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Researches Regarding the Factory Test of Electric High-duty and High voltage Equipment

This paper shows a review of the present methods of testing the high-duty and high voltage electric machines and transformers, to which the authors brought their own contributions concerning their elaboration and exploitation. We have especially presented the methods which make possible the concluding heating tests in factories and the elimination of the eventual errors which can occur at the installation place.

Keywords: AC machines, heating test, simulation

1. Introduction

The heating test in factories is essential in determining the electromagnetic and mechanical solicitations and constructive solutions of all the electric equipment, especially those of high-duty and high voltage. In the paper we present new methods of testing the transformer with three windings of synchronous machines and we will do a detailed study with the use of actual dynamic mathematical model, the features and limits of the Ytterberg testing method of the induction machines.

2. Main results

2.1. A new method for heating test of the high power three windings transformers

The heating test of the transformers is obligatory in order to start the mass production. To make this test possible on limited power try-out stand, the international standards recommend for the two windings transformers a short-circuit regime. Therefore, the necessary test power is drastically diminished approximately with ratio U_{scN}/U_N. This solution could not be applied to three windings transformers.

The following demonstrates the possibility of conclusive testing of the high power three windings transformers when the installed power of the try-out stand is not exceeded.

The three windings of the transformers are designed for equal or different power per winding. In case of different power per winding, the sum of secondary powers is greater than or equal to the primary power ($P_1 \leq P_2 + P_3$). For the transformer with different powers, the windings must be tested simultaneously. Only such a test is conclusive in terms of heating.

This paper demonstrates [2] the possibility of the above-mentioned test using impedances series connected with the secondary windings in order to obtain simultaneously the rated currents in all three windings. Figure 1 shows the transformer equivalent circuit, including the supplementary impedances $\underline{Z}'_{2s}$, $\underline{Z}'_{3s}$.

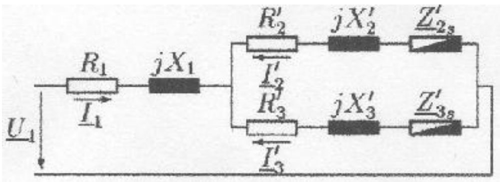


Figure 1. Equivalent circuit of the three windings transformer, including the supplementary impedances.

The parameters of the equivalent circuit are calculated from the short-circuit tests and are given by the following expressions:

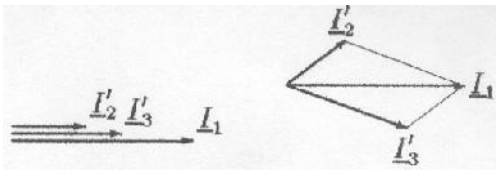
$$X_1 = \frac{X_{sc12} + X_{sc13} - X'_{sc23}}{2}; \quad X'_2 = \frac{X'_{sc23} + X_{sc12} - X_{sc13}}{2}; \quad X'_3 = \frac{X'_{sc23} + X_{sc13} - X_{sc12}}{2}; \quad (1)$$

where: $X'_{2sc} = K_{12}^2 X_{sc23} = K_{13}^2 X_{sc32}$

For resistances, expressions similar with (1) are obtained. The supplementary impedances $\underline{Z}'_{2s}$, $\underline{Z}'_{3s}$ are determined so voltage $\underline{U}_1$ and, consequently, power of the supply source are minimized.

The possibility of connecting in short-circuit one of the secondary winding must be taken into consideration.

If the sum of the apparent secondary power is equal with the apparent power of the primary winding ($P_2 + P_3 = P_1$), the secondary currents result in the same phase (figure 2.a).



a) b)

Figure 2. Secondary currents: a) in the same phase, b) different phase.

Because the reactances usually prevail in the equivalent circuit of the transformer, in practice it is sufficient to connect a supplementary reactance X' with a suitable value to one of the two branches, in order to obtain a simultaneous loading of the secondary windings.

The reactance X' should be placed adequately, to minimize the value of the voltage $\underline{U}_1$. In practice, this reactance is represented by a transformer with the secondary in short-circuit with a corresponding reactance equivalent to the short-circuit.

In general case, when $P_1 \leq P_2 + P_3$, the secondary currents are in different phase (figure 2.b) and supplementary suitable impedances $\underline{Z}'_{2s}$, $\underline{Z}'_{3s}$ must be introduced.

In this paper, the impedances $\underline{Z}'_{2s}$,$=R'_{2s}+jX'_{2s}$, $\underline{Z}'_{3s}$,$=R'_{3s}+jX'_{3s}$, are implemented using synchronous machines which can be easily controlled. The basic electrical system used to load the three windings transformer is shown in figure 3. The reactances X'_{2s}, X'_{3s} are obtained by adjusting the excitation currents of the machines M_1, M_2. The resistances R'_{2s}, R'_{3s} obtain the necessary values actively loading the machines M_1, M_2.

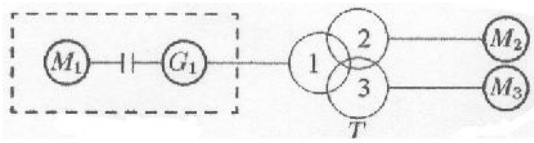


Figure 3. Basic electrical system.

G_1 represents the supply generator which is driven by the motor M_1. M_2 and M_3 represent the synchronous machines which are connected to the secondary windings of the transformer T and operate in the adequate regime to obtain the imposed currents.

The scheme was experimentally verified by testing the 5/3/2 MVA transformer when a reactance X' was determined and the 31, 5/20/20 MVA transformer when M_2 and M_3 synchronous machines were used.

Observations:

The method has the following advantages:

1. The obtainment of a simultaneous rated loading of all three windings and, therefore, a concluding heating test;

2. The necessity of diminished test power for the try-out stand by establishing an operation regime close to short-circuit.

2.2. A particular recovery system of two synchronous machines. A new method for test at rated load for high power synchronous machines

Analysis of single supply back-to-back operation of synchronous machines is of great theoretical and practical interest and there are no detailed references in literature [7] a.o. The paper [4] studies the fundamental aspects of this particular operation.

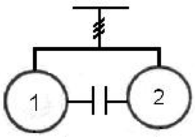
A major contribution of this study is the identification of a recovery method [3] for testing the high power synchronous machines at rated load (U_N, I_N, $\cos\varphi_N$) by a limited power try-out stand. The experimental results are of high interest for design and exploitation areas, such as verification of thermal and electromagnetic strengths.

For full load test of high power synchronous machines, the literature [11], and IEC standards regarding the methods of determining synchronous machine quantities from tests, indicate recoverable solutions, involving, besides the studied machine, a large number of supplementary machines rated to comparable powers. This aspect limits the possibility of using the well-known methods for powers of $1000 \div 2000$ kW. Otherwise, the test stand would have to be fitted out with too large machines, and this does not occur in practice. When the powers exceed the powers available in the stands, artificial tests are performed.

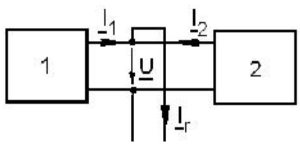
In this paper we consider as high power synchronous machines, those machines whose power is 3-6 (10) times the installed power of try-out stand of the manufacturer plant.

The transient process at the connection of the two machines on the supply mains needs a special investigation. In [5], the case of a "strong" (infinite power) mains is considered; the possibility of synchronous operation is pointed out. In [6] the possibility of connecting the high power machine system to a "weak" (reduced power) mains are validated. On this basis, the proposed recovering method for testing the high power synchronous machines at rated load is legitimated.

The subscripts 1 and 2 denote the two synchronous machines mechanically coupled and parallel connected on the same supply mains (figure 4.a); the forward direction for currents and voltage of the 1, 2 machines corresponds to the source (figure 4.b).



a)



b)

Figure 4. a) Simplified schema of the coupled machines; b) The forward direction for currents and voltage.

The following conclusion outcomes [4]: large changes of the two machines excitation currents lead to a large scale modification of active and reactive load. In a particular case this load can be the rated one. The electrical angle ~ of rotors is essential to establish the second machine load.

Based on the presented method, it is shown the possibility of direct, recoverable loading, at rated load for synchronous machines, rated at powers greater than the installed power of the test stands, without needing special equipment and measures.

In accordance with the method, the tested machine is firmly mechanically coupled with an identical machine or a machine rated at a power which is at least equal; the group of machines is supplied by common supply mains. The required active and reactive loads, particularly to the rated regime, can be established for one machine by adjusting the excitation currents.

Suitable values for the mechanical shift of the rotors ~ must be taken, in order to get admissible values for loadings corresponding to the auxiliary machine and to the supply mains. In the simplified diagram (fig. 5), where the losses are neglected, it is considered that 2 is the machine operating as an over-excited motor, at given values I_2, $\cos\varphi_2$. The internal angle α-θ of the machine 2 is obtained immediately. Further on, it is considered that 1 is the auxiliary machine. It is noticed that this loading can be achieved for different values of α.

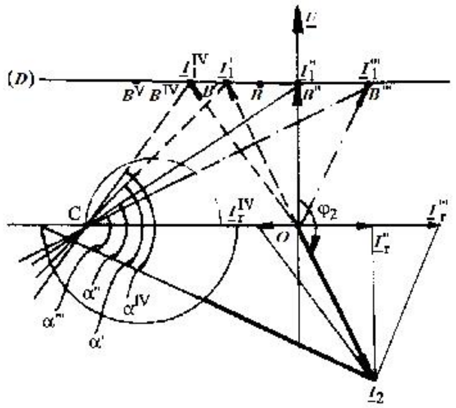


Figure 5. Phase diagram for P_2 = const., α = var.

Table 1. Experimental and computed results (630 kVA)

		α_1	I_1(A)	I_r(A)	α_i	$\Delta\alpha$	I_1(A)	I_{E1}(A)	I_{E2}(A)	I_r(A)	P_r(kVA)
Analytical method	Simplified	76°	60.8	0	69°	7°	55.6	-	-	15	156
	Exact.	73°	54.9	6.5	69°	4°	51.5	122.5	224	10.25	106.5
Graphical method	Simplified	77°	60.8	0	69°	8°	56.5	-	-	15.5	161
	Exact.	73°	55.0	7.0	69°	4°	51.5	124.1	224.5	10.5	109
Experimental results		U=6kV, I_2=60.8A, η=0.935, P_N=530kW, $\cos\varphi_2$=0.9, p=3					53.1	130.2	229.4	9.7	101 P_{ra}=66kW

The possible values of the mechanical shift are analysed because in the real case of the machines coupled by bolts, one is interested in obtaining values α_i as close as possible by those obtained by computation. It is shown that the mechanical shift can be modified by relative rotation of the couplings, by terminals permutation, and by reversal of the rotation sense (when the machines do not have determined rotation sense). If α_{g0} is the existing geometric shift between the rotor axes, and the coupling has n bolts, the possible values of α_i, measured in electrical degrees are given by the relation:

$$\sim_i = p\left(\sim_{g0} + K_i \frac{360^o}{n}\right) \pm 120^o \qquad (2)$$

2.2.1. Experimental verification of the proposed method for rated loading

Let 1, 2 be the group of machines mechanically coupled under the electric angle ~ . The group is considered to be put in operation by connecting and synchronizing one of the machines (the machine 1) to the mains (the machine 3) on the basis of the well–known methods (fig. 6).

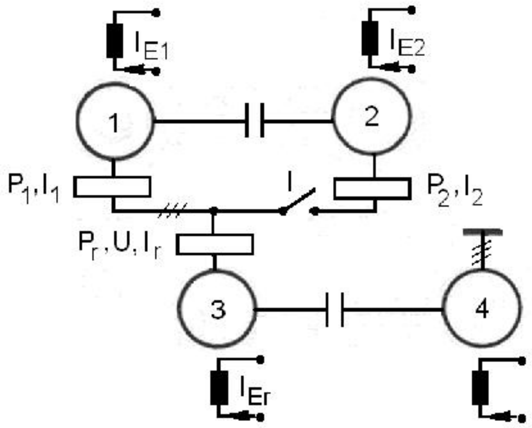


Figure 6. The electrical machines system.

The connecting of the second machine to the mains (closing the contact switch I) is equivalent for the first already connected machine, to a sudden application of a torque to the shaft. The rated loading test has been performed on identical machines 1, 2 rated at 630 kVA. Identical synchronous machines 3, 4 rated at 150 kVA have been used as weak source. The determinations have been performed both analytically and graphically when the losses are considered and neglected respectively. The table I systematizes the results obtained at the test of the machine 2, operating as a motor.

The angle $\alpha_1=73^o$ has been determined analytically and graphically for condition $I_{rr}=0$ and taking into account the losses; we also considered the simplified calculation ($I_r=0$) for which we get $\alpha_1=76^o$. The phase shift $\alpha_0=p\alpha_{g0}=39^o$ and the number of bolts is n = 8 ; in accordance with (2) the possible values are: $\alpha_i=39^o$, 54^o, 69^o, 84^o, 99^o, 114^o. The angle $\alpha_1=69^o$ is the closest available one to the determined angle $\alpha_1=73^o$. We have to mention the good concordance between the experimental results and those given especially by the exact method. We have also to mention the reduced mains power needed.

Observations

The study of the behaviour of two mechanically coupled synchronous machines, connected to the same supply mains is the main contribution of the paper and leads to the following conclusions:

- when operating at synchronous speed, the variation of the coupled machines excitations modifies in large limits, as we wish, their active and reactive loadings; - from the point of view of static stability, the group of coupled machines can be considered as a single synchronous machine at no-load operation and therefore it is characterized by a good static stability irrespective of the electrical angle ~ between the rotors;

From the analysis of the presented method for rated load, we reach he following results:

- it is recoverable and therefore economic; it is theoretically proved and experimentally verified that up to powers reaching approximately six times the supply mains power, the method can be applied without special measures;

- over this ratio of the powers, a series of measures must be taken, but these measures are not difficult from the practical point of view (for example by considering some couples with a larger number of bolts);

- the method is applicable to a test stand which is less equipped, by eliminating the machines chain;

- the scheme operation is stable, there is no danger for occurring the oscillations or for losing the synchronism;

- the active power required from the supply mains is less than in the case of the recoverable methods with machines chain indicated in literature, because the losses of the machines belonging to the chain do not occur anymore;

- the differences between the theoretical pre-determined loadings of the coupled machines, when the losses are considered, and the experimental ones, show that this consideration is correct and reflects the reality to a sufficient practical extent.

The original proposed method has been used for over five years by an electric machine producer. All the above conclusions have been confirmed, as well as the utility of this study for the industrial practice.

2.3. The quasi-stationary and transient regime of the induction machine supplied by two frequencies in the stator

The Ytterberg method is essentially in the category of synthetic loadings. Its opportunity, in many ways is highlighted, at the scale of time, in publications [8], [9], [10], [12], or books regarding the testing of electric machines [1], a.o. The testing experience offers quantitative information regarding the necessary balance of voltages and frequencies of the two sources.

Being a quasi-stationary regime, it is constituted of a succession of dynamic regimes, the basic processes are not the same as in a simple usual functioning and we could not exploit the mechanical characteristics, the vector diagrams which are afferent to the stationary regime etc. The amplitudes of the machine's currents oscillate in the limits which must be necessarily taken into consideration. The same thing regarding the oscillations of the resulting electromagnetic couple etc.

All these aspects can be convincingly highlighted by simulations.

A 340 kW induction machine subject to simulations, is considered started, supplied with nominal voltage and frequency and in idle running. At t=2s we apply the voltage u_2 of frequency f_2.

The simulations regarded especially the currents $i_{sd}(t)$ and the voltages $\underline{u}_s$, u_{sd} (t) of the stator windings, the electromagnetic couples m(t) şi m(ω).

We analysed the effect of the frequency f_2 for a given balance U_2/U_{1N}=0.2. The considered frequencies were f_2/f_{1N}=0.90.

In fig. 7 we showed the current i_{sd} (t), the same with the current of the stator A phase winding. We highlighted the dynamic process from t=2s ending with an oscillating one.

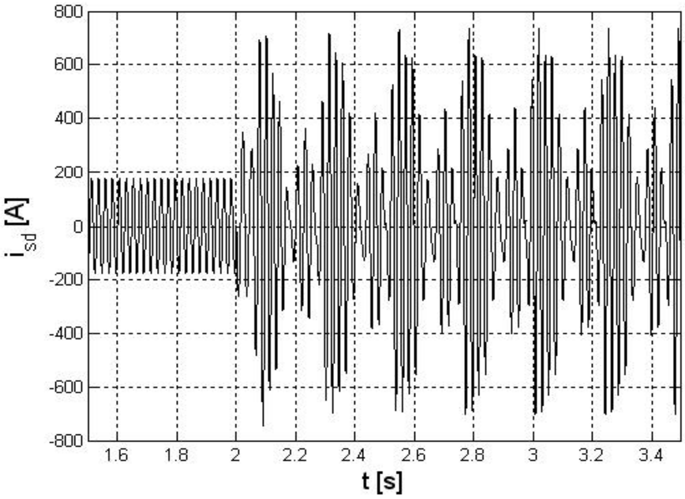


Figure 7. The characteristic $i_{sd}(t)=i_A(t)$.

In figure 8 we have represented the winding voltages of the stator phase $\underline{u}_s$ and $u_{sd}(t)=u_A(t)$. The representations show some evolutions of the amplitudes which are framed in the limits U_1ïU_2 .

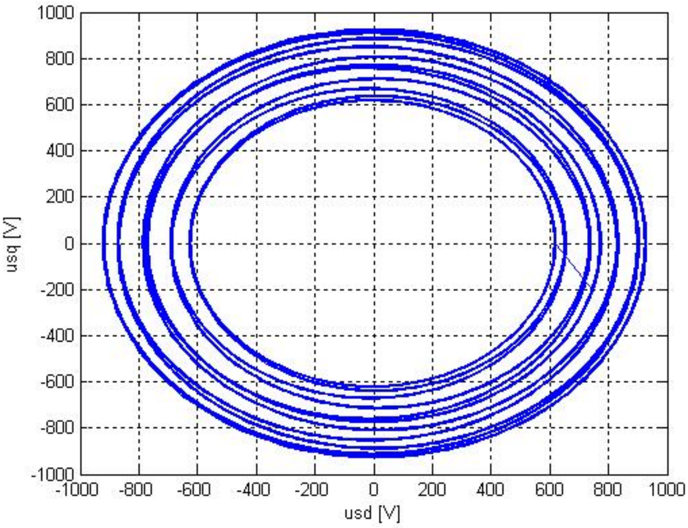


Figure 8.a. The characteristic $\underline{u}_2$.

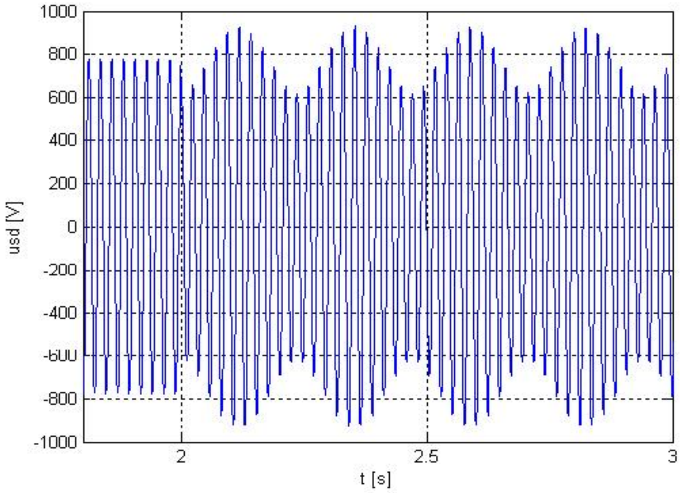


Figure 8.b. The characteristic $u_{sd}(t)=u_A(t)$.

Figure 9 represents the detailed characteristic m(ω) for t >2s: we have presented the transition from the transitory evolution to the quasi-stationary one on a limit cycle. Being dynamic characteristics, the point 1 of synchronism in frequency f_1, placed within the limit cycle, corresponds to important positive and negative dynamic couples.

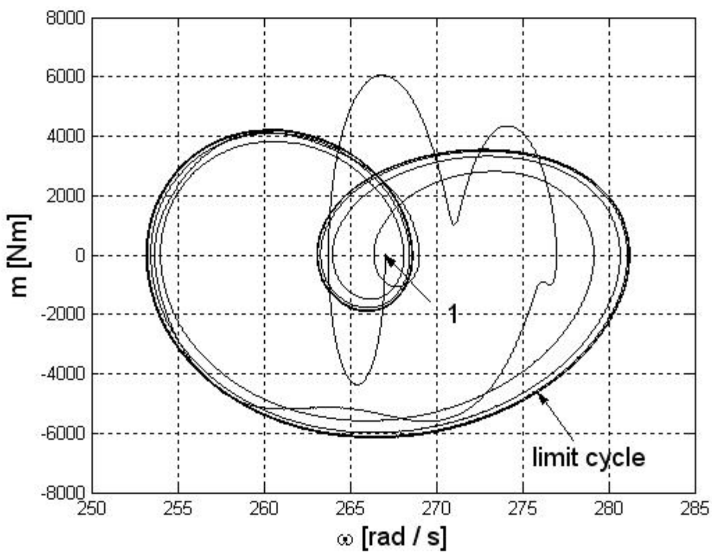


Figure 9. The characteristic m(ω) – detail.

Observations

An advantage of this method is the absence of the mechanical couple necessity with a machine of the same power and revolution. This advantage becomes major in the case of induction machines with vertical shaft.

The disadvantages of the method, which affect the precision of the factory experimental determinations, are highlighted by the presented simulations. The application to the machine terminals of a non-sinusoidal voltage determines:

- major oscillations, first of all in amplitude, of the machine's winding currents. If we have in view the distorting regime and the speed oscillations of the rotor, even if the effective wanted values are kept from the harmonic regime of the stator currents, the losses in these windings are high;

- the electromechanic transitory process provoked by a sudden introduction of the secondary source (u_2, f_2), is major even for limit final reduced cycles and must be avoided.

On the whole, the main and supplementary losses in the induction machine windings can differ notably form those in the harmonic regime; the same thing about the iron losses. The average power absorbed by the induction machine corresponds to a power of the measure order of the total losses.

In order to limit the disadvantages of the method highlighted above, the information offered during the time by an important number of experimental tests must be taken into account as reference points.

3. General conclusions

The proposed test method is obligatory for the three windings transformer with different power per winding.

On the whole, the theoretical and experimental study has emphasized functional particularities of the synchronous machines and, on this basis, the possibility of establishing several regimes, which are of interest in practice. The proposed method represents the single way to perform the thermal test of the high power synchronous machines, at the manufacturer.

The above analysis, with the use of dynamic mathematical models notably increases the information volume under the theoretical aspect and for the practical reality, regarding the Ytterberg method, some of them are very difficult to be anticipated in other ways.

References

[1] Biriescu M., Masini electrice rotative. Parametrii, caracteristici, incercari, Editura de Vest, Timisoara, 1997.

[2] Campeanu A., “Metoda de punere sub sarcina pentru incercarea la incalzire a transformatoarelor cu trei infasurari de puteri mari si neegale”, Brevet de inventie. Publicatie OSI 42705/1964.

[3] Campeanu A., “Medoda de incercare directa la sarcina nominal a masinilor sincrone cu recuperare de energie”, Brevet de inventie. Publicati OSI nr.46606/1967.

[4] Campeanu A., Vlad I., Enache S., Ionescu A., Study of a Particular Recoveri Regime of the Sinchronous Machine and its Applications, ACEMP 07-ELECTROMOTION 07, Bodrum, Turkey, 2007.

[5] Campeanu A., The transient electromechanical oscillations of the synchronous machine, in a special case, Proc. of OPTIM ’98, Vol. 1, Brasov, 1998, pp. 295-298.

[6] Campeanu A., a.o., Connection to weak electrical supply network of two synchronous machines operating in recovery regime, Proc. ICEM ’06, Chania, Crete Island, Greece, 2006, CD-ROM.

[7] Krause P., Analysis of electric machinery, McGraw-Hill Book Company, New York, 1986.
[8] Kron A.W., Messungen an Asynchron motoren bei bifrequente Speisung, ETZ-A, 94, 2, 1973.
[9] Lenz M., Syntetische Velasting von Drehstromasyncron machinen mit Kirfe der zweifrequenzmethode, ELIN-ZEITSCHRIFT, 3, 1975.
[10] Liuba G., Biriescu M., Incercarea la incalzire a masinilor electrice de mare putere, pe un stand de probe industrial, prin metoda celor doua frecvente, Conferinta Nationala de Electrotehnica si Energetica, Craiova, 1984.
[11] Nurenberg W., Die prufung elektrischen maschinen, Springer Verlag, Berlin, 1959.
[12] Radic P., Strupp N., Mesure de l'schaufement sour moteurs asinchrones par la metode des deux frequencies, Revue Brown Boveri, 63, 8, 1976.

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