Comparison of EAF dip test short circuit impedance measurement with impedance computation

The conventional method of determining the short circuit impedances of electric arc furnaces, which are characteristic design quantities, is by dip tests where electrodes are dipped into the molten steel and appropriate measurements taken. This technique has a number of limitations and inaccuracies, so BSE has developed an off-line computational method that is both more accurate, more flexible, and does not disrupt steel production.

Author: Dirk Riedinger
Badische Stahl Engineering GmbH

SHORT CIRCUIT TEST (DIP TEST) MEASUREMENT

The short circuit impedances of an electric arc furnace (EAF) determine the electrical behaviour of the furnace. Their knowledge is important for power input computations. Typically they are estimated and then measured at furnace commissioning or when the high current system is modified, eg, when conventional bus tube arms are exchanged with conductive arms.

Due to their importance the measurement of the short circuit impedances is standardised in IEC 60676. The impedances are determined under approximately sinusoidal conditions from the measured root mean square (RMS) voltages, currents and active powers. They can then be treated as complex quantities Z with a resistive (R, real part) and a reactive (X, imaginary part) component, where:

$\underline{Z} = R + j\,X,\ X = \omega L,$
where ω = angular frequency, L = Inductance

For EAFs, the resistive component is typically up to 10 times smaller than the reactive component. Thus the reactance has the main influence on the electrical behaviour of an EAF; it also varies during furnace operation. Typical average values of the reactance are in the range of 2-4mOhm.

How to connect and evaluate the measurement and how to calculate one impedance value per phase from the measured loop impedances is defined as follows:

- The measurement has to be done with three consecutive one-phase short circuit tests. The phase-phase voltages are measured and three loop impedances determined.
- The measurement is done on the primary side (high voltage side).
- The furnace transformer is idealised as a very good approximation and considered by its symmetric short circuit impedance, short circuit losses, winding ratios and vector group.
- A series reactor is considered by its series impedance and tap.

One-phase short circuit means that only one electrical circuit of the three phase system is active, ie, one electrode is current-less. The other two are dipped into the liquid steel bath with supply voltage on, and so carry equal currents. The current-less electrode must only be raised as far as to ensure no current as higher positions would change the inductive coupling of the three phases too much (compared to the desired standard configuration with levelled arms).

GENERAL PROBLEMS OF MEASUREMENT

In general the result of measurements is influenced by the following factors:

A. Experience shows that there are usually some geometrical uncertainties during measurements. The arm positions and electrode lengths are not accurately known and three independent consecutive one-phase dip tests have to be conducted with electrodes 1+2, 2+3 and 3+1. As a result, the desired standard configuration with all arms in an equal position cannot be ensured and the three loop impedances determined do not belong to the one single configuration as is desired.

B. Sometimes the electrodes are not deep enough in the steel, so the short circuit is insufficient and the determined impedances are corrupted.

C. A short circuit test always interrupts the production process and requires suitable measurement equipment and pre-preparations so as to do it properly. Also the electrodes are affected by the dipping into the steel and it is possible for the carbon level of the steel to rise if the electrodes are dipped too long (usually 10 seconds is enough).

D. For furnace transformers with high secondary voltages on the lowest tap the short circuit currents can become too ▷

One-phase measurement connection	Internal delta closure	External delta closure
Primary side	**Case 1** Three loop impedances are determined that can be transformed into the three phase impedances $\underline{Z}_1$, $\underline{Z}_2$, $\underline{Z}_3$ of the EAF. The internal delta belongs to the transformer and its effect is negligible. Bus tube impedances between transformer and high current cables are included.	**Case 2** Three loop impedances are determined that can be transformed into three total phase impedances $\underline{Z}_{1t}$, $\underline{Z}_{2t}$, $\underline{Z}_{3t}$ of the EAF. Delta impedances are included. Delta and phase impedances cannot be determined separately by the measurement.
Secondary side	**Case 3** The measurement determines the phase impedances $\underline{Z}_1$, $\underline{Z}_2$, $\underline{Z}_3$. a) The connection between transformer and cables is not included in the impedances if the voltages are measured at the points 1s, 2s, 3s. b) The connection between transformer and cables is included in the impedances if the voltages are measured at the points 2U, 2V, 2W.	**Case 4** The measurement determines the phase impedances $\underline{Z}_1$, $\underline{Z}_2$, $\underline{Z}_3$ if voltages are measured at the points 1s, 2s, 3s. The delta closure impedances between transformer and cables are not included. A measurement at the points 2U1-2U2, 2V1-2V2, 2W1-2W2 inside the delta does not deter mine correct impedances and is not meaningful.

Table 1 Overview of the peculiarities of the dip test configurations

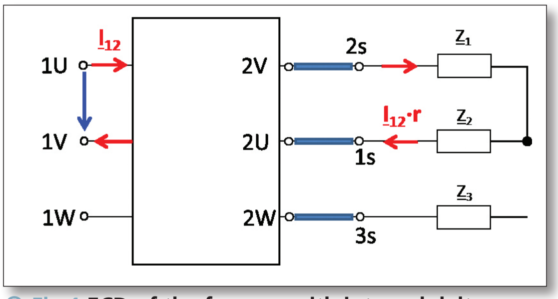

Fig 1 ECD of the furnace with internal delta closure. Phases 1 and 2 active

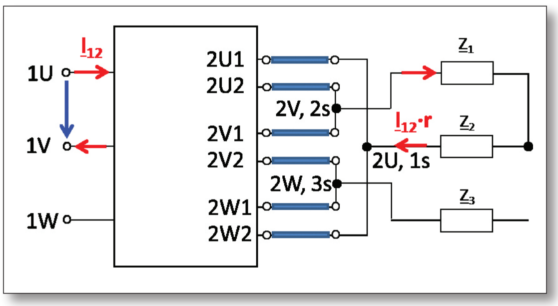

Fig 2 ECD of the furnace with external delta closure. Phases 1 and 2 active

high. In this case the test has to be avoided in order not to trip or endanger the electrical equipment.

Points A) to D) illustrate that the measurement is not trivial and deviations are dominated by unknown electrode lengths and arm positions (compared to the desired standard configuration with equal electrodes and arm positions).

EQUIVALENT CIRCUITS OF THE EAF IN SHORT CIRCUIT CONDITION

The equivalent circuits (ECD) are depicted in *Figures 1* and *2*. The transformer tubes/bars are the blue lines between transformer terminals and cable connections 1s, 2s, 3s. Arc furnace transformers are built typically with primary and secondary side windings connected in delta to have lower currents inside the transformer. Two different transformer designs exist: the internal and the external secondary delta closure. The transformer design has influence on the furnace impedances (*see Table 1*). The transformer terminals are designated U, V, W.

Figure 3 depicts the resulting impedances that are determined by the evaluation of the measurement.

ANALYSIS OF THE DIP TEST CONFIGURATIONS

Table 1 summarises what impedances are determined depending on the configuration of the system.

EXAMPLES OF DIP TEST MEASUREMENTS

A good result in terms of correct impedances can only be expected if two electrodes are simultaneously dipped solidly into the steel bath and if the third electrode is current-less but in a proper position. *Figures 4 and 5* depict one bad and one very good dip test as examples. The bad dip test shows much too high active power (red/orange lines). This indicates arcing is occurring between electrodes and metal or slag, ie, not properly dipped in the steel. It is thus not useful for impedance evaluation. The blue lines show current.

COMPUTATION OF IMPEDANCES

Computation of the short circuit impedances of the high current system according to the ECD depicted in *Figures 1 and 2* is possible by applying appropriate simulation methods that reflect reality. More detail is given in the references [1-3]. The computation results are more accurate than those of the measurements if the geometrical model is realistic enough and can be achieved applying the Finite Network Method (FNM) developed by BSE based on the method created by Prof. A. Farschtschi [1]. Computation and measurement results will be compared with the following example.

EAF no.1 of Badische Stahlwerke GmbH (BSW) has a high current system with external delta closure (*see Figure 6*). This system has been computed applying the FNM simulation. The colours depict the computed current density distribution in A/mm^2 as shown on the right hand scale.

The FNM simulation allows a very accurate impedance computation because all current displacement effects that appear in the high current system are considered (eddy currents, skin and proximity effects). As can be seen in *Figure 6*, the current density distribution is very inhomogeneous along the high current system, and this affects the impedances significantly. FNM is the only system to date that allows realistic simulations of high current systems. Technically speaking, FNM generally solves the very difficult to handle eddy current problem.

The computed six individual impedance elements are:

Phases:

$\underline{Z}_1$ = 0.317 +j 2.48 mOhm
$\underline{Z}_2$ = 0.303 +j 1.84 mOhm
$\underline{Z}_3$ = 0.314 +j 2.42 mOhm

External delta closure:

$\underline{Z}_a$ = 0.111 +j 0.626 mOhm
$\underline{Z}_b$ = 0.109 +j 0.654 mOhm
$\underline{Z}_c$ = 0.077 +j 0.384 mOhm

The delta impedances can be transformed into star impedances which can only then be added to the phase impedances.

Then the transformed total phase impedance elements $Z_{\mu t}$ according to *Figure 3* result in:

$\underline{Z}_{1t}$ = 0.346 +j 2.62 mOhm
$\underline{Z}_{2t}$ = 0.344 +j 2.09 mOhm   Ux = 21.8 %
$\underline{Z}_{1t}$ = 0.342 +j 2.57 mOhm
$\underline{Z}_{avt}$ = 0.344 +j 2.43 mOhm

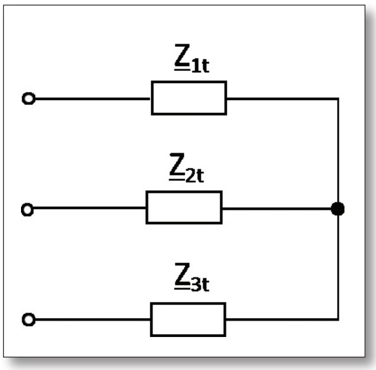

Fig 3 System impedances determined by the dip test

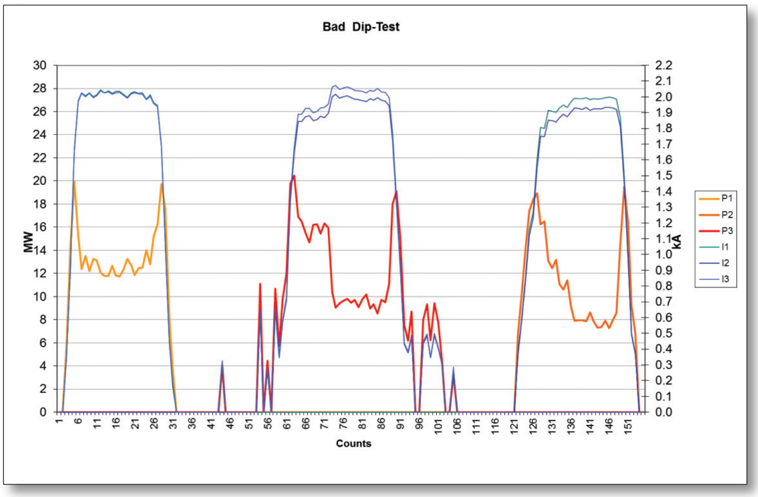

Fig 4 Bad result of dip test: active powers Pμ too high

The phase asymmetry Ux is determined according to IEC 60676.

The computed impedances will now be compared to a primary side short circuit test (dip test) that has been carried out at BSW's EAF 1 applying IEC 60676.

The transformer was set to the lowest voltage tap of 615V and the serial reactor was set to 100% (0.9Ohm). Electrodes were adjusted for equal lengths below the holders and the three one-phase short circuits resulted in full short circuit currents. The power factor during the measurement was less than 0.09. Transformer and reactor impedance are excluded.

The resulting measured impedances according to *Figure 3* are:

$\underline{Z}_1$ = 0.32 +j 2.82 mOhm
$\underline{Z}_2$ = 0.22 +j 2.31 mOhm   Ux = 19.3 %
$\underline{Z}_3$ = 0.35 +j 2.77 mOhm
$\underline{Z}_{av}$ = 0.30 +j 2.63 mOhm

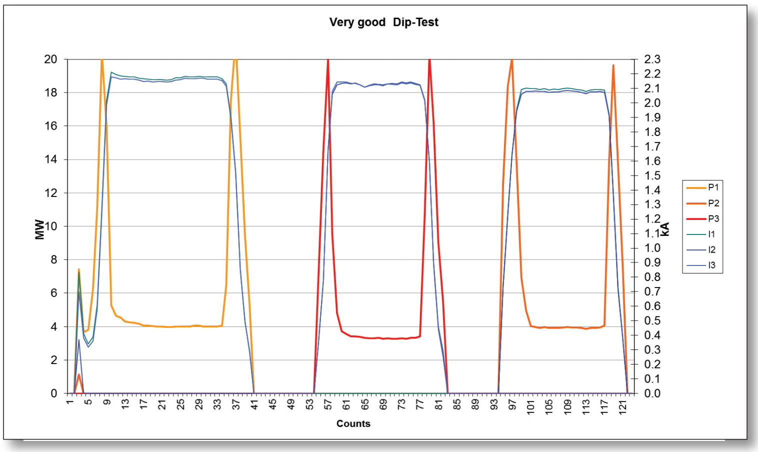

Fig 5 **Very good result of dip test: low active powers Pμ**

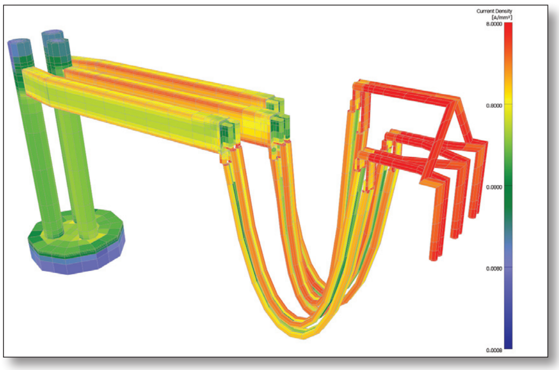

Fig 6 **High current system of EAF 1 with computed current density distribution during short circuit. Phase 1 is in front**

COMPARISON

There is a fundamental difference between measurement and computation. The computation simulates a three-phase dip test with all phases under current. During real dip tests one phase is always current-less, and eddy currents are induced into it by the other two phases. This procedure is not optimal for impedance determination but is the only possible correct way of measurement. A three-phase dip test measurement does not provide meaningful impedances per phase, whether measured on the primary or secondary side.

The difference in reactance between computation and measurement is 0.2mOhm on phases 1 and 3 and 0.22mOhm on phase 2. Thus the reactance asymmetry Ux is a little different. The deviations are explainable by the one-phase measurement procedure and by unknown real electrode lengths. The computation assumes an average electrode length. It is possible that the real electrodes were a little longer, in the range of one electrode diameter, which is the uncertainty of length adjustment. In conclusion, however, the comparison indicates good agreement between measurement and computation.

Generally, there is not only one short circuit impedance of a high current system. Impedances depend on the system geometry and this varies during furnace operation. A short circuit test, no matter if properly measured or computed, always provides the impedances of that specific system configuration. This configuration is not well known for the measurement but exactly given for the computation.

CONCLUSIONS

- It has been shown that carrying out a proper dip test according to IEC 60676 is not a trivial exercise and that the result depends on some uncertainties of the dip test itself and EAF design.
- With the FNM system developed by BSE, a dip test measurement is no longer required and the computation results are more accurate than measurement.
- The computation also provides more information than a measurement, for instance different arm positions and electrode lengths can be computed, and the reactance variation compared. Thus the variation range can be determined whereas a measurement just provides one single configuration.
- Additionally, the impedances of the external delta can be computed separately, enabling a tailored accurate design of the external delta to be ascertained for the first time. This is important because the delta can be used to mitigate asymmetry of the furnace high current system (cables to electrodes).
- The FNM simulation works very efficiently with computation time for a model being only about 30-40 minutes. This allows rapid comparison of many scenarios at the desktop. MS

Dirk Riedinger is Senior Consultant at Badische Stahl Engineering GmbH, Kehl, Germany.

CONTACT: dirk.riedinger@bse-kehl.de

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