Improving the Cross-Border Activation of the Regulating Reserve to Enhance the Provision of Load-Frequency Control

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ABSTRACT This paper presents the Cross-Border activation of the Regulating Reserve (CBRR) between participating Control Areas (CAs), which is being developed to reduce the costs of balancing energy. The main objective of the CBRR is to activate the regulating reserve in participating CAs, to release the regulating reserve and to reduce the balancing energy as part of the safe operation of the power system. However, the classic CBRR includes a frequency term and, therefore, inherently affects the frequency response of the participating CAs, which is not discussed in the literature. In this paper, the impact of the classic CBRR on frequency quality and the provision of Load-Frequency Control (LFC) is thoroughly evaluated with dynamic simulations of a three-CA test system and an eigenvalue analysis of a two-CA system. It is clearly demonstrated that the classic CBRR reduces the damping of the entire power system. Therefore, a modified implementation of the classic CBRR is presented, and a modified CBRR is proposed, which has no impact on the system’s eigendynamics. Furthermore, the results of the dynamic simulations confirm that the frequency quality can be improved by the classic CBRR, although there are also cases where it can deteriorate. However, the modified CBRR improves the frequency quality in all cases. The modified CBRR also improves the indicators for the provision of LFC compared to the classic CBRR. Moreover, the modified CBRR reduces the unintended exchange of energy and the demand power, thus increasing the financial effects of the CBRR’s activation.

INDEX TERMS Balancing energy, cross-border activation, eigenvalue analysis, Load-Frequency Control, regulating reserve.

NOMENCLATURE

\( N \)
Number of participating CAs.

\( \Delta P_{ei} \)
Actual (electrical) control power of the \( i \)-th CA.

\( \Delta P_{sci} \)
Scheduled control power of the \( i \)-th CA.

\( \Delta P_{li} \)
Load-power variation of the \( i \)-th CA.

\( K_i \)
CBRR activation factor of the \( i \)-th CA.

\( P_{di}, P_{dii} \)
Demand power for CBRR and modified CBRR of the \( i \)-th CA.

\( P_{cori}, P_{cor}^* \)
Correction power for CBRR and modified CBRR of the \( i \)-th CA.

\( x, A \)
State vector and matrix.

\( u, B \)
Input vector and matrix.

\( \lambda_n \)
Eigenvalue of \( A \).

\( a_n \)
Coefficient of a characteristic polynomial.

\( H_i \)
Inertia time constant of the \( i \)-th CA.

\( D_i \)
Damping coefficient of the \( i \)-th CA.
I. INTRODUCTION

A. MOTIVATION AND LITERATURE REVIEW

Interconnections between neighboring Control Areas (CAs) have become a global trend in the development of power systems to increase the stability of the power system and to achieve a variety of economic benefits [1]. As a result, Transmission System Operators (TSOs) face new challenges in the operation of power systems because of the increased cross-border energy trade, the development of ancillary-services markets, increased penetration of renewable-energy sources and the reduction in the cost of operating the power system [2]–[7]. Therefore, advanced control techniques and methods are continually being developed to enhance the reliability, security, and efficiency of power supplies in future power systems [8]. In the first quarter of 2020, the development of the Cross-Border Activation of the Regulating Reserve (CBRR) began, which is to be implemented in continental Europe by the members of the European Network of Transmission System Operators for Electricity (ENTSO-E) in the third quarter of 2022 [9]. The CBRR aims to activate the regulating reserve in participating CAs and reduce the balancing energy [10]. As a result, the associated financial costs can be reduced. However, several questions need to be answered regarding the impact of the CBRR on the power system’s dynamics and the provision of Load-Frequency Control (LFC), mainly because the quality of the frequency is declining [11].

The frequency of a power system depends on the balance between the generation and consumption of electrical energy. A change in the active-power demand at one point of a power system is reflected throughout the system in a frequency deviation [12]. Maintaining frequency and power interchanges with CAs at the scheduled values are the two main objectives of a power system’s LFC [13], which is one of the functionalities of Automatic Generation Control (AGC) [14]. TSOs are therefore obliged to maintain the balance between generation and consumption in their CA by activating regulating reserves. Grid Control Cooperation (GCC) was introduced in Europe [15] to avoid the counter-activation of regulating reserves in participating CAs. The Imbalance Netting Process (INP) was implemented with the involvement of four German TSOs in 2008 [16]. The activation of the regulating reserve is thus reduced in addition to the reduced financial costs [17]. Shortly after that, international extensions were made, and the GCC developed into the International GCC (IGCC) [18], [19].

However, the further development of the INP is necessary due to new network codes and the increasing demand for cost optimization, which must be implemented so that the CBRR will be enabled [9]. CAs with the same sign of demand power will be able to activate the demand for balancing energy in participating CAs [10]. The TSOs agreed to use the control-demand approach for the CBRR, which is the same approach as currently used for the INP. The main objective of the design, implementation, and operation of the CBRR is to integrate the markets for balancing services and thus improve the efficiency of the European balancing system [20]. Like the INP, a corrective power is introduced to calculate the Area Control Error (ACE) due to the CBRR. The corrective power is calculated by the optimization module of the CBRR and is determined from the actual responses of the participating control units, including the activated regulating reserves [21]. The main difference between the INP and the CBRR lies in the conditions to compensate for the imbalances between participating CAs. The INP is used to avoid the simultaneous activation of regulating reserves with opposite signs in participating CAs, i.e., the compensation is possible between CAs with different signs of demand power. In contrast, the CBRR allows CAs with the same sign of demand power to activate the demand for balancing energy in participating CAs. Both the INP and the CBRR connect all the CAs to a common portal of virtual tie-lines at the ENTSO-E level in continental Europe. The INP and CBRR intend to complement each other, since only the INP or CBRR can perform the compensation at once.
A comprehensive literature review of the used LFC and AGC models for the diverse configurations of power systems are investigated and classified for conventional, modern and future smart power systems. Furthermore, the proposed control strategies for LFC and AGC are studied and categorized into different control groups [22]. An agent-based analysis of the impact of different cross-border balancing arrangements, i.e., separate markets, ACE netting, and balancing energy trade on the performance of the balancing market in northern Europe, is outlined in [23]. Since one of the objectives of the CBRR is to integrate the markets, possible distortions resulting from the insufficient harmonization of national arrangements must be identified, and minimum requirements and long-term recommendations for the implementation of cross-border balancing in Europe must be derived [24]. As such, the possibilities of TSO cooperation for regulating reserve dispatch and procurement must be analyzed in addition to a theoretical analysis of the cross-border reserve cooperation, with a focus on European network codes [25]. An optimization-based method for the cross-border balancing energy exchange and the results from the application of the proposed method to the Swiss transmission grid are shown in [26]. A more cost-effective Europe-wide cross-border activation of the replacement reserve with a novel methodology is suggested for the conversion of balancing energy offers submitted during the integrated scheduling process of the European central-dispatch systems into replacement reserve standards [27]. To increase the financial effects of the CBRR, the dynamic dimensioning of regulating reserves with the CBRR should also be considered [28].

B. CONTRIBUTION AND PAPER STRUCTURE

The compensation of imbalances through the CBRR should positively impact on frequency quality and the provision of LFC. However, this issue needs to be addressed as frequency quality is declining [11]. The impact of the INP on power-system dynamics is shown in [29], which incorporates a frequency term and inherently affects the frequency response of the participating CAs. Since the same control-demand approach is used for the CBRR, the correction power includes load variation and a frequency term. Consequently, the impact of the CBRR is inherent to the frequency response of the participating CAs. To the best of our knowledge, no previous studies have investigated the impact of the CBRR on the power-system dynamics and the provision of LFC. Furthermore, only a limited number of studies have been conducted that consider the cross-border energy trade. The main contributions of this paper are as follows.

- A modified CBRR is proposed that does not affect the eigendynamics of participating CAs.
- The impact of the classic CBRR on the eigendynamics of participating CAs is outlined.
- An eigenvalue analysis of a two-CA system is additionally performed, showing the impact of the tie-line parameter, the inertia time constant, the droop characteristic, and the frequency-bias coefficient.
- The impact of the CBRR on the power-system dynamics and the provision of LFC is thoroughly examined through dynamic simulations with a random load variation.

This paper is organized as follows. Section II describes the basic principle of LFC and the CBRR. Additionally, the classic CBRR optimization is explained, and a modified CBRR is proposed. The impact of the classic and modified CBRR on the dynamics of the power system and the provision of LFC is shown with an eigenvalue analysis of a two-CA system, given in Section III. The impact of the activation factor on the eigenvalues of the system matrix is also evaluated numerically. In Section IV, a three-CA test model with the classic and modified CBRR is described, which was used for dynamic simulations with a random load variation. The results are presented in Section V. First, indicators for the evaluation of the LFC provision are outlined. The results for the standard deviation of the frequency deviation, the standard deviation of the ACE, the mean value of the Rate of Change of Frequency (RoCoF), the unintended exchange of energy and the demand power are presented. Finally, Section VI summarizes the important conclusions and outlines future work.

II. LFC AND CBRR

A. LFC

The frequency of a power system depends on the balance of active power. A change in active-power demand at one point of a power system is reflected in a frequency deviation throughout the entire system. Therefore, the frequency is controlled at a scheduled value. In a large-scale power system consisting of several CAs connected with transmission lines, in addition to the frequency control, the generation within each CA must be controlled to maintain the scheduled power interchanges. Maintaining the frequency and power interchanges with CAs at the scheduled values are the two main objectives of a power system’s LFC [12]–[14]. These objectives are achieved by reducing the ACE, which is used as the input signal to the LFC. The power imbalance between generation and consumption is, for the $i$-th CA, defined as

$$ACE_i' = B_i \Delta f_i + \Delta P_i,$$  \hfill (1)

where

$$\Delta f_i = (f_{ai} - f_{ai})$$  \hfill (2)

and

$$\Delta P_i = (P_{ai} - P_{si})$$  \hfill (3)

are the frequency deviation and interchange power variation, respectively. Here, $f_{ai}$ and $P_{ai}$ denote the actual, i.e., measured, values, while $f_{si}$ and $P_{si}$ denote the scheduled values. Furthermore, $B_i$ is the frequency-bias coefficient that reflects the size of the CA. The value of $B_i$ is determined on an annual basis by all the TSOs in a synchronous area, taking into account the sum of the primary control reserve in relation to the maximum steady-state frequency deviation,
the auto-control of the generation, and the self-regulation of the load [15]. Furthermore, a CA is characterized as "short" if \( ACE_i' < 0 \), which means that the consumption is higher than the generation. In contrast, a CA is characterized as "long" if \( ACE_i' > 0 \), which means that the generation is higher than the consumption. Note that the terms "short" and "long" will be used subsequently.

The basic LFC framework of the \( i \)-th CA is shown in Fig. 1 with a solid line. Here, LPF denotes Low-Pass Filter, which has a maximum cut-off frequency of 0.5 Hz, while SH denotes Sample and Hold, with typical values of a sampling time \( T_s \) between 1 to 5 seconds [14]. Furthermore, PI is a Proportional-Integral controller, where a negative control-feedback is included as \(-1\) gain. The output of the LFC is the scheduled control power \( \Delta P_{sc} \), which is distributed to the participating control units, which change the actual (electrical) control power \( \Delta P_e \) accordingly. If the losses are neglected, then \( \Delta P_e \) is, for the \( i \)-th CA, defined as

\[
\Delta P_e = \Delta P_{L1} + \Delta P_1, \tag{4}
\]

where \( \Delta P_{L1} \) denotes the load-power variation.

The provision of LFC is an expense for the TSO that depends on the size of the actually activated reserve power and the LFC reserve. Note that the term activated reserve power is also known as balancing energy, while the term regulating reserve is typically used instead of LFC reserve.

### B. CBRR

CBRR was developed to reduce the expenses associated with the high costs of balancing energy. The block diagram for the classic CBRR, suggested by ENTSO-E [9], is the same as the block diagram for INP. Therefore, the same control-demand approach was suggested. The only difference is that the INP optimization module is substituted with the CBRR optimization module, as shown in Fig. 1. Because of limited literature on CBRR optimization, a more straightforward block diagram is presented for an easier interpretation. This is shown in Fig. 2. Generally, all \( N \) CAs can be connected through the virtual tie-lines, i.e., they can all activate the CBRR. Instead of the CBRR optimization module, the activation factors \( K_i \), \( K_j \), \ldots, \( K_N \) are added to the block-diagram structure shown in the green rectangle. Note that the factor \( K_j \) characterizes the size of the CBRR activation of the \( j \)-th CA in the \( i \)-th CA, where \( K_j = 0 \) means that the possible CBRR activation is equal to 0\%, whereas \( K_j = 1 \) means that the possible CBRR activation is equal to 100\%. In addition, the values of \( K_i, K_j \), \ldots, \( K_N \) can be different. The participating CAs are connected to the "green" summator, thus forming virtual tie-lines, as shown in Fig. 2. Note, a virtual tie-line represents a telemetered reading or value that is updated in real-time and used as a tie-line flow in (1), but for which no physical tie or energy metering actually exists [15]. The input variables to the "green" summator are the demand powers of the participating CAs, i.e., \( P_{di}, P_{dj}, \ldots, P_{dN} \). The demand power of the \( i \)-th CA determines the maximum activation power for the \( i \)-th CA between the participating CAs and is defined as

\[
P_{di} = \Delta P_{ei} - ACE_i' \tag{5}
\]

according to [9], [12].

By introducing (1) and (4) in (5) the following relation is obtained

\[
P_{di} = \Delta P_{L1} - B_i \Delta f_i. \tag{6}
\]

The power imbalance between generation and consumption in addition to \( K_i P_{di} \) from \( i \)-th CA, \( K_j P_{dj} \) from \( j \)-th CA, \ldots, \( K_N P_{dN} \) from \( N \)-th CA is, for the \( i \)-th CA, defined as

\[
ACE_i = B_i \Delta f_i + \Delta P_i - K_i P_{di} + (K_j P_{dj} + \ldots + K_N P_{dN}). \tag{7}
\]

The output variables of the "green" summator are the correction powers of the participating CAs, i.e., \( P_{cori}, P_{corj}, \ldots, P_{conN} \), calculated with a delay of \( T_s \) due to the SH. The correction power of the \( i \)-th CA determines the maximum activation power for the \( i \)-th CA between the participating CAs with the same sign of \( ACE_i' \), and is included as

\[
ACE_i = (B_i \Delta f_i + \Delta P_i) + P_{cori}. \tag{8}
\]

where the terms in brackets denote \( ACE_i' \). Note that \( ACE_i' \) does not include a correction term due to the CBRR.

Furthermore, only CAs with the same sign of demand power, i.e., \( \text{sign}(P_{di}) = \text{sign}(P_{dj}) \), can activate the demand for balancing energy. If any of the participating CAs is "long" and the other is "short" then INP is used instead of the CBRR and vice versa [30]. Consequently, all the participating CAs must be either "short" or "long", depending on whether...
a positive or negative CBRR is activated. In this way the balancing energy in those CAs that activate the balancing energy in the participating CAs can be reduced, while at the same time the regulating reserve is released. The \( P_{\text{cor}i}, P_{\text{cor}j}, \ldots, P_{\text{cor}N} \) is calculated by the CBRR optimization module, taking into account various target functions, which is explained in Section II-C.

When considering \( N \) CAs, then \( P_{\text{cor}i} \) is, for the \( i \)-th CA, expressed as

\[
P_{\text{cor}i} = -P_{\text{di}}K_i + P_{\text{dj}}K_j + \ldots + P_{\text{dN}}K_N.
\]

By considering (6), then the \( P_{\text{cor}i} \) between \( N \) CAs is, for the \( i \)-th CA, expressed as

\[
P_{\text{cor}i} = -(\Delta P_{Li} - B_{i}f_{i})K_i + (\Delta P_{Lj} - B_{j}f_{j})K_j + \ldots + (\Delta P_{LN} - B_{N}f_{N})K_N.
\]

Thus, the correction power of the \( i \)-th CA compensates the load variation, which is mixed by the frequency deviation of the participating CAs. From a system point of view, this corresponds to an additional frequency-based feedback and cross-couplings with other participating CAs that inherently changes the eigendynamics of the \( i \)-th CA.

C. OPTIMIZATION OF THE CBRR

The CBRR optimization module shown in Fig. 1 can be described with the activation factors \( K_i, K_j, \ldots, K_N \), which characterize the size of the \( P_{\text{di}}, P_{\text{dj}}, \ldots, P_{\text{dN}} \) activation in the participating CAs, as shown in Fig. 2 and described in Section II-B. The aim of this chapter is merely to present the target functions used by the ENTSO-E optimization module. According to ENTSO-E [9] the common objective function of the CBRR optimization consists of four target functions. The first and most important target function is the largest-possible activation of the balancing energy. Furthermore, the limit of \( P_{\text{di}} \) and the limit of the Available Transmission Capacity (ATC) between the participating CAs, which can be different for each direction of the activation, must be taken into account. The goal is to control the \( ACE'_i \) to zero; therefore, the amount of \( P_{\text{cor}i} \) to be activated should cover \( P_{\text{di}} \). In addition, the amount of activated \( P_{\text{di}} \) in the \( i \)-th CA should be minimized and should be activated in the \( j \)-th CA. The second is the target function of fairness, which splits the \( P_{\text{di}} \) between the participating CAs when multiple CAs are connected by a common point. In the case of parallel tie-lines, the third target function is required for the advantageous use of the tie-lines with the highest ATC. In addition, the fourth target function is also possible for an economic optimization that minimizes the costs of the participating CAs. Only the economically most efficient bids for \( P_{\text{di}} \) activation should be chosen. Note that CBRR optimization is not used and discussed in this paper. The aim of this paper is to show the impact of the CBRR on the power-system dynamics and the provision of LFC, regardless of whether the activation factors \( K_i, K_j, \ldots, K_N \) are chosen optimally or not.

D. MODIFIED CBRR

The demand power \( P_{\text{di}} \) of a CBRR includes a frequency term, as expressed by (6), which is reflected in the correction power \( P_{\text{cor}i} \), as is expressed by (10). Furthermore, the activation between the \( i \)-th and \( j \)-th CA is only possible if \( \text{sign}(P_{\text{di}}) = \text{sign}(P_{\text{dj}}) \). This condition might not be fulfilled for the frequency term in (6), i.e., \( \text{sign}(\Delta P_{Li}) = \text{sign}(\Delta P_{Lj}) \), although cases of \( \text{sign}(\Delta f_i) \neq \text{sign}(\Delta f_j) \) exist in the transient state. Consequently, the correction of the frequency term in one CA would be incorrect. Hence, the motivation for changing the CBRR implementation was suggested as one of the contributions of this paper, as shown in Fig. 3 with a solid and a dotted line. Generally, all \( N \) CAs can activate the modified CBRR. The CBRR shown in Fig. 2 is further referred to as the classic CBRR to distinguish it from the proposed, i.e., the modified CBRR. However, only the implementation of the CBRR in the LFC framework is changed, whereas the CBRR optimization module, suggested by ENTSO-E [9], is not. Thus, the modified demand power is given as

\[
P_{\text{di}}^* = \Delta P_{ei} - \Delta P_i
\]

and when introducing (4) in (11) it results in

\[
P_{\text{di}}^* = \Delta P_{Li}.
\]

The output variables of the green summator are modified correction powers of the participating CAs, i.e., \( P_{\text{cor}i}^*, P_{\text{cor}j}^*, \ldots, P_{\text{cor}N}^* \), calculated with a delay of \( T_\text{s} \) due to the SH, which is included for the \( i \)-th CA as

\[
ACE_i^* = (B_{i}f_{i} + \Delta P_i) + P_{\text{cor}i}^*.
\]

Furthermore, when considering \( N \) CAs, similar to in Section II-B, then the modified \( P_{\text{cor}i}^* \) is, for the \( i \)-th CA, expressed as

\[
P_{\text{cor}i}^* = -\Delta P_{Li}K_i + \Delta P_{Lj}K_j + \ldots + \Delta P_{LN}K_N.
\]

In contrast to the classic CBRR, only the load variation is compensated in this way. Consequently, the eigendynamics of the \( i \)-th CA is not affected.

A thorough analysis of the impact of the modified CBRR is given in the following and the advantages over the classic CBRR are shown undoubtedly.
III. EIGENVALUE ANALYSIS OF A TWO-CA SYSTEM WITH THE CLASSIC AND MODIFIED CBRR

A linearized 4th-order system with constant parameters is used to describe the i-th CA, as proposed in [12], [14]. The generator-load dynamics are represented by the inertia time constant $H_i$ and the damping coefficient $D_i$. A governor-and-turbine system is described as a steam non-reheat turbine with the time constants $T_{G1}$ and $T_{CH1}$, respectively. A primary frequency loop with a constant droop characteristic $R_i$ is considered. Furthermore, the LFC is modeled by a PI controller with a gain $K_i$ and a time constant $T_i$. In addition, the classic and modified CBRR are also included according to Fig. 2 and Fig. 3, where the activation factor $K_i$ characterizes the size of the activation of $P_{dj}$ in the i-th CA, whereas $K_j$ characterizes the size of the activation of $P_{dj}$ in the i-th CA, as described in Section II-B. The tie-line between CA$i$-CA$j$ is described by a synchronizing coefficient $T_{ij}$ [31]. Note that the LPF and the time delays due to the SH are not considered.

A. STATE-SPACE MODEL

Two CAs connected by a tie-line represent a 9th-order system, which is given in the state-space matrix representation as

$$\dot{x} = Ax + Bu.$$  (16)

The vectors of the state-space and input variables are given, respectively, as

$$x^T = [\Delta f_1, \Delta P_{m1}, \Delta P_{g1}, \int ACE_1 dt, \Delta f_2, \Delta P_{m2}, \Delta P_{g2}, \int ACE_2 dt, \Delta P_{12}]$$  (17)

and

$$u^T = [\Delta P_{L1}, \Delta P_{L2}].$$  (18)

Here, $\Delta P_{m1}$ and $\Delta P_{m2}$ are the turbine outputs, whereas $\Delta P_{g1}$ and $\Delta P_{g2}$ are the governor outputs. For the two participating, i.e., CA1 and CA2, the only possible corrections are given as

$$P_{cor1} = -P_{d1}K_1 + P_{d2}K_2$$  (19)

and

$$P_{cor2} = -P_{d2}K_2 + P_{d1}K_1$$  (20)

due to the classic or modified CBRR. Furthermore, the system and the input matrices A and B depend on the type of the CBRR being used. When considering the classic CBRR given in Section II-B, then the matrices $A$ and $B$ are given by (15), as shown at the bottom of the page. When considering the modified CBRR given in Section II-D, then the matrix $A$ corresponds to a system without a CBRR, i.e., $K_1 = 0$ and $K_2 = 0$, which is one of the contributions of this paper. However, for a system with the classic and modified CBRR, both have the same input matrix $B$. The impact of the activation factors $K_1$ and $K_2$ on the matrices $A$ and $B$ is summarized in Table 1. Considering (10) and (14) means that Table 1 applies to a system with N CAs.

B. NUMERICAL EVALUATION OF THE IMPACT OF THE ACTIVATION FACTORS $K_1$ AND $K_2$ ON THE EIGENVALUES OF $A$

A numerical evaluation of the impact of the activation factors $K_1$ and $K_2$ on the eigenvalues of $A$ is performed, since exact analytical expressions for the eigenvalues are complicated. Note that the determination of optimal activation factors $K_1$ and $K_2$ are not studied in this paper. Two identical CAs were assumed, with typical parameters and control settings [12], [14] that are summarized in Table 4. Note, the only differences between the CAs were the PI controller time constants, which were $T_{G1} = 60$ s and $T_{G2} = 30$ s. Moreover, for the two CAs, only two corrections are meaningful. When considering $K_2 = 0$ and $0 \geq K_1 \geq 1$, then $P_{cor1} = -P_{d1}K_1$ and $P_{cor2} = P_{d1}K_1$. When considering $K_1 = 0$ and $0 \geq K_2 \geq 1$, then $P_{cor1} = P_{d2}K_2$ and $P_{cor2} = -P_{d2}K_2$. Only the classic

| matrix | without CBRR | classic CBRR | modified CBRR |
|--------|--------------|--------------|---------------|
| A      | NO           | YES          | NO            |
| B      | NO           | YES          | YES           |

TABLE 1. Impact of the activation factors $K_1$ and $K_2$ on the matrices $A$ and $B$.  

$$A = \begin{bmatrix}
-\frac{D_1}{2T_1} & -\frac{1}{2T_1} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2T_1} \\
0 & -\frac{1}{T_{G1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{1+R_1K_1B_1(1+K_1)}{K_1T_{G1}} & -\frac{1}{T_{G1}} & -\frac{K_1}{T_{G1}T_{r1}} & \frac{K_1B_2K_2}{T_{G1}} & 0 & 0 & 0 & -\frac{K_1}{T_{G1}} & 0 \\
B_1(1+K_1) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2T_2} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{G2}} & 0 & 0 \\
\frac{K_2B_1K_1}{T_{G2}} & 0 & 0 & 0 & 0 & 0 & \frac{1+R_2K_1B_2(1+K_2)}{T_{G2}} & 0 & -\frac{K_2}{T_{G2}} \\
-B_1K_1 & 0 & 0 & 0 & B_2(1+K_2) & 0 & 0 & 0 & -1 \\
2\pi T_{12} & 0 & 0 & 0 & -2\pi T_{12} & 0 & 0 & 0 & 0 \\
\end{bmatrix}.$$  (15)
CBRR is considered, since it affects the matrix $A$ according to Table 1. The obtained characteristic polynomial is given as

$$
\sum_{n=0}^{9} a_n \lambda^n
$$

where $\lambda$ is an eigenvalue of $A$, while the coefficients $a_n$ are given in Table 2 for both the discussed corrections.

The impact of the activation factor $K_1$, while $K_2 = 0$ on the eigenvalues of $A$ for the classic CBRR is shown in Fig. 4. The most critical are the complex conjugate eigenvalues $\lambda_1$ and $\lambda_2$. Increasing the activation factor $K_1$, while $K_2 = 0$ results in a decrease of the damping $\zeta$ of $\lambda_1$ and $\lambda_2$, as given in Table 3, and has a negative impact on the system eigen dynamics. Similar conclusion can be made also when increasing the activation factor $K_1$, while $K_2 = 0$. However, such cases, where both of the two participating CAs activate CBRR simultaneously, i.e. CA$_1$ in CA$_2$ and vice versa, are not meaningful.

According to [32], [33], the tie-line parameter $T_{ij}$, the inertia time constant $H_i$ and the droop characteristic $R_i$ have a major impact on frequency stability. Different values of $T_{ij}$, $H_i$ and $R_i$ were used to show the impact of the activation factor $K_1$, while $K_2 = 0$ on the damping of the dominant eigenvalues $\lambda_1$ and $\lambda_2$ of $A$. Furthermore, the frequency-bias coefficient $B_i$ was also varied. In Fig. 5 it is clear that an increase of $T_{ij}$ results in a decrease of $\zeta$, in addition to the decrease of $\zeta$ with the increase of $K_1$ for the eigenvalues $\lambda_1$ and $\lambda_2$. In Fig. 6 it is clear that an increase of $H_i$ results in an increase of $\zeta$, in addition to the decrease of $\zeta$ with the increase of $K_1$ for the eigenvalues $\lambda_1$ and $\lambda_2$. In Fig. 7 two cases were considered. First, a case was assumed, where $B_i$ was varied, while $R_i = 1/(B_i - D_i)$ [12], which is shown with the dashed lines. Second, the value of $B_i$ was constant and set as 0.3433 pu/Hz, while $R_i$ was varied, which is shown with
the solid lines. It is clear that an increase of $R_i$ as well as $B_i$ results in an increase of $\zeta$, in addition to the decrease of $\xi$ with the increase of $K_1$ for the eigenvalues $\lambda_1$ and $\lambda_2$. Note that the results obtained for considering the activation factor $K_2$ as a free parameter, while $K_1 = 0$ are similar.

IV. DYNAMIC SIMULATIONS

A three-CA test system was considered in which CA1–CA2 and CA2–CA3 were connected with physical tie-lines, while CA1–CA3 were not connected by a tie-line. In addition, all three CAs were connected by virtual tie-lines due to the CBRR. A Matlab/SIMULINK model was developed in which dynamic simulations were performed with a step size of 50 ms.

A. DYNAMIC MODEL

1) STRUCTURE

To test the classic and modified CBRR, an individual CA was described with a linearized, low-order, time-invariant model [14, 34], as shown in Fig. 8. Note that the classic and modified CBRR are not shown so as to make the figure more transparent. The model assumes that the voltage control (reactive power) does not impact on the frequency control (active power). Furthermore, a group of multiple generators was replaced by one equivalent, neglecting the fast dynamic of voltage and angle, which reduced the complexity of the modeling. Therefore, the generator-load dynamics are described by the inertia time constant $H_i$ and the damping coefficient $D_i$ that accounts for the frequency dependence of the CA load. In addition, three different types of governor-turbine systems were considered, i.e., a steam non-reheat unit, a steam reheating unit, and a hydraulic unit, which are presented with the following transfer functions

$$M_{ij} = \frac{1}{sT_{CHi} + 1} \frac{1}{sT_{Gi} + 1},$$

$$M_{2i} = \frac{1}{sT_{RH} + 1} \frac{1}{sT_{Gi} + 1},$$

$$M_{3i} = \frac{1}{sT_{W} + 1} \frac{1}{sT_{Gi} + 1}. $$

respectively [12]. Here, $T_{CHi}$ is the time constant of the main inlet volume and steam chest, $F_{HPi}$ is a fraction of the total turbine power generated by the high-pressure turbine section, $T_{RH}$ is the time constant of the re-heater, $T_{Ri}$ is the reset time, $T_{Di}$ is the permanent droop, $R_{Pi}$ is the permanent droop, $T_{Wi}$ is the governor time constant. The tie-line control to the neighboring CAs is described by $T_{ij}$, which is defined by the line reactance, magnitude and angle difference of the line terminal bus voltage [31]. The ramp rate and participation factors $\alpha_{ij}$ of the control units were considered in addition to a constant droop characteristic $R_{Gi}$. Furthermore, a PI controller and a 1st-order LPF were modeled as

$$G_{ii} = \frac{K_{ii}(sT_{ii} + 1)}{sT_{ii}},$$

$$G_{LPFi} = \frac{1}{sT_{LPFi} + 1}, $$

where the gain and time constant of the PI controller are denoted as $K_{ii}$ and $T_{ii}$. The LPF time constant is denoted as $T_{LPFi}$. Moreover, three different structures were modeled, i.e., with the modified CBRR, with the classic CBRR and without the CBRR.

2) PARAMETERS

The parameters of the model used for the dynamic simulations are specified in Table 4. They are defined according to [12, 14] for the discussed three-CA dynamic model. The model parameters were set to be the same for all three CAs. The only differences were the PI controller time constants $T_{ij}$. The frequency-bias coefficient was determined as a constant, defined as

$$K_{ii} = \frac{1}{R_{ii} + 1/R_{2i}} + 1/R_{3i} + D_i .$$

FIGURE 6. Impact of the activation factor $K_1$, while $K_2 = 0$ on the damping of the complex conjugate eigenvalues $\lambda_1$ and $\lambda_2$ of $A$ for different values of $H_i$.

FIGURE 7. Impact of the activation factor $K_1$, while $K_2 = 0$ on the damping of the complex conjugate eigenvalues $\lambda_1$ and $\lambda_2$ of $A$ for different values of $R_i$ (solid line) and $B_i$ (dashed line).

FIGURE 8. Block diagram of the $i$-th CA.
TABLE 4. Model parameters used for dynamic simulations.

| parameter | value | parameter | value | parameter | value |
|-----------|-------|-----------|-------|-----------|-------|
| $H_i$     | 0.1 pu s | $\alpha_{d,i}$ | 1/3   | $T_{PP,i}$ | 0.3 s |
| $D_i$     | 0.01 pu/Hz | $K_{i1}$ | 0.3 | $T_{i1}$ | 60 s |
| $T_{i}$   | 1/30 pu/Hz | $R_{i}$ | 3 Hz/pu | $T_{i2}$ = $T_{i3}$ | 30 s |

Tableau 5

TABLE 5. Amount of $P_{d,i}$ activation for a three CA test system.

| Case 1 | Case 2 | Case 3 |
|-------|-------|-------|
| $P_{d1}$ | $P_{d2}$ | $P_{d3}$ |
| 0 $P_{d1}$ | 1 $P_{d2}$ | 0 $P_{d3}$ |
| 0.1 $P_{d1}$ | 0.8 $P_{d2}$ | 0.1 $P_{d3}$ |
| 0.2 $P_{d1}$ | 0.6 $P_{d2}$ | 0.2 $P_{d3}$ |
| 0.3 $P_{d1}$ | 0.4 $P_{d2}$ | 0.3 $P_{d3}$ |
| 0.4 $P_{d1}$ | 0.2 $P_{d2}$ | 0.4 $P_{d3}$ |
| 0.5 $P_{d1}$ | 0 $P_{d2}$ | 0.5 $P_{d3}$ |

FIGURE 9. Random variations of $\Delta P_{d,i}$ for a three CA test system.

The loads of the individual CAs were changed simultaneously, having the same sign, i.e., all three CAs were either short or long. A condition for the CBRR activation at all times of the simulation was ensured in this way. In addition, the limit of the ATC for power interchange between neighboring CAs was not considered, to achieve maximum activation with the classic or modified CBRR. Two test cases of $P_{d,i}$ activation in the neighboring CAs were considered for the dynamic simulations of a three-CA test system, as shown in Table 5. In Case 1 CA2 activated from 0% to 50% of $P_{d2}$ in CA1 and CA3. In Case 2 CA1 and CA3 activated from 0% to 100% of $P_{d1}$ and $P_{d3}$ in CA2. In addition, subcases a–f were considered as, given in Tables 6 and 7.

V. RESULTS

For a test system with three CAs, dynamic simulations were performed to analyze the impact of the classic and modified CBRR on the system’s response. Indicators were used to evaluate the LFC provision, i.e., performance indicators, RoCoF, unintended exchange of energy and demand power. The impact was evaluated according to the results obtained.

A. PERFORMANCE INDICATORS

The quality of the frequency is evaluated with the Standard Deviation of $\Delta f_i$, denoted as $\sigma_{\Delta f_i}$, which is given in [15], [36]. The term frequency quality can also be used as a measure of the maintenance of the balance between the generation and consumption of electrical energy in the power system [37]. In addition, the provision of the LFC is typically assessed using indicators defined by Control Performance Standards (CPS) [15], [36]. The Standard Deviation of $ACE_{i}$, denoted as $\sigma_{ACE_{i}}$, is used as a common indicator that is also comparable to the performance criterion defined by the ENTSO-E [38]. It is also comparable to CPS2 given by the North American Electric Reliability Corporation (NERC) [36]. Note that 15-minute averages, as defined in [15], of the discussed variables have been taken into account.

The results of $\sigma_{\Delta f_i}$ are shown in Fig. 10 left for Case 1 and right for Case 2. In Case 1 the classic CBRR reduced $\sigma_{\Delta f_i}$ and $\sigma_{\Delta f_j}$ in CAs, which activated $K P_{d2}$, while $\sigma_{\Delta f_3}$ was increased with the increase of $K$. The modified CBRR additionally reduced $\sigma_{\Delta f_1}$ and $\sigma_{\Delta f_j}$, whereas $\sigma_{\Delta f_2}$ was also reduced in contrast to the classic CBRR. In Case 2 classic CBRR reduced $\sigma_{\Delta f_1}$ increased in $\sigma_{\Delta f_j}$, while $\sigma_{\Delta f_2}$ in CA, which activated $K P_{d1}$ and $K P_{d3}$, was reduced with the increase of $K$. The modified CBRR...
TABLE 6. Amount of $P_{di}$ activation in Cases 1 a–f for a three CA test system.

| CA1 a-f | a | b | c | d | e | f |
|---------|---|---|---|---|---|---|
| CA2 d-f | 1 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 |
| CA3 e | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 |

TABLE 7. Amount of $P_{di}$ activation in Cases 2 a–f for a three CA test system.

| CA1 a-f | a | b | c | d | e | f |
|---------|---|---|---|---|---|---|
| CA2 d-f | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 |
| CA3 e | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 |

FIGURE 10. Values of $\sigma_{1}$ for Case 1 (left) and Case 2 (right) in relation to $K$.

additionally reduced $\sigma_{\Delta f_1}$ in all three CAs, in contrast to the classic CBRR.

Fig. 11 shows an average value of $\sigma_{\Delta f_1}$, left for Cases 1 a–f and right for Cases 2 a–f. In all cases the modified CBRR reduced $\sigma_{\Delta f_1}$ in all three CAs in comparison to the classic CBRR.

The results of $\sigma_{ACE_i}$ are shown in Fig. 12 left for Case 1 and right for Case 2. In Case 1 the classic CBRR increased $\sigma_{ACE_1}$ and $\sigma_{ACE_3}$, while $\sigma_{ACE_2}$ was reduced with the increase of $K$. The values of $\sigma_{ACE_1}$ and $\sigma_{ACE_3}$ due to the modified CBRR, were also increased in comparison to the system without CBRR; however, $\sigma_{ACE_2}$ was increased. Furthermore, $\sigma_{ACE_1}$ in all three CAs was additionally reduced with the modified CBRR in comparison to the classic CBRR.

Fig. 13 shows the results of an average value of $\sigma_{ACE_1}$, left for Cases 1 a–f and right for Cases 2 a–f. In Cases 1 a–f $\sigma_{ACE_1}$ and $\sigma_{ACE_3}$ were reduced in CAs, which activated $KP_{d1}$, while $\sigma_{ACE_2}$ was either increased or reduced with the modified CBRR in comparison to the classic CBRR. In Cases 2 a–f $\sigma_{ACE_1}$ and $\sigma_{ACE_2}$ were reduced, while $\sigma_{ACE_3}$ was either increased or reduced with the modified CBRR in comparison to the classic CBRR; however, the differences were negligible.

B. RoCoF

According to [39] this is the time derivative of the power system’s frequency, i.e., $\frac{df}{dt}$. Traditionally, it has been of little importance for power systems whose generation is based mainly on synchronous generators (SGs), since the inertia
of SGs inherently counteracts the load imbalances and thus limits the RoCoF. However, it becomes relevant in the case of significant load-generation imbalances, when larger RoCoF values can be observed due to the low system inertia caused by the high penetration of non-synchronously connected generation systems. Therefore, the Mean Value of the RoCoF, denoted as $\mu_{RoCoF}$, is evaluated. The calculation is performed separately for positive and negative values, each of which is,
respective, denoted as $\mu_{\text{RoCoF}_i^+}$ and $\mu_{\text{RoCoF}_i^-}$. In addition, $\mu_{\text{RoCoF}_i^+}$ and $\mu_{\text{RoCoF}_i^-}$ are also evaluated for different values of the inertia time constant $H$ and activation factor $K$.

The results of $\mu_{\text{RoCoF}_i^+}$ and $\mu_{\text{RoCoF}_i^-}$ are shown in Fig. 14 and Fig. 15 left for Case 1 and right for Case 2. In both Case 1 and Case 2 the classic CBRR increased $|\mu_{\text{RoCoF}_i^+}|$
and \(|\mu_{\text{RoCoF}_i}|\) in all three CAs with the increase of \(K\). The modified CBRR reduced \(|\mu_{\text{RoCoF}_{i+}}|\) and \(|\mu_{\text{RoCoF}_{i-}}|\) in all three CAs compared to the system with the classic CBRR and in some cases also compared to the system without the CBRR.

The results of \(\mu_{\text{RoCoF}_{i+}}\) and \(\mu_{\text{RoCoF}_{i-}}\) for different values of \(H\) are shown in Fig. 16 and Fig. 17 left for Case 1 and right for Case 2. The value of \(|\mu_{\text{RoCoF}_{i+}}|\) and \(|\mu_{\text{RoCoF}_{i-}}|\) is reduced with the increase of \(H\), whereas it is increased with
the increase of $K$. However, the impact of $H$ in combination with $K$ is reduced on $|\mu_{RoCoF_{+i}}|$ and $|\mu_{RoCoF_{-i}}|$ when using the modified CBRR.

Figs. 18 and 19 show the results of an average value of $\mu_{RoCoF_{+i}}$ and $\mu_{RoCoF_{-i}}$, left for Cases 1 a–f and right for Cases 2 a–f. In all cases the modified CBRR reduced...
|µRoCoF| and |µRoCoFe| in all three CAs in comparison to the classic CBRR.

C. UNINTENDED EXCHANGE OF ENERGY

According to [19] this is the difference between scheduled exchanges and measured physical flows of electrical energy between TSOs. In addition to the interchange power variation, the correction power should also be taken into account. Thus, the unintended exchange of energy is calculated as

$$\Delta W_{uni} = \Delta W_i - W_{cor} = \int_0^t (\Delta P_i - P_{cor}) dt \quad (29)$$

for the observed time period. The calculation is performed separately for positive and negative values, each of which is, respectively, denoted as $\Delta W_{uni+}$ and $\Delta W_{uni-}$. Note that 15-minute averages, as defined in [15], of the discussed variables were taken into account.

The results of $\Delta W_{uni+}$ and $\Delta W_{uni-}$ are shown in Fig. 20 and Fig. 21 left for Case 1 and right for Case 2. In both cases the classic CBRR increased the value of $|\Delta W_{uni+}|$ and $|\Delta W_{uni-}|$ in all three CAs with the increase of $K$. The modified CBRR reduced the value of $|\Delta W_{uni+}|$ and $|\Delta W_{uni-}|$ in all three CAs compared to the system with the classic CBRR. The reduction was in the range 2–3.3%.

Figs. 22 and 23 show the results of an average value of $\Delta W_{uni+}$ and $\Delta W_{uni-}$, left for Cases 1 a–f and right for Cases 2 a–f. In all cases the modified CBRR reduced $|\Delta W_{uni+}|$ and $|\Delta W_{uni-}|$ in all three CAs in comparison to the classic CBRR.

D. DEMAND POWER

The demand power of the $i$-th CA determines the maximum activation power for the $i$-th CA between the participating CAs with the same sign of $ACE_i$. The demand power $P_{di}$ is calculated with (6) for the classic CBRR, while it is calculated with (12) for the modified CBRR. The calculations are performed separately for positive and negative values, each of which is, respectively, denoted as $P_{di+}$ and $P_{di-}$. Note that 15-minute averages, as defined in [15], of the discussed variables have been taken into account.

The results of $P_{di+}$ and $P_{di-}$ are shown in Fig. 24. Note that $K$ does not affect $P_{di}$. Consequently, the values of $P_{di}$ for Case 1, Case 2, Cases 1 a–f and Cases 2 a–f are the same. It is clear that the modified CBRR reduces the values of $|P_{di+}|$ and $|P_{di-}|$ in all three CAs. The reduction for $|P_{di+}|$ is approximately 3.9%, while the reduction for $|P_{di-}|$ is approximately 2.5% in all three CAs.

VI. CONCLUSION

In this paper, a thorough analysis of CBRR activation was performed. It is clear that for a two-CA system the classic CBRR leads to reduced damping of the dominant eigenvalues, which negatively impacts the entire power system. Furthermore, using the classic CBRR, the impact of a tie-line parameter, inertia time constant, droop characteristic and frequency-bias coefficient on the system’s eigenvalues did not change significantly. The proposed, i.e., modified CBRR, has no impact on the system’s eigenvalues, thus inherently maintaining the system’s eigendynamics.

Thorough dynamic simulations of a three-CA test system with the classic and modified CBRR were performed to evaluate the impact of the classic and modified CBRR on...
the provision of LFC. The results of the random load variations confirmed that the classic CBRR impacts the frequency responses of participating CAs. The classic CBRR reduces the frequency deviations in the CAs where the activation is performed, while the modified CBRR reduces the frequency deviations in all the CAs. The classic CBRR increases the ACE deviations in the CAs where activation is performed, while the modified CBRR always improves the RoCoF. Moreover, the impact of the inertia time constant on the RoCoF is reduced with the modified CBRR. Due to the reduced unintended exchange of energy and demand power in all the CAs, positive financial effects can be expected when using the modified CBRR.

Future work should focus on the dynamic dimensioning of the CBRR. It was shown that CBRR activation reduces the overall use of regulating reserves, which is not taken into account in the reserve dimensioning. In this way, a possible over-sizing of the regulating reserves could be reduced.

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M. Topler et al.: Improving the CBRR to Enhance the Provision of LFC

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