% |
| 75 | 88% | 104% | 60% | 19% | 30% |
| 100 | 70% | 81% | 48% | 34% | 29% |
| 125 | 81% | 86% | 59% | 41% | 34% |
| ... | - | - | - | - | - |

*2) Case 2:* 345 kV one route outage and one generator trip

The voltage trajectory of pilot bus 5 for each criterion as in Fig. 12 represents the occurrence of dynamic voltage instability at 70%. Dynamic voltage stability is secured when the blocking tap changer is the CEQR rate of change over two steps at 30% or 50%. The operation of too late blocking tap changer is not effective because it does not reset the timer for operation of protective devices such as OEL.

These simulations confirmed the characteristics of the CEQR applied to ensure dynamic voltage stability that local grid conditions are individually monitored and the operating time of the countermeasures is also adjusted.

## VI. Conclusion

This study proposed the concept of CEQR from the perspective of power system operations. The CEQR is a regional and time-varying indicator, which can determine the clustered area that is highly related to each pilot bus and can calculate the realistic reactive power reserve supplied by the generator with reactive power sensitivity ratio. This concept has the advantage of intuitively recognizing the local dynamic reactive power condition for monitoring and controlling than deal with the reserve of each generator separately. Applying it to the online envirionment is easy with simple calculations. The characteristics of the CEQR as an operation indicator

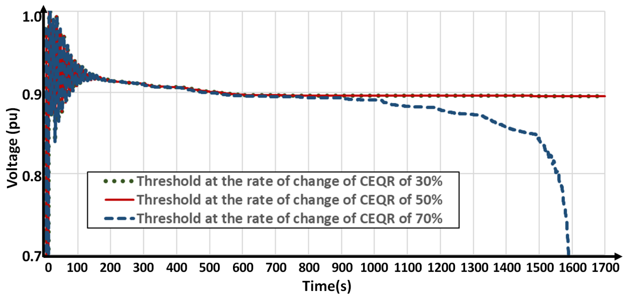



Fig. 11: [Case1] Voltage at bus 2 through tap-blocking level

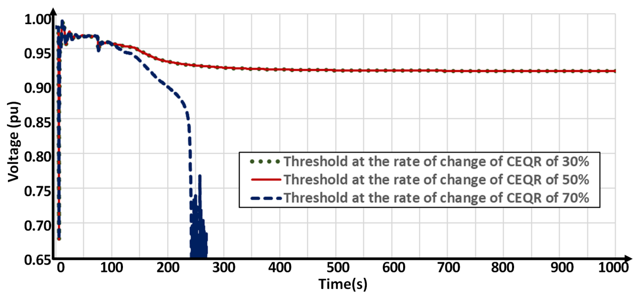



Fig. 12: [Case2] Voltage at bus 5 through tap-blocking level

are demonstrated through simulation results in the practicable dynamic voltage collapse scenarios in the KEPCO system. From the two cases, we confirmed that the CEQR is calculated and clustered differently in each regional pilot bus depending on the system states and contingency location. This study also verified the utilization of the CEQR as an control measure in the operational aspect for the blocking tap changer scheme to prevent dynamic voltage collapse.

Further research will focus on how to improve the computational accuracy and utilization in power systems with high renewable energy penetration. Furthermore, a study on the impact of renewable resources on dynamic reactive power reserve by region will also be performed.

## Appendix A
## Simulation System Parameters

The Over Excitation Limiter (OEL) of the KEPCO system had an inverse time characteristic and used the MAXEX2 model that reflects this characteristic in PSS/E. The Over Excitation Tripping (OET) function, which is mounted by several generators, was not reflected due to difficulties in implementation. The rated field currents of each generator were used the values obtained at the maximum rated power outputs of the generator through simulation. The parameters of OEL are provided Table IV.

TABLE IV: Parameters of OEL

| | Tae-an thermal power generation | Dang-jin thermal power generation |
|---|---|---|
| Rated field current | 4,631 A | 3,492 A |
| OEL pick up value (1) | 1.12 pu | 1.05 pu |
| OEL operating time (1) | 108 sec | 120 sec |
| OEL pick up value (2) | 1.22 pu | 1.15 pu |
| OEL operating time (2) | 52 sec | 44 sec |
| OEL pick up value (3) | 1.32 pu | 1.25 pu |
| OEL operating time (3) | 33 sec | 26 sec |

The On-Load Tap Changer (OLTC) is a device at the 154kV-22.9kV transformer that automatically responds according to the setting values. The OLTC1T of PSS/E is used and the parameters are as follows.

TABLE V: Parameters of OLTC

| Time delay of first tap operation | Time delay of subsequent tap operation | Bandwidth | Number of taps |
|---|---|---|---|
| 100 sec | 3 sec | 0.75pu – 1.0pu (1.25% of each taps) | 21 tap |

The Zone-3 quadrilateral distance relay is used in the KEPCO system and modeled using RXR1. The setting rules of each transmission lines and the characteristic angles are as follows.

TABLE VI: Setting rule of quadrilateral distance relay

| Zone number | Setting Rule (at 345 kV, 154 kV transmission lines) |
|---|---|
| Zone1 | • 85% of self-section line impedance<br>• Delay time : instantly |
| Zone2 | • Maximum of<br>1. 125% of self-section line impedance<br>2. self-section line impedance + {shortest line impedance of the next section 50% × (apparent coefficient / 2)}<br>• Delay time : 20 Cycle(154kV), 24 Cycle(345kV) |
| Zone3 | • Maximum of<br>1. 225% of self-section line impedance<br>2. self-section line impedance + (shortest line impedance of the next section 120% × apparent coefficient)<br>• Delay time : 100 Cycle |

TABLE VII: Characteristic angles of distance relay

| | $\delta_a$ | $\delta_b$ | $\delta_c$ | $\delta_d$ |
|---|---|---|---|---|
| Line impedance characteristic | 30° | 15° | 0° | |

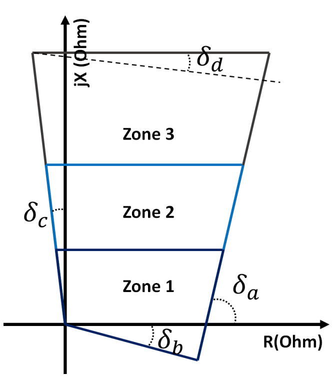



Fig. 13: Characteristic of quadrilaterial distance relay

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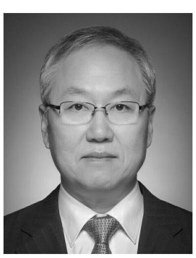

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