Reliability Standards for Large Interconnections

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***Abstract*-Every interconnection must be operated so that the system frequency is maintained at given setpoint and all control areas of the interconnection meet their active power exchange obligations. Compliance with reliability standards is required. The paper discusses performance indices and standards definitions used in North America and Europe (synchronous interconnection of 24 European countries joining UCTE - Union for the Co-ordination of Transmission of Electricity) with the aim of choosing the most appropriate set. A particular example of indices and standards applied for the Czech control area of the UCTE interconnection including their use in Ancillary Services planning is provided.[*]**

I. INTRODUCTION

Generation and load in an electric grid must be balanced to assure stable grid operation. New power market conditions resulting from the process of liberalization and privatization dramatically changed the responsibilities of power generation companies, transmission owners, dealers and other market players. The process of transfer of ownership and operation of all high-voltage transmission lines to a regional power pooling and transmission entity with no interest in generation has been completed in North America and Europe where linkages between distribution, transmission, and generation occur across markets – regulated and unregulated – rather than through internal organization. The ultimate instance assuring stable frequency and defined power flows in the grid are balancing authorities responsible for individual control areas. Operation of control areas should be orchestrated so the cooperation, in terms of exchange of balancing power, is mutually balanced, otherwise penalties apply.

The state of the power system is described by the frequency error of the interconnection Δf and an area control error ACE_{area}. Additionally the area net interchange error ΔP_{area} might be also considered. The system frequency error is calculated as

$$\Delta f = f_{actual} - f_{desired} \ , \tag{1}$$

and each control area calculates the Area Control Error (ACE) as an inadvertent interchange less frequency bias

$$\begin{aligned} ACE_{area} &= \left(Interchange_{actual} - Interchange_{scheduled} \right) \\ &+ K_{area}\Delta f = \Delta P_{area} + K_{area}\Delta f \end{aligned} \tag{2}$$

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where K_{area} in MW/Hz is an amount of power that would be theoretically released through automatic primary control in generators when the system frequency drops 1Hz from the scheduled value. K_{area} is the frequency bias setting for the area. $Interchange_{actual}$ is the sum of active power measured on all tie-lines and $Interchange_{scheduled}$ is the desired, scheduled value. Interchange is positive when the area is exporting, area generation exceeds area load. Note that the standard formula for calculating ACE [1] uses frequency bias coefficient B_{area} in MW/0.1Hz (a negative number, not necessarily constant) rather than K-factor with the obvious relation

$$K_{area} = -10 B_{area} \ . \tag{3}$$

The load at each time instant is a random variable and this randomness penetrates to the variables measured and monitored, such as interconnection frequency and the active power flows on the tie lines.

These variables are assumed to be random processes described by the mean value and variance. The correlation between frequency error and ACE of the area is chosen as a metric of each area’s control performance. We need to impose an upper bound on that correlation whereas we need not care about the negative correlation since it indicates a favorable performance of the particular area.

The generic performance criterion considered says that the expected correlation between interconnection frequency error and the area’s ACE should be bounded by the allowed frequency discursion and the required frequency bias of the area:

$$E\left\{ \Delta f_1 \cdot ACE_{1area} \right\} \le std(\Delta f_1) \cdot \left(K_{area} \cdot std(\Delta f_1) \right) = \left(std(\Delta f_1) \right)^2 \cdot (-10 B_{area}) \ , \tag{4}$$

where index 1 means a clock-minute (1 minute) average of the respective variable. The operator E{·} is an expected value and std(·) stands for standard deviation of the argument. The principle forms the basis of currently applied standards in North America’s interconnections and is followed by European’s UCTE interconnection in an indirect way as well.

Similarities and differences between performance standards used in the above mentioned interconnections and a particular example of standards adopted by the Czech Transmission System Operator are going to be discussed in the following chapters.

II. PERFORMANCE STANDARDS

A. Performance Standards in North America

Today, North American Electric Reliability Corporation (NERC) defines three Control Performance Standards (CPS) for the assessment of control areas generation control performance: CPS1, CPS2 and DCS [1]. All control areas in North America implemented CPS by 1998.

The motivation to develop the theories that led to the development of CPS1 and CPS2 came from the need to find criteria whose fulfillment would equitably divide responsibility between control areas for satisfying the condition

$$\mathrm{RMS}\{\Delta f_T\} = \varepsilon_T \ , \qquad (5)$$

where Δf_T is average frequency error over T minutes, ε_T is the target to be chosen by the interconnection and RMS stays for root mean square error.

CPS1 requires each Balancing Authority to operate such that, on a rolling 12-month basis, the scaled average of clock-minute averages of the ACE of the area multiplied by the corresponding clock-minute averages of the interconnection's frequency error is less than a specific limit. CPS1 is a statistical measure of ACE variability. CPS1 measures ACE in combination with the interconnection's frequency error. The 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

$$\mathrm{AVG}_{\mathrm{Period}}\left[\frac{ACE_{1area}}{K_{area}}\Delta f_1\right] \le \varepsilon_1^2 \ . \qquad (6)$$

The constant ε_1 in Hz 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).

CPS1 measures control performance by comparing how well a control area's ACE performs in conjunction with the frequency error of the entire interconnection. Criterion (7) can be viewed as a correlation between ACE and Δf. Positive correlation means undesired performance (the area control error contributes to the frequency deviation from the desired value) and is therefore limited by the upper bound ε_1^2. Negative correlation occurs when ACE helps to compensate the total ACE of the interconnection and is helping to offset the system frequency deviation.

CPS2 is a statistical measure of ACE magnitude designed to bound ACE ten-minute averages and provides an oversight function to limit excessive unscheduled power flows that could result from large ACE:

$$\begin{aligned}\mathrm{AVG}_{10\_\mathrm{minute}}(ACE_{area}) &\le 1.65\varepsilon_{10}\sqrt{K_{area}K_{interconnection}} \\ &= L_{10}\end{aligned} \ , \qquad (7)$$

where $K_{interconnection}$ is the sum of K-factors in the entire interconnection and ε_{10} is the targeted RMS of ten-minute average frequency error. Each Balancing Authority shall operate such that its average ACE for at least 90% of clock ten-minute periods (6 non-overlapping periods per hour) during a calendar month is within a specific limit, referred to as L_{10}. which is a statistically derived ten-minute average ACE limit. Analysis and further discussion on CPS1 and CPS2 can be found in [5, 6, 7].

The purpose of the Disturbance Control Standard (DCS) is to ensure the Balancing Authority is able to utilize its contingency reserve to balance resources and demand and return interconnection frequency within defined limits following a reportable disturbance. The application of DCS is limited to the loss of supply and does not apply to the loss of load. A disturbance is defined as any event that is ≥80% of the magnitude of the control area's most severe single contingency. A control area is responsible for recovering from a disturbance within 10 minutes by recovering the amount of the disturbance or returning ACE to zero. A disturbance is not reportable if it is greater than the control area's most severe contingency.

Control area must comply with the DCS 100% of the time. Extra reserves must be carried for the quarter following the quarter in which the non-compliance occurs.

Each control area can meet the CPS standards by any means they wish. Some balancing authorities developed AGC logic that allows meeting CPS and DCS standards automatically.

A control area not meeting the CPS is not allowed to sell control services to other parties external to its metered boundaries. This impacts those purchasing control services from this control area. This is a significant penalty given new operating environments.

B. Performance Standards in Europe

Speaking about Europe we focus on the largest European interconnection, the UCTE. According to the UCTE Operation Handbook (OH) [2] the individual ACE_{area} needs to be controlled to zero on a continuous basis in each control area. In addition, frequency deviation should decay to the given setpoint in less than 15 minutes and any power outage should be compensated accordingly. Both large and/or long lasting ACE deviations should be avoided as much as possible. No additional explicit requirement on ACE behavior is explicitly defined. This is because UCTE requires each Balancing Authority to apply well defined characteristics of the primary frequency control loops distributed throughout each area and an area secondary load-frequency controller characteristics are prescribed as well so the method used by generators and TSOs is not arbitrary. The only parameter that can influence meeting the general OH requirements would be the amount of regulation reserve available for primary and secondary control and also the level of tertiary reserves available to restore the capacity of the secondary load-frequency control so it does not operate close to the saturation level set by the reserved capacity. In addition, as the tertiary control doesn't run in automatic mode, the use of tertiary reserve depends on the dispatch rules of the TSO's operator.

The general quality requests are sometimes specified in more rigorous way by individual balancing authorities for their internal use. An example specification is described in the next section. The mean and the standard deviation of ACE is used sometimes for comparing operations of control areas of a single interconnection [3].

C. Performance Indices Adopted by Czech TSO

Performance indices introduced and used by the Czech TSO were designed at the time when Czech Republic was part of the CENTREL control block of the UCTE (CZ,HU,PL,SK). Internally, there were strict requirements every TSO had to follow. In addition to the UCTE's OH, $|ACE_1|$ should be kept below 100MW and $|ACE_{60}|$ below 20MW. These requirements formed the basis for introducing indices for the CZ TSO.

The important principle, which is by the way adopted in setting limit values for CPS1 and CPS2 criteria, is that the grid performance should not deteriorate in time. Calculating individual performance indices on historical data and periods where the grid operation was generally considered to be satisfactory, gives the indices setting which we wouldn't like to exceed in the future. CPS1 and CPS2 set the limit values in relation to the area's K-factor, which distributes the responsibility of balancing authorities throughout the interconnection on fair and well defined basis.

Seven indices describing reliability are defined in [8] and shown in Table I. Indices $rACE_1$ and $rACE_{60}$ are statistical measures of ACE having relation to NERC's CPS2. $rACE_{1t}$ is linked to UCTE requirement on frequency recovery in less than 15 minutes after a forced generation unit outage and thus it is related to NERC's DCS index.

While NERC's CPS2 limit L_{10} gets adapted and may change from year to year and stationary 90% compliance is required over years, CEPS' limits L_1 and L_{60} are constant and compliance required is not stationary and gets adapted according to area's recent performance

TABLE I – CZ Performance Indices

$rACE_1$	%	Probability that the absolute average value of one-minute (clock minute) averages of *ACE* exceeds L_1 = 100 MW over given period.
$rACE_{60}$	%	Probability that the absolute average value of one-hour averages of *ACE* exceeds L_{60} = 20 MW over given period.
$rACE_{1t}$	%	Probability of arriving Events*) over given period.
μ_{ACE_1}	MW	Average value of one-minute averages of *ACE* over given period.
σ_{ACE_1}	MW	Standard deviation of one minute averages of *ACE* over given period.
$\sigma_{ACE_{60}}$	MW	Standard deviation of one hour averages of *ACE* over given period.
E_{Event}	MWh	Summed energy (absolute value) of all Events recorded over given period.

*) The Event shown in Figure 1 is defined as ACE_1 exceeding L_1 for at least 10 consecutive minutes. Errors exceeding L_1 lasting for less than 10 minutes are not counted. Event energy is calculated from ACE_1 time series.

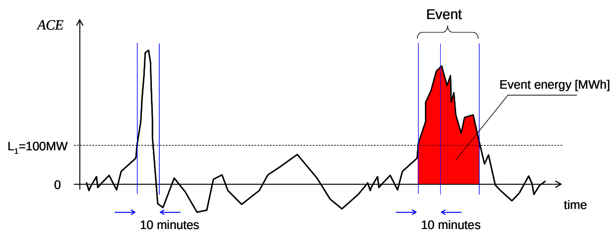

Figure 1. Event identification.

The limit values for CEPS' performance standards (Table II) are determined statistically from historical records of *ACE*.

TABLE II –Settings from recent ACE evaluation approved by the TSO

Performance index	Limit value
$rACE_1$	3.8 %
$rACE_{60}$	2.2 %
$rACE_{1t}$	0.053%

Let's define CZ performance standards in the way reminding NERC's CPS and DCS standards.

CPS_{CZ1} is designed to bound ACE one-minute averages and provides an oversight function to limit excessive unscheduled power flows that could result from large ACE:

$$\mathrm{AVG}_{1\_\mathrm{minute}}(ACE_{area}) \le \mathrm{L}_1 = 100\mathrm{MW} \quad (8)$$

Czech TSO shall operate such that its average ACE for at least (100-$rACE_1$)% of clock one-minute periods (60 non-overlapping periods per hour) during a calendar year is within a specific limit, referred to as L_1.

CPS_{CZ2} is bounds sixty-minute averages of ACE and provides an oversight function to limit excessive unscheduled power flows that could result from large and/or longer lasting ACE:

$$\mathrm{AVG}_{60\_\mathrm{minute}}(ACE_{area}) \le \mathrm{L}_{60} = 20\mathrm{MW} \quad (9)$$

Czech TSO shall operate such that its average ACE for at least (100-$rACE_{60}$)% of clock one-minute periods (60 non-overlapping periods per hour) during a calendar year is within a specific limit, referred to as L_{60}.

DCS_{CZ} ensures that the TSO is able to utilize its contingency reserve to balance resources and demand and return ACE within defined limits following a reportable disturbance that is any disturbance resulting in ACE exceeding L_1 limit both for loss of generation as well as loss of load. A control area is responsible for recovering from a disturbance within 15 minutes in at least (100-$rACE_{1t}$)% of fifteen-minute periods (4 non-overlapping periods per hour) during a calendar year by returning ACE below L_1.

While control area must comply with NERC's DCS 100% of the time, the compliance with DCS_{CZ} is weaker. On the other hand larger number of reportable disturbances are taken into account because the L_1 limit is set much lower.

III. Use of Performance Indices and Standards

In order to determine power reserves in the form of AS, which would technically suffice for proper power balance control with acceptable reliability, it is necessary to refer to reliability standards. The principle of using performance indices $rACE_1$ and $rACE_{60}$ for determining total reserves needed to guarantee that the control area will perform according to the standards is shown in Figure 2 illustrating how total minimal volumes of power reserves $RZ^{\pm}_{\Sigma\min} \ge 0$ and

$RZ^{-}_{\Sigma\min} \geq 0$ are determined from the cumulative distribution function of ACE_{OV}, estimated ACE of the uncontrolled area. According to the reliability standards, the absolute value of ACE is allowed to exceed the threshold 100 MW in $rACE_1$ % of cases during the defined period. If this splits symmetrically to positive and negative values, ACE_{OV} higher than 100MW should be compensated by the control reserves except for (100-$rACE_1$/2)% of cases. Hence, we need at least $RZ^{+}_{\Sigma\min} \geq 0$ and $RZ^{-}_{\Sigma\min} \geq 0$ reserves to meet the standards of reliability, the level of which is derived from the control area satisfactory performance in the past provided by Table II. Reserves decrease number of occasions when ACE violates the threshold illustrated in Figure 2 by changing the shape of the probability distribution function of ACE of the uncontrolled area (curve 1) to the one of controlled area (curve 2). Legend attached to point 3 shows how to read the information described by the probability distribution function associated with ACE.

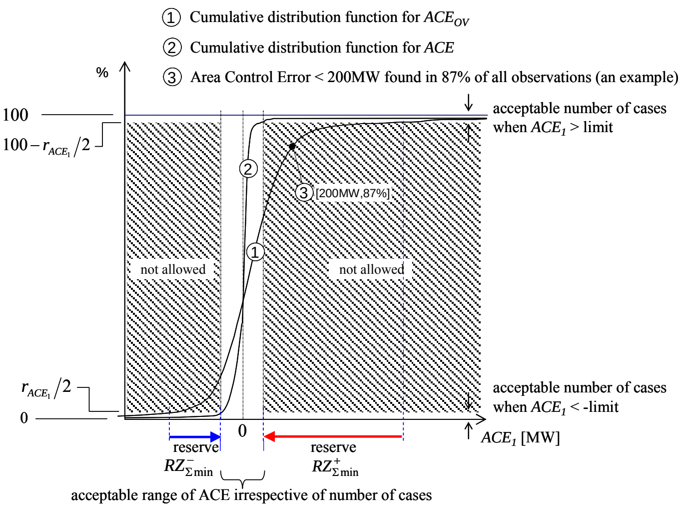

Figure 2. Cumulative distribution function of the open-loop ACE and its use.

The secondary reserve $RZSR_{\min}$ should compensate for the fast variations of the open-loop ACE and the tertiary reserves $RZTR^{+}_{\min}$, $RZTR^{-}_{\min}$ compensate for the slow ACE variations. The minimal needs of these services are determined similarly to the total needs but with utilizing cumulative distribution functions of ACE_{OV_slow} and ACE_{OV_fast}.

The values of the minimal AS requirements are in the form of time series, which reflects the fact that the behavior of ACE also varies; typically, it is more uncertain in “transitions periods” with changeable weather and temperature, such as in spring or fall.

More information on the use of reliability standards in power reserve planning can be found in [4].

IV. Conclusion

NERC’s CPS1 offers a system wide approach which favors behavior leading to better overall system performance while allowing more freedom to individual areas concerning the way how the area’s balancing authority manages its ACE. Keeping ACE as close to zero as possible at all times, as implicitly demanded by the UCTE Operation Handbook, is more restrictive as it does not count for solidarity exceeding the level provided by primary frequency control.

The question what performance standards are better suited for practical needs, those used in North American or European interconnection, is difficult to answer as technical and market conditions differ. There is, however, no much difference in the performance of the interconnection when looking at the RMS value of one-minute average frequency error based on frequency performance over a given year for instance, $\varepsilon_{1UCTE\_2007} = 21\text{mHz}$, $\varepsilon_{10UCTE\_2007} = 17\text{mHz}$, $\varepsilon_{1Eastern\_1998} = 18\text{mHz}$. The Czech performance indices were not originally linked to NERC’s CPS1, CPS2 and DCS standards, however a link between them exists. Thorough investigation is carried out to find limitations of both sets and decide what indices are more relevant to practical needs of the ISO/TSO not only for performance monitoring but also for Ancillary Services planning.

Note that Czech Area compliance with CPS1 for the year 2007 was over 100% having

$$\text{AVG}_{12\_\text{month}}\left[\frac{ACE_{1CZ}}{K_{CZ}}\Delta f_{1UCTE}\right] = 0.00042\text{Hz}^2 < \varepsilon^2_{1UCTE} = 0.00044\text{Hz}^2 \qquad (10)$$

and the minimum compliance with CPS2, where

$$L_{10CZ} = 1.65\varepsilon_{10UCTE}\sqrt{K_{CZ}K_{UCTE}} = 101 \text{ MW} , \qquad (11)$$

was 98.2%, which is much better than the required 90% in DCS. Using (11) for calculating L_{1CZ} and L_{60CZ} provides the following result

$$L_{1CZ} = 122.4 \text{ MW}, L_{60CZ} = 61.4 \text{ MW} . \qquad (12)$$

This result indicates that CENTREL’s limits L_1=100MW and L_{60}=20MW for CZ were rather strict. On the other hand compliance with limits (12) would be required in DCS monthly while compliance with CENTREL limits was required on yearly basis only.

The paper opens the discussion on selection and use of performance standards in large interconnections.

References

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