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Energy correction procedure on cross-border energy exchange using a virtual measuring point

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ABSTRACT

Measurement procedures in cross-border energy exchanges usually neglect the associated measurement uncertainties, which is likely to result in financial damage to one, or both, transmission system operators. In this paper, measurement uncertainty analysis at the measurement point is extensively described and a correction procedure for its systematic contributions is presented. Aiming to develop a fair procedure for the exchanged energy distribution among transmission system operators, the concept of the virtual measuring point is introduced, taking into consideration measurement uncertainties and generated transmission losses. After performing the correction procedure, the virtual measuring point is converted into the corrected virtual measuring point, whose energy measurement is used for the final billing procedure. The presented method was tested in a practical example with data from a Croatian transmission system operator Ltd. and it was confirmed that the correction procedure can be of great interest for transmission system operators.

1. Introduction

Development of modern transmission systems in a competitive market environment requires fully committed transmission system operators (TSO). The compromises between the technical and economic requirements should be considered while maximizing the fulfilment of both. One of the major components providing system integrity are cross-border transmission lines that connect TSOs and enable interconnecting power flows. In order to satisfy strict technical and economic requirements, metering points of superior quality are of key interest considering the entire measurement process, from primary measurements to the accounting of exchanged energy. It is clear that measurement results are influenced by numerous factors related to the measurement equipment, measurement model, and measurement conditions up to the operator. All the known and unknown effects should be considered and quantified. It is also clear that the measurement results are useless without strictly quantifying how far they are from the actual value of the measurands [1]. The complete measurement results, expressed in accordance with internationally recommended guidelines, consist of the measured value and a reasonably associated measurement uncertainty that represents a lack of the knowledge about the measurand [1–3]. In the cross-border energy exchange process, the measurement results and the associated uncertainty have a final financial effect through the energy billed, so ensuring their quality is of common interest. Due to lack of international recommendations related to cross-border energy exchange, the previous statement is usually overlooked in practice [4]. The reference value for energy accounting are values measured using energy meters, while the measurement uncertainty is neglected. Such measurement results are likely not to be trustworthy, in particular when a great amount of energy is exchanged. Hence, TSOs are interested in revealing the real nature of the present uncertainties and their implementation in the accounting procedure.

One of the greatest issues in the measurement procedure is the propagation of the uncertainties from input quantities $\boldsymbol{X} = (X_1,X_2,...,X_N)^T$, through the mathematical model of the measurement $\boldsymbol{Y} = f(\boldsymbol{X})$ to the output quantities $\boldsymbol{Y} = (Y_1,Y_2,...,Y_N)^T$ [5,6]. Input quantities are represented using their possible values $\boldsymbol{\xi} = (\xi_1,\xi_2,...,\xi_N)^T$ and output quantities are represented using $\boldsymbol{\eta} = (\eta_1,\eta_2,...,\eta_N)^T$ [7]. The latter procedure is extensively described in a widely accepted international document called 'Guide to the expression of uncertainty in measurement' (GUM) [3]. Interested readers are advised to find more details about the GUM method in [5,8–13].

In general, measurement uncertainty consists of two components. The first component is an aleatory (random) component that is described using a probability density function and is determined through practical experiments. The second component is an epistemic

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(systematic) contribution that represents the state of the art of the measurement system. Because the latter originates from the known behaviour of the system, it can be compensated for and its mathematical expectation becomes equal to zero. Therefore, the measurement results only have their random component remaining and a probabilistic approach can be applied [14].

The GUM method implies a pure probabilistic approach for measurement uncertainty estimation and assumes that 'the result of a measurement has been corrected for all recognized significant systematic effects and that every effort has been made to identify such effects'. Additionally, it states: "it is now widely recognized that, when all the known or suspected components of error have been evaluated, and the appropriate corrections have been applied, there still remains an uncertainty about the correctness of the stated result, that is, a doubt about how well the result of a measurement represents the value of the quantity being measured" [3].

Hence, the latter should always be considered the best practice when applying the GUM framework, as well as in the energy correction procedure that is presented below. This paper is aimed at presenting the importance of declaring measurement uncertainty in cross-border energy exchange results, i.e. performing an energy correction procedure.

The proposed energy correction method is presented in Section 2, measurement uncertainty analysis is presented in Section 3, and the numerical calculations and a comparison with the traditional method are presented in Section 4. Finally, Section 5 contains our concluding remarks.

2. Energy correction

TSOs in the European region are joined in a higher level association named 'European network of transmission system operators for electricity (ENTSO-E)' [15]. Energy transits within the association are a result of demands in their own region, circular transits and transits for third parties. Each member, i.e. each TSO, has the right for charging a special fee for compensating for costs arising as a result of energy transits [16,17]. As a matter of fact, this fee is very small, i.e. in the order of a few percent of the exchanged energy. Therefore, the associated fee may become comparable to the measurement uncertainty in the metering point. For this reason, an extensive description of the nature of measurement uncertainties, i.e. uncertainty budget, in cross-border metering points and their involvement in the process of exchanged energy accounting is of common interest. Due to a lack of international regulations, the accounting procedure is left to bilateral agreements between TSOs, which is likely to be inadequate because of political influences and because negotiation skills can lead one party to a favourable position. In order to achieve objectivity, prescribing a theoretical framework for accounting of the exchanged energy and enforcing its application in the whole association is of key interest. In conditions of high energy transits, this becomes not only a technically difficult task, but financially difficult as well [18,19].

The aforementioned systematic errors now come into focus and their correction becomes reasonable, or moreover necessary. Any omission can result in significant financial damage for one party. To avoid this, it is necessary to consider all uncertainty contributions at the metering point and any possibilities for correction of its systematic contributions.

2.1. Energy correction procedure

Energy correction procedure (ECP) implies the development of a mathematical model of the measured energy and its correction for all the aforementioned systematic errors. The measured energy is a function of voltage U, current I, and angle φ_S

$$E = f(U,I,\varphi_S), \tag{1}$$

and the respective mathematical model is

$$E = (U\cdot I\cdot cos\varphi_S)\cdot t. \tag{2}$$

It is worth noting that the aforementioned equations are valid for sinusoidal values. Measured voltage U, current I and secondary angle φ_S between current and voltage should be corrected for systematic errors, as stated in the calibration certificate, where $p_{U\%}$ and $p_{I\%}$ are the percentage errors of the voltage measurement transformers (VMT) and the current measurement transformers (CMT), respectively. δ_U and δ_I are the phase displacements of VMT and CMT, respectively. Thus, the corrected values of voltage U', current I', and angle φ_S' can be obtained as

$$U' = U(1-p_U-p_{VD}), \tag{3}$$

$$I' = I(1-p_I), \tag{4}$$

$$\varphi_S' = \varphi_S-\delta_U-\delta_I, \tag{5}$$

where $p_U = p_{U\%}/100$, $p_I = p_{I\%}/100$, and $p_{VD} = p_{VD\%}/100$, which is the voltage drop in the voltage circuit from the VMT to the energy meter (EM). Eqs. (3)–(5) are valid for each phase.

The mathematical model for correcting three-phase energy measurements is derived by multiplying each component to be corrected by the respective correction factor

$$E_{meas}' = [U_1'I_1'\cos(\varphi_{S1}') + U_2'I_2'\cos(\varphi_{S2}') + U_3'I_3'\cos(\varphi_{S3}')]t-p_{EM\%}E_{meas}, \tag{6}$$

where $p_{EM\%}$ is the percentage error of the energy measured by the EM. The correction procedure is performed on the root mean square (RMS) values. Similar approaches can be found for the measurements of the losses on power transformers and reactors [20].

From (3)–(6) follows the complete equation for the corrected three-phase energy

$$\begin{aligned} E_{meas}' = {} & [U_1(1-p_{U1}-p_{VD1})I_1(1-p_{I1})\cos(\varphi_{S1}-\delta_{U1}-\delta_{I1}) + U_2(1-p_{U2} \\ & -p_{VD2})I_2(1-p_{I2})\cos(\varphi_{S2}-\delta_{U2}-\delta_{I2}) + U_3(1-p_{U3}-p_{VD3})I_3(1 \\ & -p_{I3})\cos(\varphi_{S3}-\delta_{U3}-\delta_{I3})]t-p_{EM\%}E_{meas}. \end{aligned} \tag{7}$$

2.2. Proposed procedure for distributing the corrected energy among TSOs

Valid measurement points in cross-border energy exchanges would be at the physical border of the TSOs. Because the physical border is usually hardly accessible, e.g. when the border is above a river or other natural barriers, virtual measuring points (VMPs) are defined and placed at the actual border of the TSOs and are therefore used for measuring energy and transmission losses (TL). Their virtual measurement results are calculated by reducing measurement results at points A and B on the border of the TSOs (see Fig. 1).

The total length of the transmission line L is divided into length l_A, which belongs to TSO A, and length l_B, which belongs to TSO B, so that

$$L = l_A + l_B. \tag{8}$$

It follows that the VMP is located at a distance l_A from TSO A and a distance l_B from TSO B, and TL are divided accordingly. In the first step, the uncorrected TL E_G are calculated as the difference of the measured energy values on both sides (E_{measA} and E_{measB})

$$E_{TL} = E_{measA}-E_{measB}, \tag{9}$$

considering measurement uncertainties u_{measA} and u_{measB}, which determine the measurement uncertainty u_{TL} of the TL. The complete measurement result of TL is

$$E_{TLTOT} = E_{TL} \pm u_{TL}, \tag{10}$$

The calculated TL are shared proportionally among the TSOs. TL associated to TSO A are

$$E_{TLA} = \frac{l_A}{L}E_{TL}, \tag{11}$$