XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

INFLUENCE OF THE HARMONIC DISTORTION ON SHORT-CIRCUIT TEST POWER FACTOR MEASUREMENT

G. Crotti, G. Farina, L. Rege
Istituto Elettrotecnico Nazionale Galileo Ferraris
Torino – Italy

Abstract: The thermal and mechanical stresses resulting from a short-circuit fault in an electric circuit strongly depend on the circuit power factor. For this reason, the IEC standard related to short-circuit test indicates, for each current range, the value of the power factor with a defined tolerance. A method for the measurement of the power factor based on the analysis of the digitally recorded short-circuit current is briefly described. The method is checked by applying it to the evaluation of the power factor measurement value and uncertainty in simulated test conditions. Attention is focused on the harmonic distortion of the supply voltage: the obtained results show that the method can be applied also in this case, but with a decrease of the measurement accuracy, which depends both on the amplitude of the distortion and the value of the power factor.
Keywords: power factor, short-circuit.

1 INTRODUCTION

When a short-circuit fault occurs, strong thermal and mechanical stresses affect both the electric circuit and its protection device. These stresses strongly depend on the circuit characteristics such as supply voltage, circuit impedance and power factor (cos φ). The power factor can be defined as the ratio between the active and the apparent power in steady state conditions and is determined by the resistive and reactive components of the circuit impedance. Since its value heavy influences the severity of the short-circuit event, the behaviour of the electrical apparatus and their protection devices has to be verified under short-circuit conditions with defined prospective power factors, which are stated as a function of the test current by IEC 947-1 Standard “Low Voltage Switchgear and Controlgear” [1]. As regards the power factor measurement uncertainty, since an asymmetrical tolerance range (from –0.5 to 0) is indicated for the value of the circuit power factor, the test laboratory should be able to measure it with an uncertainty reasonably lower than the indicated range.

The power factor of the test circuit cannot be obtained by direct measurement of the circuit resistive and reactive load because of the presence of the supply equipment, transformer or generator, which can constitute an important part of the total circuit impedance, particularly in the case of high prospective currents. Different measurement methods are suggested by IEC 947-1 and can be adopted by the test laboratories, but none of them seems to be completely satisfactory as discussed in [2].

Taking into account that generally the short-circuit test laboratories are equipped with digital acquisition and processing systems, an evaluation method suitable to be introduced in a computer procedure could be very useful. To this end, a method for the determination of the power factor measurement value and uncertainty based on the analysis of the digitally recorded short-circuit prospective current has been developed [2]. In the following, after a brief description of the method, its applicability to actual circuit conditions, including harmonic distortion of the supply voltage and noise, is investigated.

2 DETERMINATION OF SHORT-CIRCUIT POWER FACTOR BY EVALUATION OF CURRENT ZERO CROSSINGS

As an alternative to other approaches [1,3-5] the power factor of the test circuit can be evaluated by the analysis of the only short-circuit current behaviour, which is expressed by the relationship [2]:

$$i(t) = \sqrt{2} I_{rms} \left[sin(\omega t + \psi - \varphi) - sin(\psi - \varphi) \cdot e^{-\frac{t}{\tau}} \right] \quad (1)$$

where I_{rms} is the root mean square value of the steady state prospective current, *w* the angular frequency, *j* the phase angle, linked to the circuit time constant *t* by the relationship *t*=tan*j*/*w*, and *y* the making angle, that is the phase delay between the beginning of the current and the zero of the supply voltage.

The power factor can be easily evaluated if the circuit time constant τ is known. To this end, being t_a and t_b the first two zero crossings of the short-circuit current shown in Fig. 1, the following expression can be obtained from (1):

$$\tan(y - j) = \frac{sin(wt_a)}{e^{-\frac{t_a}{t}} - \cos(wt_a)} = \frac{sin(wt_b)}{e^{-\frac{t_b}{t}} - \cos(wt_b)} \quad (2)$$

where τ is the only unknown.

Once t_a and t_b are evaluated from the recorded current behaviour, τ can be numerically computed and the power factor is obtained according to the expression:

$$\cos j = \frac{1}{\sqrt{1 + w^2 t^2}} \quad (3)$$

3 TEST OF THE METHOD

The method has been tested by simulating the behaviour of short-circuit currents with different imposed power factors and making angles. Since the method has to be implemented in a digital acquisition and analysing procedure, the tests have been performed by considering sampling frequency, bit resolution and noise of the digital converter. By fitting to a straight line $i = m \cdot t + q$ the n sampled current values i_n before and after the zero crossings, the current start instant t_o and the zero-crossing t_1 and t_2 (Fig. 1) have been obtained according to the expression:

$$t_k = -\frac{q_k}{m_k} \qquad \text{with } k=0,1,2 \quad (4)$$

As regards the power factor measurement uncertainty $u_{\cos j}$, it has been estimated from (3) as a function of the standard measurement uncertainties u_t and u_w of τ and ω respectively. Since $\tau=\tau(t_o,t_1,t_2)$, the standard uncertainty of each t_k has been obtained from (4) by applying the law of propagation of errors, estimating the uncertainty of m_k and q_k as a function of the standard uncertainty u_{kn} of the n current samples involved in the fitting [6]. The u_{kn} have been determined taking into account the uncertainty components due to each element of the current measurement chain, which usually includes a current transducer, the amplifier, the A/D converter and the software for data acquisition and analysis.

Fig. 2 shows the deviation between the computed and the prospective power factor and the related expanded uncertainty as a function of the prospective one.

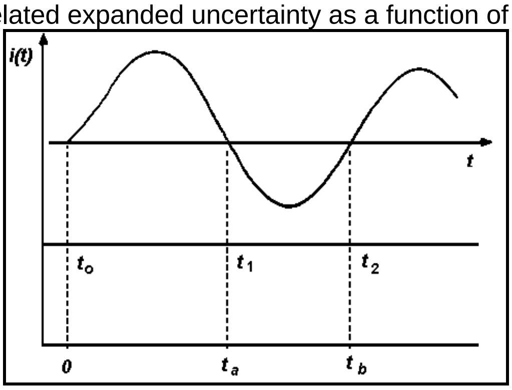


Fig.1. Short-cirquit behaviour;
t_a and t_b: zero crossing instants.

Fig. 2. Deviation between computed and prospective power factor.

The reported data refer to tests carried out applying the method to simulated behaviours of short-circuit currents acquired with an A/D converter with sampling frequency of 50 kHz and 12 bit resolution. The presence of the A/D converter noise, which may significantly affect the current values around the zero crossing, has been simulated by adding to the current values in the proximity of the zero crossings a quantized random noise of maximum amplitude equal to three bits.

The comparison between the results obtained with two different making angles (—■— ψ=0°, —●— ψ=90°) shows how the deviation between the imposed and the computed cosφ is always lower than 0.002 but, as expected, the measurement uncertainty highly increases when the current tends to become symmetrical ($t_a \cong t_b$). However, since usually the test making angle can be set with satisfactory resolution, if the tests are carried out with suitable making angles, such as ψ ≅ 0° for power factors lower than 0.6 and ψ ≅ 90° for the higher values, the power factor measurement uncertainty is about one order of magnitude lower than the tolerance range indicated by the standards.

4 APPLICATION TO TEST CIRCUIT WITH HARMONIC DISTORTION OF THE SUPPLY VOLTAGE

The described method can be conveniently applied to the evaluation of the measurement value and uncertainty of the test circuit power factor, provided that the characterisation of the current measurement chain has been performed. However, in several situations the voltage which supplies the test circuit can be affected by a significant harmonic content which leads to a not negligible distortion of the short-circuit current.

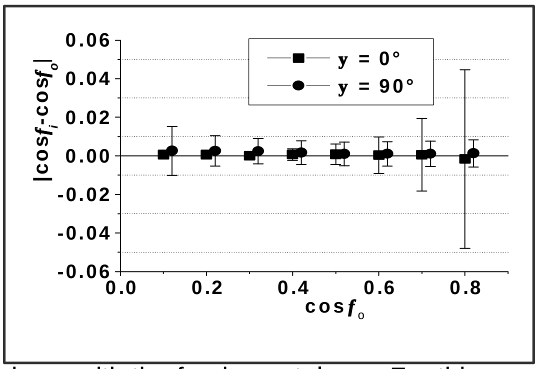
The value of the prospective power factor is expressed by the ratio between the active and apparent power according to the expression:

$$\cos j_o = \frac{\sum_m V_m I_m \cos j_m}{\sqrt{\sum_m V_m^2 \sum_m I_m^2}} \tag{5}$$

where V_m, I_m are the m-order harmonic of the voltage and current respectively and $\cos j_m$ is the related power factor.

In order to verify if the method can be still used and which accuracy can be achieved, short-circuit current behaviours have been simulated by considering the presence of harmonic components of the supply voltage of increasing order and amplitude. The power factor has been then computed by the method above described and compared with the prospective one.

As an example, the absolute deviations between the circuit power factor and that obtained by zero crossing evaluation when the voltage is affected by the presence of 5th and 7th order harmonics is shown in Fig. 3, in the case of ψ=0, for increasing amplitude of the supply voltage harmonic content, supposing all the harmonics in phase with the fundamental one. For this specific case the maximum deviation from the prospective and computed power factor was 0.007.



As expected, the presence of a not negligible harmonic distortion leads to a deviation between the computed ($\cos j_i$) and prospective ($\cos j_o$) power factor. The value of this deviation depends both on the making angle and on the amplitude and phase of each harmonic component, which can vary with time and whose behaviour is not known a priori. On the basis of these considerations, the approach described in the following has been adopted to verify the feasibility of the method.

First, a defined harmonic distortion (order and amplitude of the harmonic components) representative of that affecting the supply voltage of the involved test circuit has been identified. Then, for each considered prospective power factor, the mean value d_m of the deviation $d_i = \cos\varphi_i - \cos\varphi_o$, its experimental standard deviation s_{dm} and the experimental standard deviation $s_{\cos\varphi i}$ of $\cos\varphi_i$ have been evaluated taking into account a defined range of variation of the making angle and the different phase combinations between the harmonics. The standard uncertainty of each $\cos\varphi_i$ has been obtained by quadratically summing the measurement uncertainty of $\cos\varphi_i$, evaluated as described in §3, and its experimental standard deviation $s_{\cos\varphi i}$.

Table I shows the results obtained considering the case of a circuit supplied by a voltage with 4% and 1% of the 5th and 7th harmonic respectively. For each power factor, a limited range of variation of the making angle has been considered, taking into account the considerations developed in the previous paragraph. The values of d_m, s_{dm} and $s_{\cos\varphi i}$ have been then computed by varying, besides the making angle, the phase of each considered harmonic with respect to the fundamental in the range from 0° to 360°, with step of 10°. For each test condition, the simulation has been repeated ten times because of the random noise.

The experimental standard deviation s_{dm} of d_m has resulted always much lower than d_m and its value is not reported in table I. As can be seen, with the exception of $\cos\varphi_o$=0.05, the absolute value of the mean deviation d_m is always a few parts in 10^{-3} of the related power factor and can be considered negligible if compared to the standard uncertainty associated to each $\cos\varphi_i$. The expanded uncertainty $U_{\cos\varphi i}$ has been evaluated, taking into account the effective degrees of freedom of $\cos\varphi_i$, assuming a coverage factor k_p=1.96 [7].

Table I – Test of the method with harmonic distortion of the supply voltage

Prospective power factor $\cos\varphi_o$	Range of making angle Ψ	Mean deviation $\lvert d_m \rvert$	Standard uncertainty $u_{\cos\varphi i}$	Expanded uncertainty $U_{\cos\varphi i}$
0.050 0.100	0÷20 0÷20	0.0007 0.0006	0.0017 0.0015	0.003 0.003
0.150 0.200	0÷20 0÷20	0.0005 0.0005	0.0027 0.0034	0.005 0.007
0.250 0.300	0÷20 0÷20	0.0004 0.0004	0.0046 0.0050	0.009 0.010
0.350 0.400	0÷20 0÷20	0.0004 0.0004	0.0056 0.0058	0.011 0.011
0.450 0.500	0÷20 0÷20	0.0004 0.0004	0.0058 0.0059	0.011 0.012
0.550 0.600	90÷110 90÷110	0.0004 0.0004	0.0071 0.0071	0.014 0.015
0.650 0.700	90÷110 90÷110	0.0011 0.0011	0.0085 0.0084	0.017 0.017
0.750 0.800	90÷110 90÷110	0.0008 0.0007	0.0066 0.0063	0.013 0.012

5 DISCUSSION OF RESULTS

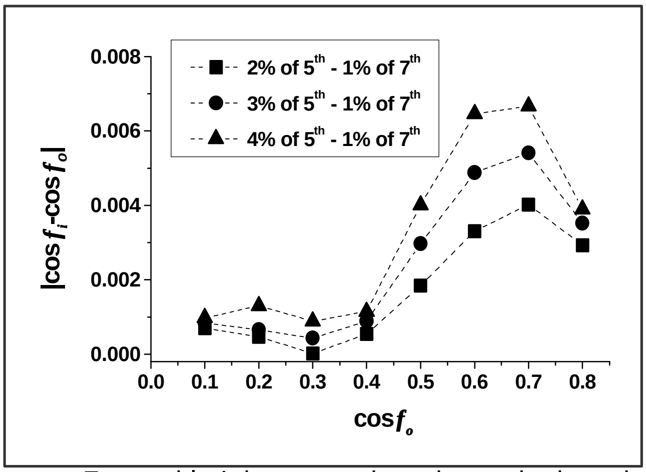


Fig. 3. Deviation between computed ($\cos\varphi_i$) and prospective ($\cos\varphi_o$) power factor with different harmonic content of the supply voltage.

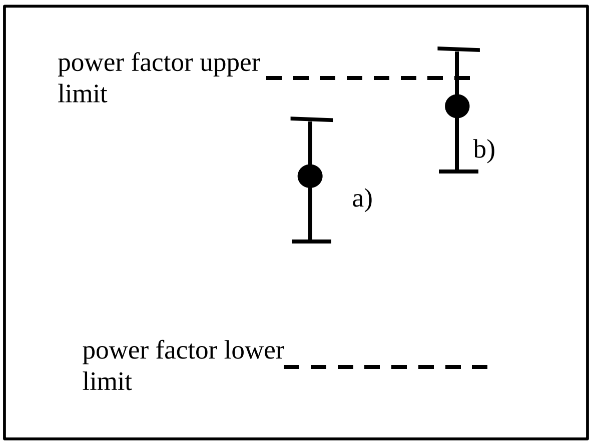


Fig. 4. Power factor tolerance range: a) measurement value and uncertainty within the specification limits; b) measurement value within, but uncertainty outside one limit.

From table I, it appears how the method can be conveniently applied in the case of low values of power factors, provided that the making angle is included in the suitable range. However with higher power factors there is a significant increase of the expanded uncertainty, which for $\cos\varphi$ equal to 0.7 is about one third of the tolerance range associated to it. In this case, if it is required that both the measurement value and the expanded uncertainty lie within the lower and upper limits specified by the standard, as shown in Fig. 4a, the range of measurement values that can be accepted is significantly reduced. A very fine resolution is then required to the laboratory in order to set the circuit power factor to the desired value. On the other hand, it must be remarked that short-circuit tests are carried out in most cases for prospective high currents and, consequently, with low power factors.

Moreover, if the supply voltage is affected by a lower harmonic distortion, the power factor measurement uncertainty significantly decreases. As an example, if a voltage with a 2% and 0.5% of 5^{th} and 7^{th} harmonic respectively is considered, the uncertainty to be associated to $\cos\varphi$ equal to 0.7 reduces from 0.017 to 0.010.

6 CONCLUSION

The method for the measurement of the power factor in short-circuit tests based on the evaluation of the current zero crossing instants has been applied to the analysis of circuits supplied with voltage affected by harmonic distortion. The method permits the evaluation of the power factor measurement value and uncertainty from the analysis of the only current signal, provided that the characteristics of the measuring system and the amplitude of the supply voltage harmonic components are known.

The obtained results have shown that the method is applicable to circuit with relatively high harmonic distortion, with a decrease of the measurement accuracy which depends both on the amplitude of the distortion and on the power factor value.

The described method will be implemented in a digital acquisition and processing system and the results obtained in presence of harmonic distortion will be compared with those given by the other methods usually adopted in short-circuit test laboratories.

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AUTHORS: G. Crotti, G. Farina, L. Rege, Istituto Elettrotecnico Nazionale Galileo Ferraris, Corso Massimo d’Azeglio, 42 - Torino (ITALY). Phone ++39 011 3919 777, Fax ++39 011 6509471,
e-mail: rege@ienelt.ien.it.