EXPERIMENTAL TEST OF THE FACTORS AFFECTING THE SURGE VOLTAGE PHENOMENA IN HIGH-VOLTAGE MOTORS (SURGE IMPEDANCE, VELOCITY OF PROPAGATION)*

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I. Introduction

The windings of the electrical rotating machines are much more complicated than those of transformers. Consequently, when giving an *exact treatment* of the phenomena of surge voltage in rotating machines, a much more complicated physical aspect is to be taken as starting-point than in the case of transformers. Besides the *self-inductance* of the single coils the *mutual inductance* between the coils may be considerable too (it is especially significant between coil parts which are electrically distant from each other, but placed closely in space, *e. g.* in a single slot). The coils are placed partly in iron, partly in air (coil ends) ; the inductance of the coil parts embedded in iron is much higher and depends on the frequency. Out of the capacitances, that of the coils *to ground* is the most important. The capacitance between the coils placed in different slots is insignificant, the *mutual capacitance* between the coil sides — usually belonging to different phases — located in the same slot may, however, be of considerable value. The *capacitance between turns* within the coils cannot be neglected either. The *ohmic resistance* greatly affects the phenomenon and its value depends on the frequency (skin effect).

For practice a simple and perspicuous *approximation*, which, though not giving a perfectly exact idea of the phenomenon, offers results suitable for practical calculations, has a considerably greater importance than the theory** based on the real — and, as it appears from what is said above, very complicated — physical aspect. In consideration of this point of view, the

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** It is to be remarked that the phenomenon is complicated to such an extent that all factors cannot be taken into consideration at the same time, even the theory starting from the real physical aspect has to make some omissions. In this respect two papers of B. C. ROBINSON [1, 2] are the most important. Here the self-inductance of the coils, the coil capacitance to ground, the mutual inductance and the mutual capacitance between the different coils placed in the same slot are taken into account. On the basis of ROBINSON's theory the phenomenon taking place in the machine can be well explained, the formulas are, however, less suitable for practical calculations. There is a rather considerable difference between the calculated values and the measured ones. The theory is not of general validity, it refers only to the two-pole turbo-alternators having single-conductor windings.

authors treating the surge phenomena in rotating electrical machines, in general, use the approximation taking into account only the two most important factors of those enumerated above, namely the self-inductance of the winding and the capacitance to ground of the coils. Thus the winding is considered as a transmission line consisting of series inductances and parallel capacitances (Fig. 1). Employing the line equations, they speak of the surge impedance of the winding $\left(Z = \sqrt{\frac{L}{C}}\right)$, of the velocity of propagation within the winding $\left(v = \frac{1}{\sqrt{LC}}\right)$, of damping, of reflection. (L and C are the inductance and capacitance of the unit length of the winding.) This equivalent circuit is more simple than that valid for transformers, as here the series capacitances corresponding to the capacitive connection between the coils do not appear. In rotating machines the capacitance to ground of the single coils is, owing to the proximity of iron, considerably higher than the capacitance between coils, therefore, this latter may be neglected in the equivalent circuit. Thus, the

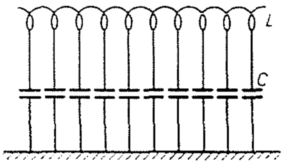

Fig. 1. Simplified equivalent circuit of the winding of an electrical rotating machine

surge phenomena of the electrical rotating machines can be treated in a more simple way than those of the transformers, although the real physical aspect is for more complicated in the case of rotating machines.

On the basis of the theory of lines M. WELLAUER [3] determines from the surge impedance of the machine, using the laws of reflection and refraction, the value of the voltage arising at the terminals and in the neutral of the machine. The effect of the ohmic resistance of the winding is taken into consideration by employing a damping factor. The theoretical calculations are proved by measurements. The winding of the rotating machines is considered in the first approximation as a "transmission line" also by B. HELLER and A. VEVERKA [4], as well as by R. STRIGEL [5], and the correctness of their supposition is proved by tests. B. KERN [6] states the stress of the slot insulation of the machines by means of the reflections within the winding. In his calculations he assumes that the winding of the machine has a determined surge impedance, although the surge impedance of the machines examined by him was not constant, but varied to a great extent during the time in which the travelling wave traversed the winding.

The theory of lines may be applied with good approximation to most of the electrical rotating machines. It is very expedient to study the phenomenon on this basis, chiefly, because in this way the stresses arising in the winding can be calculated very simply. From the *surge impedance* of the winding not only the reflections within the machine, and by means of them the stresses to ground can be stated, but it is decisive also for the behaviour of the machines with regard to the switching surges [4, 7, 8]. The *velocity of propagation* within the machine may serve to determine the highest stress of the interturn insulations [4]. For the engineer constructing the machines these stresses form the basis of the correct dimensioning of the insulation.

From a practical point of view it is very important to find the correct relation between these two wave characteristics (surge impedance, velocity of propagation) and the constructional features of the machine. This is not possible on the basis of the tables or diagrams known from the literature, because the data to be found there, showing a strong dispersion, may serve at most to discern the character of the relations, but they are not suitable for calculation purposes. This is due to the fact that these data refer to machines of different sizes, constructions, coil arrangements, etc. There are even machines to which the theory of lines cannot be applied at all (*e. g.* where the mutual inductance and capacitance between the coils are very high). *For a group of machines, however, namely for machines of not strongly deviating geometrical dimensions and of similar coil arrangement, it is possible to make, by means of the theory of transmission lines, general conclusions, on the basis of which the wave characteristics of the machines may be determined from the constructional data.*

This statement was proved by the tests carried out in the *Central Laboratory of the Electrical Works "Klement Gottwald" (Ganz)* on H. V. motors of medium output, most frequently manufactured in the factory. The reason why this type of motor was chosen for the tests is that these machines are mostly exposed to danger both in view of atmospherical overvoltages and of surges due to switching operations. The original purpose of the tests was to determine the stresses arising in the winding of the tested machines under the influence of surge voltage. The test results proved, however, also the fact that the theory of lines can be applied with very good approximation to the tested motors. The *surge impedance* of the motors and the *velocity of propagation* within the winding was practically determined by the self-inductance of the winding and its capacitance to ground.

In this paper the part of our series of tests relating to the wave characteristics is described. On the basis of the test results the relation between the wave characteristics and the constructional features of the machines is stated. By means of these relations the wave characteristics of machines with dimensions not deviating greatly from those of the tested machines, and showing similar coil arrangement, can be determined with good approximation.

II. Data of the tested motors

The main data of the tested motors are indicated in Table 1. It appears from this Table that the features of the tested machines differed from each other to a great extent. Two kinds of winding were used in the motors : the

Table 1

Data of the tested motors

N°	P	U	2p	Winding	H	q	N	l_t
1	147	3000	4	concentric 3-plane	72	6	19	2060
2	280	3500	10	,, ,, ...	120	4	12	2270
3	320	3000	4	,, ,, ...	84	7	10	2260
4	430	5500	12	concentric 2-plane	108	3	16	2580
5	460	3300	4	concentric 3-plane	96	6	7	2510
6	590	3000	10	,, ,, ...	120	4	6	2550
7	235	3500	10	double-layer diamond type winding	120	4	6	2160
8	240	3000	6	,, ,, ,, ,,	90	5	4	2460
9	450	6000	6	,, ,, ,, ,,	90	5	7	2210
10	550	3000	2	,, ,, ,, ,,	72	12	4	2640
11	960	3000	2	,, ,, ,, ,,	72	12	5	2820
12	1200	3000	2	,, ,, ,, ,,	72	12	4	3340

P (kW) : rated output
U (V) : terminal voltage
2p : number of poles
H : number of slots
q : number of slots per phase and per pole
N : number of turns per coil
l_t (mm) : length of turn

machines N^{os} 1 to 6 were built with single-layer concentric winding, while machines N^{os} 7 to 12 with double-layer diamond type winding. In the coils the turns were set in one column, one above the other. All motors were Y-connected, with insulated neutral.

In respect of the geometrical dimensions the tested machines differed from each other to a relatively slight extent. The largest bore diameter was not quite the double of the smallest one. There was a somewhat larger difference between the core length of the longest machine and that of the shortest one. The largest winding length was scarcely more than one and a half times that of the shortest one, as it appears from the last column of the Table.

The tests were carried out with a L. V. recurrence surge generator, supplying a 1×50 μs wave.

III. Determination of the surge impedance and of the velocity of propagation by measurements

The *surge impedance* of the winding was measured with the machines connected as per Fig. 2/a. The three terminals of the three-phase winding with insulated neutral were joined, and a practically pure ohmic resistance of known value was connected before the winding. When a surge voltage was applied to this resistance, a stepped voltage curve appeared on the terminals of the machine. The height of the single steps was determined by the additional resistance, the surge impedance of the winding and the damping factor of the winding, according to the relations defined by the law of refraction and reflection [3]. The resulting surge impedance (Z_3) of the three phases of the winding — being parallel to each other from the point of view of the surge voltage — may be calculated from the peak value of the surge voltage applied to the resistance (U), *from the height of the first step of the stepped voltage curve* (u), and from the known resistance (R) connected before the winding, according to the following equation :

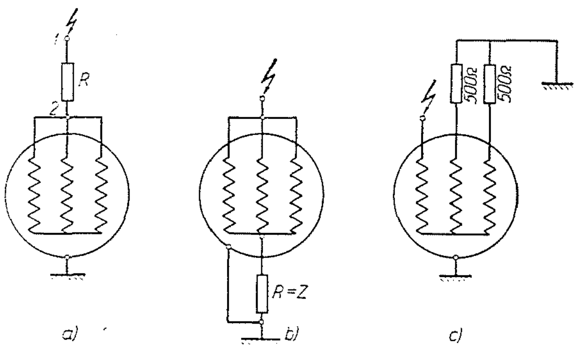

Fig. 2. Connections used in the tests

$$Z_3 = R \frac{\frac{u}{U}}{2 - \frac{u}{U}} \tag{1}$$

From this results for the surge impedance of a single phase :

$$Z_1 = 3 Z_3 \tag{2}$$

By way of example, Fig. 3 shows the oscillograms taken on one of the double-pole machines, Fig. 4 shows those of a fourpole machine.

From the oscillograms, besides the surge impedance the time during which the travelling wave traversed the winding — from the terminal to the

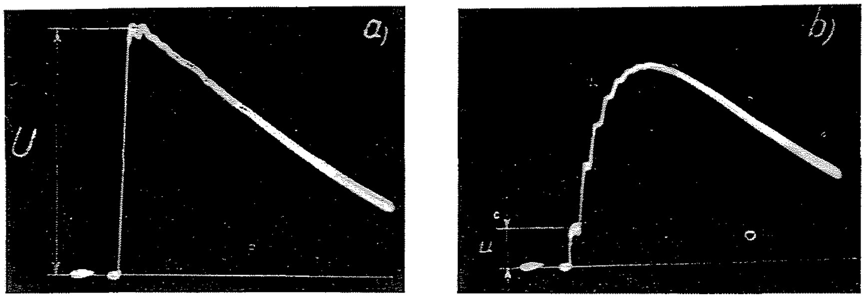

Fig. 3. Oscillograms taken for the purpose of determining the surge impedance of motor N°. 11. *a)* wave shape on the measuring resistance (point 1) *b)* wave shape on the terminals of the machine (point 2)

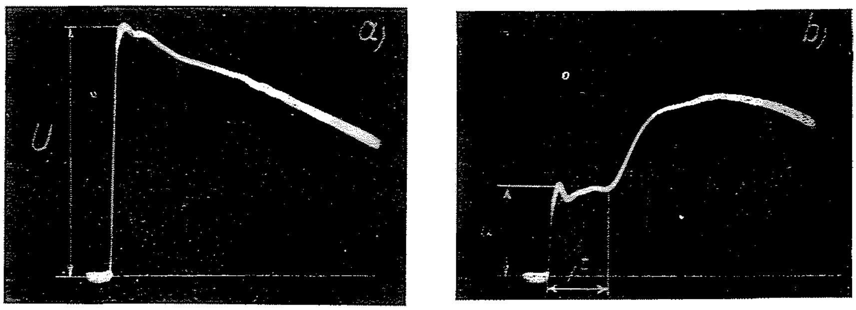

Fig. 4. Oscillograms taken for the purpose of determining the surge impedance of motor N°. 1. *a)* wave shape on the measuring resistance (point 1), *b)* wave shape on the terminals of the machine (point 2)

neutral — can be determined too.* Namely, on the basis of the law of reflection the space between the single steps of the stepped curve (marked with t on the oscillogram of Fig. 4) gave just the double of this time. From the time t measured on the oscillogram and the winding length of one phase (l_{ph}) the average *velocity of propagation* was calculated by means of the formula

$$v_a = \frac{2\, l_{ph}}{t}$$

With the described method it was possible to determine from the stepped curve appearing on the terminals of the machine for every one of the tested machines both the surge impedance of the winding and the time necessary for the surge wave to traverse the winding. The surge wave arriving to the ter-

* The time determined in this way is equal to the traversing time of the *toe* of the surge wave.

minals of the machine encounters in the first instant this surge impedance, and its value changes only slightly in function of the time.

The fact that each of the tested machines had a determined measurable surge impedance proves that *the theory of transmission lines may be applied to these machines.*

IV. Relation between the surge impedance and the constructional features of the machine

The surge impedance of the transmission lines is given by the formula :

$$Z = \sqrt{\frac{L}{C}} \tag{3}$$

where L is the inductance of the unit length of the line and C the capacitance falling to the unit length. In case of rotating machines it is advisable, when applying this formula, to reckon with the inductance (L_c) and capacitance (C_c) of *one coil*. If the length of conductor of a coil is l_c, then — assuming a winding consisting of identical coils* —

$$Z = \sqrt{\frac{L_c/l_c}{C_c/l_c}} = \sqrt{\frac{L_c}{C_c}} \tag{4}$$

The self-inductance of a coil of a rotating machine is proportional to the length of a turn (l_t) and the square of the number of turns (N). *For coils of similar shape and of geometrical dimensions deviating but slightly from each other* the proportionality factor (k_1) is nearly identical. A part of the coils (coil ends) is, however, in the air, another part of them is embedded in iron (in the slot). The inductance of a coil is the more higher the larger part of it is located in iron. Although with frequencies corresponding to the surge wave the inductance of the coil parts in iron is much lower than with the frequency of the network, the effect of the iron is nevertheless substantial [9]. If the quotient of the length of coil located in iron (l_i) and that placed in air (l_a) is represented by λ ($\lambda = l_i/l_a$), and assuming that the inductance of the part placed in iron is much larger than that of the coil ends ($k_2 \gg 1$), then the inductance of a coil is approximately given by the equation :

$$L_c = k_1 \frac{1 + k_2 \lambda}{1 + \lambda} l_t N^2 \cong k \frac{\lambda}{1 + \lambda} l_t N^2 \tag{5}$$

(the dimension of k is H/cm).

The capacitance of a coil (C_c) is practically equal to that of the coil part in iron, and knowing the geometrical dimensions of the coil, and of the dielectric

* If the winding consists of coils with different dimensions, L_c and C_c refer to their average value.

constant of the applied insulation, it is simple to calculate. Its value can easily be determined by measurements, too.

With the knowledge of the inductance and capacitance per coil the surge impedance may be calculated by means of the following equation :

$$Z = \sqrt{\frac{L_c}{C_c}} = \sqrt{k}\sqrt{\frac{\lambda}{1+\lambda}\cdot\frac{l_t}{C_c}}\,N = \sqrt{k}\,G\,N \tag{6}$$

where

$$G = \sqrt{\frac{\lambda}{1+\lambda}\cdot\frac{l_t}{C_c}} \tag{7}$$

The factor G in the equation is a constant depending on the geometrical dimensions, winding, and insulation of the machine. It appears from the equation that for all machines having coils of but slightly deviating dimensions, of similar shape, and the similarity factor G being nearly identical, *the surge impedance of the winding is proportional to the number of turns per coil.*

The coil dimensions of the tested machines were not considerably different from each other, as it appears from the length of turns (l_t) indicated in Table 1. The coils were similar to each other within the two kinds of winding, and the similarity factors G calculated for the machines but slightly deviated from each other (see Table 2). For the single-layer winding the average value

Table 2

N°	λ	l_t	C_c	G
1	0.34	206	$420 \cdot 10^{-12}$	$0.354 \cdot 10^{6}$
2	0.74	227	830	0.342
3	0.51	226	640	0.345
4	1.18	258	1350	0.323
5	0.47	251	790	0.319
6	1.22	255	1670	0.290
7	1.0	216	460	0.485
8	0.95	246	590	0.451
9	0.99	221	510	0.465
10	0.43	264	400	0.446
11	0.74	282	590	0.451
12	0.82	334	640	0.485

$\lambda = \frac{l_i}{l_a}$: quotient of the length of winding placed in iron and that in air

l_t (cm) : length of one turn of a coil

C_c (F) : capacitance to ground of one coil

G $(\mathrm{cm}^{\frac{1}{2}}\, F^{-\frac{1}{2}})$: similarity factor resulted in $G_{1a} = 0{,}33 \cdot 10^6 \text{ cm}^{\frac{1}{2}} F^{-\frac{1}{2}}$, and for the double-layer winding in $G_{2a} = 0{,}46 \cdot 10^6 \text{ cm}^{\frac{1}{2}} F^{-\frac{1}{2}}$.) In the equation the length of turn was substituted in cm, and the capacitance of coil in F.) Thus, in case of the above considerations being correct, the surge impedance of the tested machines had to change practically linearly with the number of turns per coil.

This theoretical statement was fully proved by the test results. The measured surge impedance of the tested machines in function of the number of turns per coil is shown in Fig. 5. It can clearly be seen from the diagram that the surge impedance of the machines is practically proportional with the number of turns per coil, only for the machines with single-layer winding a different proportionality factor was, of course, obtained than for the double-layer windings.

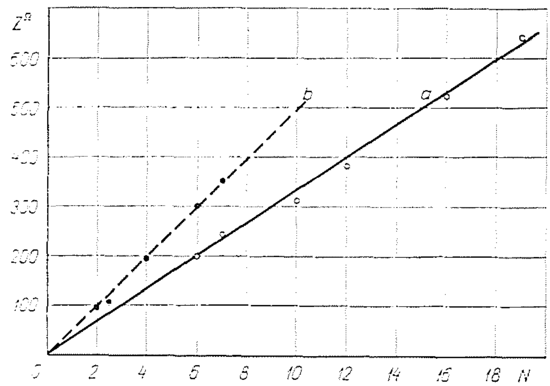

Fig. 5. Surge impedance of the tested machines in function of the number of turns per coil. *a)* machines with single-layer (concentric) winding, *b)* machines with double-layer (diamond-type) winding

All authors treating the surge voltage phenomena of electrical rotating machines mention that the surge impedance of the rotating machines depends on and is nearly proportional to the number of turns per coil. The dispersion of the results of mesurements given in the tables and diagrams [3, 4, 5, 10] is, however, so great that — as already mentioned — they cannot be used for practical calculations. This is due to the fact that the structure and the geometrical dimensions of the considered machines strongly deviated, *i. e.* the values of factors k and G were different for the single machines. For all groups of machines, however, the factors k and G of which are practically equal, the surge impedance is proportional with the number of turns per coil. In the case of the tested H.V. motors this condition was complied with, thus between the surge impedance of the machines and the number of turns per coil there was — as shown by the diagram too — a linear relation. On the basis of the diagram in Fig. 5, for windings of similar coil arrangement as that of the tested machines, and the coils of which are not very different from the tested ones in construction and in geometrical dimensions, the surge impedance may be determined with good approximation.

V. Relation between the velocity of propagation and the constructional features of the machine

In case of a transmission line the velocity of propagation may be calculated on the basis of equation

$$v = \frac{1}{\sqrt{LC}} \tag{8}$$

For motors, taking into account formulas (3) and (6), this equation gets the form :

$$v = \frac{1}{ZC} = \frac{1}{\sqrt{k}\, G} \cdot \frac{1}{NC} \tag{9}$$

Consequently, when the conditions specified in Article IV (similarity, nearly identical dimensions and structure) are fulfilled, the velocity of propagation is equal to the reciprocal value of the product of the number of turns per coil and the capacitance falling to the unit length. The velocity calculated by means of equation (9) gives *the maximum value prevailing at the beginning of the winding*. Namely, the velocity of propagation (and that of the toe of the surge wave too) decreases while it traverses through the winding. This decrease is caused partly by the arising losses [5], but also the mutual inductance between the coils has a part in it [11]. The variation of the velocity along the winding is shown in Fig. 6 on the basis of measurements carried out on machine N°. 4. The diagram was drawn on the basis of the average speeds measured on six section of equal length (consisting of 3 coils each) of one phase of the winding. As it appears, the maximum velocity (61 m/μs) prevailing at the beginning of the winding (obtained by extrapolation) is round 1,3 times the average velocity (47 m/μs). The velocity calculated from the measured values of the surge impedance and capacitance resulted for this machine in 59 m/μs, thus the two values agreed very well with each other. By means of equation (9) the maximum velocity of propagation has been determined for all tested machines, and these values, together with the average velocities calculated from the traversing time, are indicated in Table 3. The Table also contains the quotient of the maximum velocity and the average one, the value of it being about 1,4 on the average.

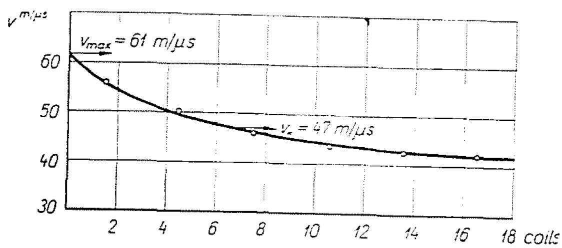

Fig. 6. Variation of the velocity of propagation along the winding.

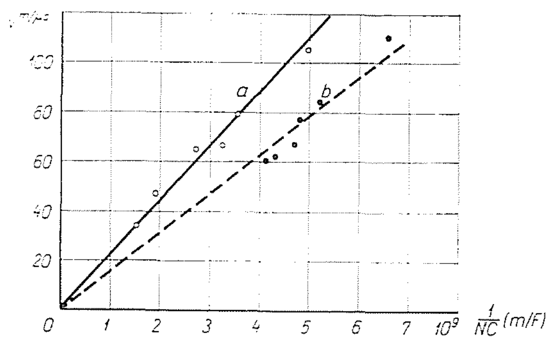

Fig. 7. Average velocity of propagation in the tested machines. *a)* machines with single-layer (concentric) winding, *b)* machines with double-layer (diamond-type) winding

Table 3

Maximum and average velocity of propagation

N°	v_a (measured) (m/μs)	v_{max} (calculated) (m/μs)	v_{max}/v_a
1	105	147.5	1.4
2	64	86	1.34
3	79	113	1.43
4	47	59	1.26
5	66	92.5	1.4
6	34	46.5	1.37
7	67	94	1.4
8	60	93	1.55
9	62	86.5	1.39
10	110	138	1.25
11	77	108	1.4
12	84.5	110	1.3

The values of the measured *average velocity* in function of the quotient 1/NC is shown in Fig. 7. Here different values were obtained for the single-layer winding and for the double-layer one.

VI. Practical applications

As already mentioned in the introduction, with the knowledge of the *surge impedance* the reflections within the winding, and from these the stress of the slot insulation can be calculated, the former value being decisive for the behaviour of the winding against the switching overvoltages too. The reflections within the winding are dealt with in detail in the paper of B. KERN [6], while B. HELLER and A. VEVERKA give practical formulas [4] for the calculation of the overvoltages due to switching operations. According to this latter paper, the relation of the peak value of the overvoltage arising at the terminals of the rotating machine when switching it off the network to the peak value of the rated voltage at the terminals, *i.e.* the so-called overvoltage factor can be calculated with good approximation by means of the equation

$$\varrho = \sqrt{1 + \left(\frac{Zi_0}{\sqrt{2}\,E}\right)^2}$$

where Z is the surge impedance of the switched-off motor, i_0 the breaking current, and E the terminal voltage of the machine (effective value).

The *velocity of propagation* may be used for determining the voltage falling to the mostly-stressed inlet turns of the machine. Namely, if T_f is the front time of the wave, T_1 the time necessary to traverse the first turn, and U the peak value of the surge voltage arriving to the terminals, then the voltage falling to the first turn is

$$\Delta U_1 = U \frac{T_1}{T_f} = \frac{U}{T_f} \frac{l_1}{v_{\max}}$$

where l_1 is the length of the first turn, and $v_{\max}$ the maximum velocity prevailing at the beginning of the winding.

The stress of the subsequent turns is lower, as the front time of the wave increases in consequence of the dispersion, while the amplitude decreases due to the dampings. This effect is counteracted to a slight extent by the decrease of the velocity of propagation, *i. e.* by the increase of the traversing time. After all, the stress of the single turns decreases along the winding.

The voltage falling to the *first coil* may be calculated by means of the above-mentioned equation, too, in which case T_1 means the time necessary to traverse the first coil and l_1 the length of the first coil. With this method, due to the afore-said reasons, the calculated voltage is always higher than the actually arising one. According to our experiments, the calculated value is by 15 to 25 % higher than the measured one. In case of the front time of the wave being shorter than the time necessary for traversing, the voltage falling to the coil is about 100 %, it may be even higher, due to the oscillations that may arise. As an example, Table 4 shows the results of measurements carried

Table 4

Stress of the coils (coil groups) most exposed to danger in per cent of the peak value of the surge voltage applied to the terminal (wave shape 0.3 × 50)

N°	$U_{calculated}$ %	$U_{measured}$ %	Number of tested coils
5	63	47	1
11	43	35	1
12	40	34	1
2	100	96	2
4	100	110	3

out on five machines connected as per Fig. 2/c. In the case of the first three machines contained in the Table, the voltage of the first coil, in the case of the fourth machine that of the first two coils, and in case of the fifth machine that of the first three coils were calculated and measured, respectively. Comparing the calculated values with the measured ones, it appears that the stress of the initial coils can be calculated with good approximation on the basis of the velocity of propagation, and with knowledge of the voltage arising at the terminals the dimensioning of the insulation is possible. The voltage of the first turns can be determined, owing to the conditions described above, even more exactly than that of the coils.

Summary

The results of measurements carried out in the Central Laboratory of the Electrical Works "Klement Gottwald" (GANZ) prove that the surge voltage phenomena of the tested H. V. motors can be treated very well applying the theory of transmission lines. A relation can be made between the wave characteristics (surge impedance of the machines, velocity of propagation) and the constructional features of the machines. Knowing the similarity factors (k, G) the surge impedance of the rotating machines and the velocity of propagation within the winding can be determined with good approximation on the basis of the given relations. These two wave characteristics are very important, because with their knowledge the insulation of the machines can be dimensioned with respect to the overvoltages due to switching operations and those of atmospherical origin.

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