

## Criteria for evaluation of power balance control performance in UCTE transmission grid

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**Abstract:** In this paper two criteria for evaluation of power balance control performance in control areas of the UCTE interconnection are proposed: the mean value of Area Control Error (ACE) and the standard deviation of ACE. A methodology for assigning fair values of the two criteria to individual control areas is presented. This methodology ensures that the UCTE grid is operated in a safe manner and no area performs control at the expense of other areas. Since the fair values of the ACE standard deviation depend on a chosen model of ACEs coincidence, two cases were investigated: a model with no coincidence (optimistic one) and a model with full coincidence (pessimistic one).

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### 1. INTRODUCTION

Secure operation of a transmission grid and prevention of black-outs or other problems with the grid instability is currently an issue of rising importance that concerns mainly regions with recently deregulated energy markets. Real-time power balancing is thus an important control task in synchronously interconnected areas, like in the European Union for the Co-ordination of Transmission of Electricity (UCTE), where several independent control areas exist.

In the UCTE, each control area is usually represented by a Transmission System Operator (TSO) that is responsible for keeping the power balance in its area or, in other words, keeping a scheduled foreign exchange with the neighbouring areas. Fig. 1 shows a typical setting of a control system for a single control area in the UCTE. The area control error (ACE) is given as

$$ACE_i = \Delta P_i + K_i \Delta f, \quad (1)$$

where index  $i$  denotes a particular control area,  $\Delta P_i$  is a power control error (measured difference between scheduled and actual interchange with neighbouring areas),  $\Delta f$  is a frequency error (deviation of the measured frequency  $f_m$  from the frequency set-point  $f_{SP}$ )

$$\Delta f = f_m - f_{SP}, \quad (2)$$

$K_i$  [MW/Hz] is a frequency bias of the control area called K-factor in the UCTE's terminology. The K-factor can be viewed as a contribution coefficient, i.e. how much a particular area contributes to the joint action of the primary frequency control in the entire interconnected area.

The term  $K_i \Delta f$  in (1), a frequency control error, compensates for the action of the distributed primary control within the area in order to avoid counter-regulation from the central PI controller at the TSO's dispatch center. This ensures that the secondary control will only be called up in the control area which is the source of the disturbance.

On condition that each control area satisfactorily compensates for its imbalances, the operation of the entire synchronous grid will be secure and provide reliable power supply. Rules of the power balance control are stated in UCTE Operation Handbook (2004), the main ones are as follows:

- Each TSO operates sufficient generating capacity under automatic control by the secondary controller to meet its obligation to continuously balance its generation and interchange schedules to its load for the control area.
- One quality criterion for secondary control is the time taken for a control error to return to zero, i.e. the time taken to restore the system frequency to its set point value and to restore power interchanges to their set point values. Frequency and power interchanges must begin to return to their set point values as a result of secondary control after 30 seconds, with the process of correction being completed after 15 minutes with a reasonable ramp rate and without overshoot.
- Each control area must have access to sufficient tertiary reserve to follow up secondary control within a short period of time after an incident in the grid.
- Each TSO must immediately activate tertiary reserve in case insufficient free secondary control reserve is

available, in order to free up secondary control reserve again.

However, the above stated rules are rather general and do not serve as a basis for fair control performance evaluation. The rules assume that behaviour of an individual TSO towards the entire grid and the other UCTE members is based on "gentlemen agreement". In reality, there are differences in the power balance control performance among the UCTE members.

Hence, in this paper we will attempt to answer two questions concerning the UCTE interconnected areas:

- Can an easy-to-use criterion for judging the control performance be found that is practical for making comparisons between the control areas?
- What would be a reasonable, fair value of the criterion for each control area ensuring safe operation of the entire synchronous grid?

State-of-the-art in the field of control performance criteria for synchronously interconnected areas is described in the Section 2.

## 2. EXISTING CONTROL PERFORMANCE CRITERIA

Quite a lot of research attention is paid to the topic of control performance evaluation in the North American region, for which a group of scientific papers dealing with this issue can be found. The existing control performance criteria are based on evaluation of two basic quantities, a frequency error  $\Delta f$  and an area control error  $ACE$ .

The North American Electric Reliability Corporation has

defined two control performance standards, CPS1 and CPS2, in the NERC Operating Manual (2006). The first one, CPS1, requires that the average of the clock-minute averages of a control area's ACE over a given period divided by its K-factor times the corresponding clock-minute averages of the frequency error shall be less than a given constant

$$AVG_{Period} \left[ \frac{ACE_i}{K_i} \Delta f \right] \leq \varepsilon_1^2. \quad (3)$$

The constant  $\varepsilon_1$  is derived from the targeted frequency bound (the targeted RMS value of one-minute average frequency error based on frequency performance over a given year). For the purpose of the control performance evaluation the CPS1 is evaluated monthly for a past (sliding) twelve-month period. The criterion (3) can be viewed as a correlation between  $ACE_i$  and  $\Delta f$ . Positive correlation means undesired performance (the area error contributes to the frequency deviation from the desired value) and is therefore limited by the upper bound  $\varepsilon_1^2$ . Negative correlation occurs when  $ACE_i$  helps to compensate the total ACE and maintains the correct frequency in the interconnection.

The other criterion, CPS2, is designed to bound ACE ten-minute averages and provides an oversight function to limit excessive unscheduled power flows that could result from large ACEs:

$$AVG_{10\_minute}(ACE_i) \leq \varepsilon_{10} \sqrt{K_i K_{total}} \quad (4)$$

where  $K_{total}$  is the sum of K-factors in the entire interconnection and  $\varepsilon_{10}$  is the targeted RMS of ten-minute average frequency error. According to the NERC reliability

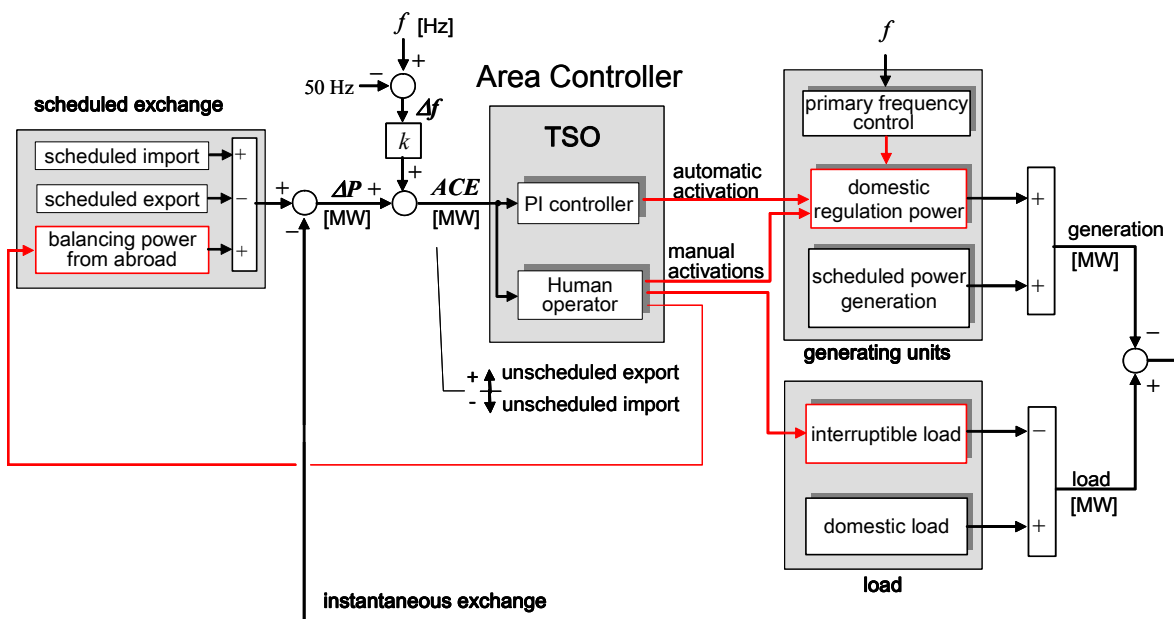


Fig. 1. Typical feedback control of a single UCTE control area

standards, the CPS2 criterion has to be satisfied at least in 90% of the cases in the evaluation period.

Gross and Lee (2001) attempted to give a more general mathematical framework for the two criteria and also came to a conclusion that the CPS2 is redundant under certain conditions if the CPS1 is satisfied. However, Jaleeli and VanSlyck (2002) do not agree with this result and suggest that without the CPS2 criterion the RMS of all averages of frequency error could grow even further. In addition, Jaleeli and VanSlyck (1999) suggested to use a modified CPS2 in the sense that minute-averages were replaced by hour-averages which could be more practical than requiring more rapid and costly control to meet ten-minute targets.

### 3. PROPOSED CONTROL PERFORMANCE CRITERIA

According to the UCTE Operation Handbook (2004) the individual  $ACE_i$  needs to be controlled to zero on a continuous basis in each control area. It is practical to understand this requirement in such a way that a mean value of  $ACE_i$  should be zero and a variance or a standard deviation of  $ACE_i$  should be kept low. Hence, we propose that the *mean* and particularly the *standard deviation* of  $ACE_i$  could be predictive measures for the power balance control performance. Their main advantage is that they are standard statistic measures that are easy to understand, so they have high potential to be accepted in the power engineering community. For instance, Stojkovic (2006) has already used the mean and the standard deviation, among other indices, for control performance comparison of the countries in the second UCTE zone (Romania, Bulgaria, Albania, Serbia, Greece, Montenegro and Macedonia).

The question is what the required values of the mean and standard deviation of ACE at each control area should be. On one hand, if their values are too high, the operation of the entire UCTE grid may start to be insecure, on the other hand, if their values are set too low, control of the grid under such requirements may be technically infeasible and/or inadequately expensive. Another question is whether or not they should be the same for all control areas. The following section provides answers to these questions.

### 4. FAIR VALUES OF THE CRITERION FOR INDIVIDUAL CONTROL AREAS

A total power imbalance in the synchronously interconnected system,  $ACE_{total}$ , can be expressed as the sum of  $ACE_i$  over all control areas

$$ACE_{total} = \sum_{i=1}^N ACE_i, \quad (5)$$

where  $N$  is the number of control areas. With regard to (1) this equation can be rewritten to the form

$$ACE_{total} = \sum_{i=1}^N \Delta P_i + \sum_{i=1}^N K_i \Delta f. \quad (6)$$

This first term must be equal to zero

$$\sum_{i=1}^N \Delta P_i = 0, \quad (7)$$

since inner cross-border power flows in a closed system cancel each other. Then we get

$$ACE_{total} = \sum_{i=1}^N K_i \Delta f = \Delta f \sum_{i=1}^N K_i = K_{total} \Delta f, \quad (8)$$

where  $K_{total}$  is a sum of the K-factors over all areas.

If the frequency error  $\Delta f$  has a mean  $\mu_{\Delta f}$  and a standard deviation  $\sigma_{\Delta f}$ , then with respect to (8) a mean and a standard deviation of  $ACE_{total}$  will be

$$\begin{aligned} \mu_{ACE_{total}} &= K_{total} \mu_{\Delta f}, \\ \sigma_{ACE_{total}} &= K_{total} \sigma_{\Delta f}. \end{aligned} \quad (9)$$

The values of  $\mu_{\Delta f}$  and  $\sigma_{\Delta f}$  in past years can be evaluated from historical measurements and, consequently, historical values of  $\mu_{ACE_{total}}$  and  $\sigma_{ACE_{total}}$  can be found. If the past operation of the UCTE grid was sufficiently secure, these historical values can be assumed as the requirement for the future.

#### 4.1 Contribution to ACE from Each Control Area

Let us state the following task : for given values of  $\mu_{ACE_{total}}$  and  $\sigma_{ACE_{total}}$  find a method to determine fair portions of these values to be assigned to the individual control areas so that no area performs power balance control at the expense of another.

The NERC performance standards tackle this problem in the following way: if we rewrite the criterion CPS1 (3) as

$$AVG_{Period} [ACE_i \cdot \Delta f] \leq K_i \varepsilon_1^2 \quad (10)$$

we can see that the bound  $\varepsilon_1^2$ , which is the same for all areas, is multiplied by the K-factor  $K_i$ , so "bigger" areas with a higher K-factor value are allowed to have higher  $ACE_i$  values (proportionally to the K-factor). If we look at the CPS2 represented by (4) we can see that the bound is multiplied by  $\sqrt{K_i}$ , so evaluation of a single area control performance is proportionally related to the square root of the K-factor in this case.

In our approach, we will also choose the K-factor as a basic measure of a control area "size". Let's consider an elementary control area characterized by the factor  $K_0$  and the corresponding control error  $ACE_0$  that will be modelled as a random variable with a standard deviation  $\sigma_{ACE_0}$ . We may assume that each of the real control areas, denoted by the index  $i$ , consists of  $M_i$  elementary areas (Fig. 2). Then  $ACE_{ij}$

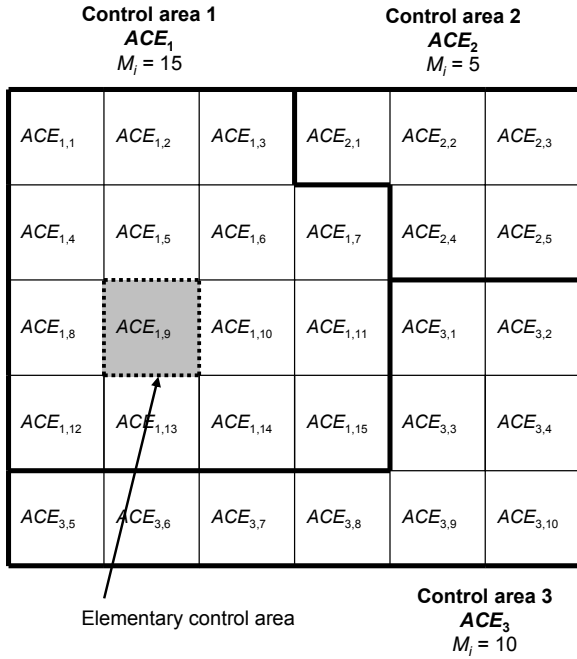


Fig. 2. Elementary vs. real control areas

denotes the control error of the  $j$ -th elementary area which is located in the  $i$ -th real control area of the UCTE grid. A relative size of the control area is a ratio of  $K_i$  and  $K_0$

$$M_i = \frac{K_i}{K_0} \quad (11)$$

The control error of the real area  $i$  is regarded as a random variable given by a sum of ACEs in the corresponding elementary control areas

$$ACE_i = \sum_{j=1}^{M_i} ACE_{ij} \quad (12)$$

having a standard deviation  $\sigma_{ACE_i}$ .

A relation between  $\sigma_{ACE_{total}}$ ,  $\sigma_{ACE_i}$  and  $\sigma_{ACE_0}$  stems from a chosen model of their interrelation. The relation between  $\sigma_{ACE_{total}}$  and  $\sigma_{ACE_i}$  will be referred to as the “inner dependency model” and the relation between  $\sigma_{ACE_i}$  and  $\sigma_{ACE_0}$  as the “outer dependency model”.

#### 4.2 Outer Dependency Model

Under a realistic assumption that the control errors of the real areas  $ACE_1, ACE_2, ACE_3, \dots, ACE_N$  are independent and thus uncorrelated, the relation between  $\sigma_{ACE_{total}}$  and  $\sigma_{ACE_i}$  is

$$\sigma_{ACE_{total}} = \sqrt{\sum_{i=1}^N \sigma_{ACE_i}^2} \quad (13)$$

Then the problem of finding the fair value of  $\sigma_{ACE_i}$  is to choose the appropriate inner model. Two extreme cases are considered, a pessimistic inner model and an optimistic inner model.

#### 4.3 Pessimistic Inner Dependency Model

In this case, there is a full coincidence of elementary ACEs in a control area. If one elementary area has a positive control error, the other areas also have positive control errors and do not compensate each other. Correlation coefficients between two elementary areas are equal to one, hence

$$\sigma_{ACE_i} = M_i \cdot \sigma_{ACE_0} \quad (14)$$

By inserting  $\sigma_{ACE_i}$  from (14) into (13) we obtain

$$\sigma_{ACE_{total}} = \sigma_{ACE_0} \sqrt{\sum_{i=1}^N M_i^2} \quad (15)$$

Combining (14) and (15) yields

$$\sigma_{ACE_{total}} = \frac{\sigma_{ACE_i}}{M_i} \sqrt{\sum_{i=1}^N M_i^2} \quad (16)$$

and with respect to (11) we get the final expression for the fair values of  $ACE_i$

$$\sigma_{ACE_i} = \frac{K_i}{\sqrt{\sum_{i=1}^N K_i^2}} \sigma_{ACE_{total}} \quad (17)$$

#### 4.4 Optimistic Inner Dependency Model

In this case, the random ACEs of the elementary areas are mutually independent, i.e. they randomly compensate each other. Correlation coefficients between two elementary areas are zero, hence

$$\sigma_{ACE_i} = \sqrt{M_i} \cdot \sigma_{ACE_0} \quad (18)$$

Then, we can obtain the expression for the fair values of  $ACE_i$  by the same procedure as with the pessimistic model:

$$\sigma_{ACE_i} = \sqrt{\frac{K_i}{\sum_{i=1}^N K_i}} \sigma_{ACE_{total}} = \sqrt{\frac{K_i}{K_{total}}} \sigma_{ACE_{total}} \quad (19)$$

The fair values of the mean  $\mu_{ACE_i}$  do not depend on the chosen model (correlation between the variables) since a

mean of a sum of random variables equals sum of mean values in both cases, hence

$$\mu_{ACEi} = \frac{K_i}{K_{total}} \mu_{ACE_{total}} \quad (20)$$

### 3.5 Comparison for Control Areas

In order to find the corresponding values of the fair criterion for  $ACE_i$  according to (17), (19) and (20), historical frequency deviations  $\Delta f$  in the UCTE grid were evaluated first (Fig. 3). The value of  $\mu_{\Delta f}$  is 2.85 mHz and  $\sigma_{\Delta f}$  is approximately 21.55 mHz. The total K-factor was chosen to be  $K_{total} = 20000$  MW/Hz according to the UCTE Operation Handbook (2004). Inserting the values of  $\mu_{\Delta f}$  and  $\sigma_{\Delta f}$  into (9) then yields  $\mu_{ACE_{total}} = 57$  MW and  $\sigma_{ACE_{total}} = 431$  MW. The K-factors of the individual control areas were calculated from annual net productions  $P_i$  of the control areas

$$K_i = \frac{P_i}{P_{total}} K_{total} \quad (21)$$

where  $P_{total}$  is the total annual net production in the UCTE.

Table 1 lists the considered UCTE control areas with their respective K-factors as well as the fair portions of the criteria values.

## 5. CONCLUSIONS

Two criteria for evaluation of power balance control performance in control areas of the UCTE interconnection were proposed: the mean value of ACE and the standard deviation of ACE. Moreover, fair values of the two criteria were assigned to individual control areas so that the UCTE grid is in safe operation and no area performs control at the expense of another. The fair values of the ACE standard deviation depend on a chosen model of ACEs coincidence. Two extreme cases were investigated: a model with no coincidence (optimistic) and a model with full coincidence (pessimistic). It seems that the optimistic one is closer to the reality since, in a larger control area, variations of load causing non-zero ACE in its sub-areas can naturally better compensate each other from a stochastic point of view. However, this is a subject for further discussions, modelling and simulation.

A future work should also involve an analysis of what the averaging and evaluation periods for  $\sigma_{ACEi}$  and  $\mu_{ACEi}$  should be to make sure these criteria are efficient in practice.

The mean and standard deviation of ACE might be used not only for performance evaluation of control area but also as targeted values when planning ancillary services, i.e. regulation power reserves to be purchased by the TSO to meet the criteria of area power balancing. This is an alternative to the approach described in (Havel et al, 2007) where seven indices describing the reliability are defined for

**Table 1. Considered control areas and fair values of  $\mu_{ACEi}$  and  $\sigma_{ACEi}$**

Control Area		K-factor [MW/Hz]	$\mu_{ACEi}$ [MW]	Optimistic $\sigma_{ACEi}$ [MW]	Pessimistic $\sigma_{ACEi}$ [MW]
AT	Austria	488	1.4	67.3	29.0
BA	Bosnia and Herzegovina	103	0.3	30.9	6.1
BE	Belgium	630	1.8	76.5	37.5
BG	Bulgaria	340	1.0	56.2	20.2
CH	Switzerland	481	1.4	66.8	28.6
CS	Serbia and Montenegro	319	0.9	54.4	19.0
CZ	Czech Rep.	603	1.7	74.8	35.9
DE	Germany	4549	13.0	205.5	270.8
ES	Spain	2075	5.9	138.8	123.5
FR	France	4249	12.1	198.7	252.9
GR	Greece	390	1.1	60.2	23.2
HR	Croatia	88	0.3	28.6	5.2
HU	Hungary	258	0.7	49.0	15.4
IT	Italy	2333	6.6	147.2	138.9
LU	Luxembourg	33	0.1	17.4	2.0
MK	Macedonia	51	0.1	21.8	3.0
NL	Netherlands	733	2.1	82.5	43.6
PL	Poland	1152	3.3	103.5	68.6
PT	Portugal	356	1.0	57.5	21.2
RO	Romania	444	1.3	64.2	26.4
SI	Slovenia	101	0.3	30.7	6.0
SK	Slovakia	224	0.6	45.7	13.3

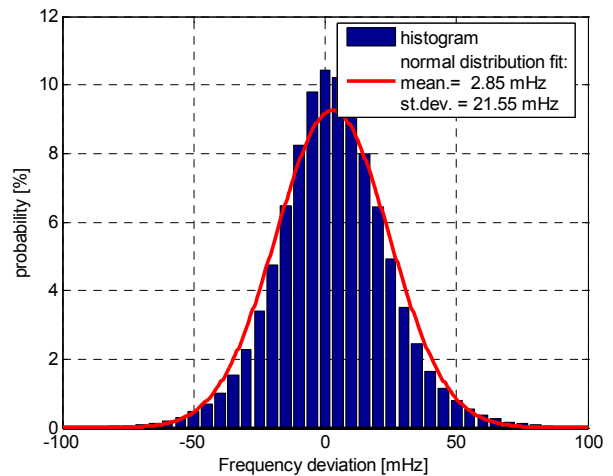


Fig. 3. Histogram of frequency deviations (minute averages in the period 1.1.2005 – 31.5.2007)

this purpose and each of them represents a probability that ACE exceeds a certain threshold and lasts for a certain time (Value-at-Risk).

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