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409.—TRANSIENT PHENOMENA MEASURED ON AND COMPUTED FOR THE SWISS 420 kV SYSTEM TAVANASA-SILS-BREITE

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SUMMARY

The first stage of the Swiss 420 kV system has been put in operation fall 1964 and at this occasion performance tests and various measurements have been carried out. In this report a description of the 420 kV system and the 220 kV feeding system is given including the data of the line, transformers, etc. Several tests are described where the switching surges were measured when charging and dropping an unloaded line. To feed the line the 220 kV system, two generators and four generators of the Tavanasa power station were used. The highest transient and power-frequency overvoltages have to be expected when two generators are employed. In the normal operation four generators are employed and for this condition the overvoltages stay well below the rating of the lightning arresters and their sparkover voltage respectively.

For one particular case the line voltages and currents have been calculated by a digital computer program and reasonable agreement with the measurement could be obtained although further work is required to improve the theory employed.

REPORT

1. DESCRIPTION OF THE 420 KV TRANSMISSION SYSTEM TAVANASA-SILS-BREITE

In 1964 the first Swiss 420 kV transmission line has been put in operation. It connects the hydraulic power plants in the Alps with the load areas in the flat part in the North of Switzerland. It was not because of the length of the transmission distance that a voltage of 420 kV has been chosen but because of the shortage of sufficient possibilities to run transmission lines in the alpine valleys and through heavily populated areas in the flat part of the country. Besides that the energy exchange between Switzerland and the neighbouring countries will be carried out more and more on the level of 420 kV in the future. In 1965 already the Swiss and the German 420 kV grid have been interconnected.

Figure 1 shows the schematic of the transmission system under consideration. The line consists of two circuits both insulated for 420 kV but one of them is temporarily still operated at 220 kV. The line has horizontally arranged two-conductor bundles composed of stranded Aldrey-conductors of 600 mm^2 cross section each. The suspension consists of a chain of 4.53 m length composed of four rod-type suspension insulators with 0.95 m length and 9 sheds each.

The characteristics of the insulation of the 420 kV system are:

Maximum rated voltage		420 kV
Coefficient of earthing		0.8
Power frequency withstand voltage		680 kV (dry and wet)
Impulse withstand voltage	apparatus	1 550 kV crest
	open disconnects	1 780 kV crest

Lightning arresters are placed close to the transformers having the following rating:

Power frequency sparkover voltage	750 kV (r.m.s.)
100 % impulse sparkover voltage	900 kV crest
Rated impulse protective level	970 kV crest
Nominal discharge current	10 kA

Rod gaps are installed on the line with a rated power-frequency sparkover voltage of 580 kV (line to earth) and a 50 % impulse sparkover voltage of 1 200-1 300 kV crest. Before putting this transmission

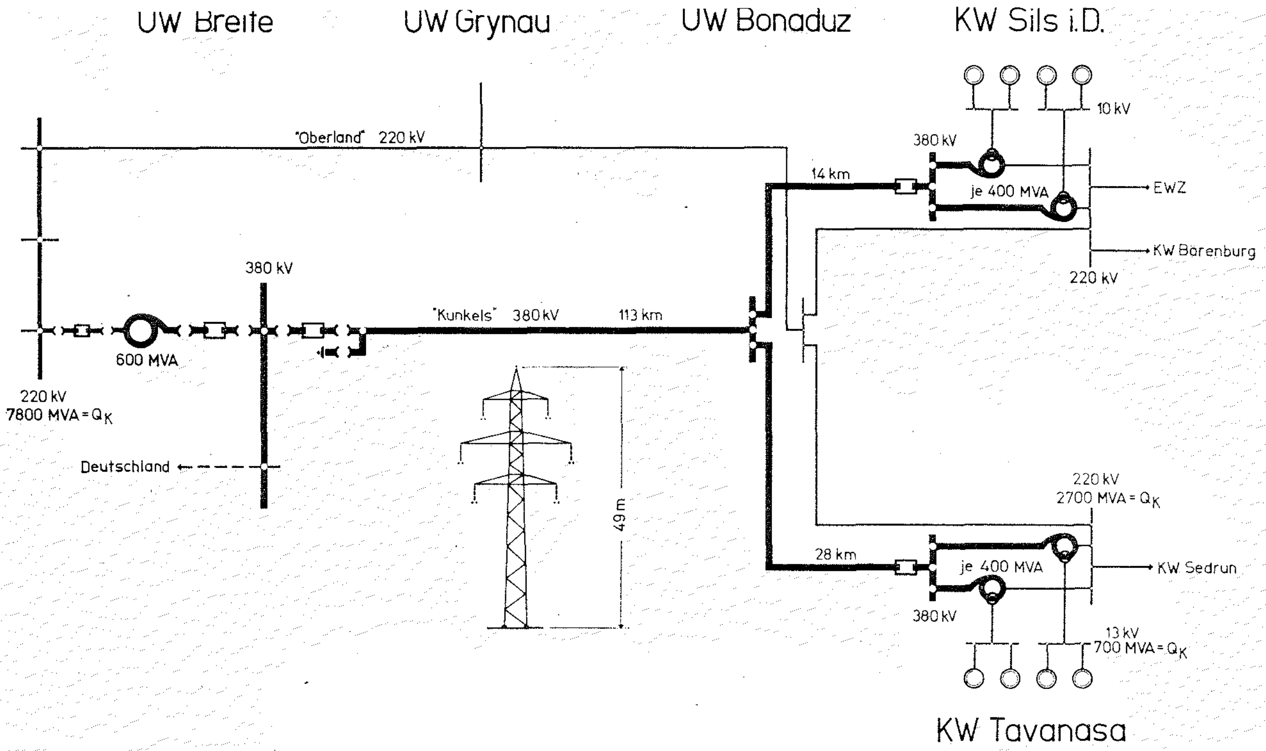

Fig. 1.—Schematic of the Swiss 420 kV and 220 kV network.
UW = substation; KW = power station; QK = short-circuit power.

line in operation a comprehensive test and measuring program has been carried out in order to determine its characteristics and behaviour. The operating parameters measured by the Material Testing Section of the Swiss Institute of Electrical Engineers (S.E.V.) are shown in table I. Table II and III contain the data of the transformers and generators.

TABLE I.

Transmission line characteristics.

Length of line Tavanasa-Bonaduz-Breite: 28 + 113 = 141 km.

	Impedance at 50 Hz	
Positive sequence (values per phase):	Per km	Total
Inductance 1,06 mH/km	0.332 Ω/km	46.8 Ω
Capacitance 11,9 nF/km	267 kΩ/km	1 894 Ω
Resistance	0.031 Ω/km	4.4 Ω
Zero sequence (values per phase);		
Inductance 3,45 mH/km	1.08 Ω/km	152 Ω
Capacitance 6,55 nF/km	487 kΩ/km	3 450 Ω
Resistance	0.21 Ω/km	29 Ω

Charging current and reactive power at 420 kV: 126 A, 93 MVA.

TABLE II.

Characteristics of the transformers.

(Values valid for central tap of the regulating poles.)

	Breite			Tavanasa		
	U_1	U_2	U_3	U_1	U_2	U_3
Rated voltage	$400/\sqrt{3}$	$242/\sqrt{3}$	16 kV	$410/\sqrt{3}$	$248/\sqrt{3}$	2 × 13 kV
Rated power	600	600	120 MVA	400	280	2 × 60MVA
Connection	star	star	delta 5	star	star	delta 5
Impedance	$U_1 - U_2$: 8.52 %; $U_2 - U_3$: 5.48 %; $U_1 - U_3$: 7.72 %.			$U_1 - U_2$: 6.4 %; $U_2 - U_3$: 8.4 %; $U_1 - U_3$: 11.8 %.		

Design: Single phase, main and regulating poles separated, the main poles are autotransformers.

The field tests on switching surges were made on the line section Tavanasa-Bonaduz-Breite and were carried out by the High Voltage

Research Committee (F.K.H.) of the Swiss Institute of Electrical Engineers (S.E.V.). The test program consisted mainly of charging and dropping the line under noload, load shedding and short circuit tests. The line was fed either by two or four generators of the Tavanasa plant or by the 220 kV grid.

TABLE III.

Characteristics of the generators of the Tavanasa power station.

Rated power: 60 MVA ; Number of units: 4 ; Rated voltage: 13,5 kV. The per unit reactances and time constants:

$x_d = 1.28$ p.u.	$x'_d = 0.33$ p.u.	$T_d' = 1.7$ s
$x_q = 0.83$ p.u.	$x''_d = 0.23$ p.u.	$T_d'' = 0.03$ s
$x_l = 0.196$ p.u.	$x''_q = 0.32$ p.u.	$T_q'' = 0.045$ s
		$H = 2.28$ s

In the following some tests on switching surges will be discussed in more detail.

2. SWITCHING SURGES MEASURED ON THE TAVANASA-BREITE LINE

2.1. Summary of the tests.—Of the tests carried out the charging and dropping of the line Tavanasa-Breite under noload (*Fig.* 1) together with the rapid reopening after 0,1 s will be dealt with in particular. The surge tests undertaken with an unloaded transformer connected to the receiving end of the line are more special cases of theoretical interest.

TABLE IV.

Switching the unloaded line Tavanasa-Breite with the 420 kV circuit-breaker in Tavanasa	Number of switching sequences			k_{max}	
	On	Off	On-off	On	Off
Fed by 2 generators	9	8	—	2.21	< 1.2
Fed by 4 generators	4	4	5	2.02	< 1.2
Fed from 220 kV system	12	12	22	2.0	< 1.2
Switching of the Tavanasa-Breite line with the unloaded transformer connected at the receiving end					
Fey by 4 generators	4	4		2.17	1.5
Fed from 220 kV system	5	5		1.49	1.57

Table IV shows the number of measurements made and the maximum overvoltages obtained in addition to the related circuit configurations. The overvoltage factors k refers to the peak value of the voltage between phase and earth at 50 Hz before the switching operation.

2.2. **Test arrangement.**—The h.v. circuit-breakers available today enable lines to be switched off without the risk of restriking such that a cathode-ray oscillograph (C.R.O.) measurement could be dispensed with for checking the breaker and the behaviour of the line. The galvanometer-type oscillograph (G.O.) connected diretly to the current and potential transformers made a simple arrangement without additional dividers possible. The accuracy of the output of the potential transformers was specially investigated during dropping the line. When charging the line the measurement accuracy is more likely limited by the G.O. (limiting frequency about 5 kHz) rather than by the potential transformer. A h.f. transmission link enabled a G.O. to be connected both at the sending and at the receiving end of the line to record the switching phenomena.

2.3. **Conclusions drawn from the tests.**—*a). Voltages at the sending end.* (i) *Charging the line.* The unloaded Tavanasa-Breite line requires the appreciable charging power of 93 MVar at a voltage of 420 kV. The 220 kV system will only slightly be affected when such a capacitive load is connected to it. If however the Tavanasa generators alone have to consume this reactive power this can result in a considerable increase of the line voltage. One generator feeding the line results in fast self-excitation, two generators can maintain a stable line voltage due to the voltage regulator action.

In discussing overvoltages it is general practice to distinguish the rise of the 50 Hz component and the transient component. The rise in the 50 Hz voltage can be calculated from the system or generator inductance and the line capacitance.

In accordance with the short-circuit power of 2,7 GVA of the 220 kV system in Tavanansa, the voltage on the 420 kV side of the transformer rises by about 5 % when the unloaded line is charged up (measured and calculated).

When the generators alone charge the line the power-frequency overvoltage is determined by the transient reactance after the subtransient phenomena have died out. The influence of the voltage regulator is not noticeable during the first few cycles.

The results of the tests with 2 and 4 generators are graphically summarized in *Figure* 2. The rise in the 50 Hz voltage and the maximum voltage peaks are given as relative values of the 50 Hz peak voltage values between phase and earth before the switching operation. The points S and T in *Figure* 2 represent the 50 Hz voltage increases calculated from the line capacitance and the subtransient (S) and transient (T) generator reactance. It was found that the value measured after about 3 cycles, i.e. when the transient phenomena have died out, already corresponds to the rise due to the transient reactance.

The measurement of the increase in the 50 Hz voltage reveals a considerable dependence on the voltage level. The reduction in this rise with increasing voltage (or increasing current), is caused by saturation as it occurs in the leakage paths of both stator and rotor.

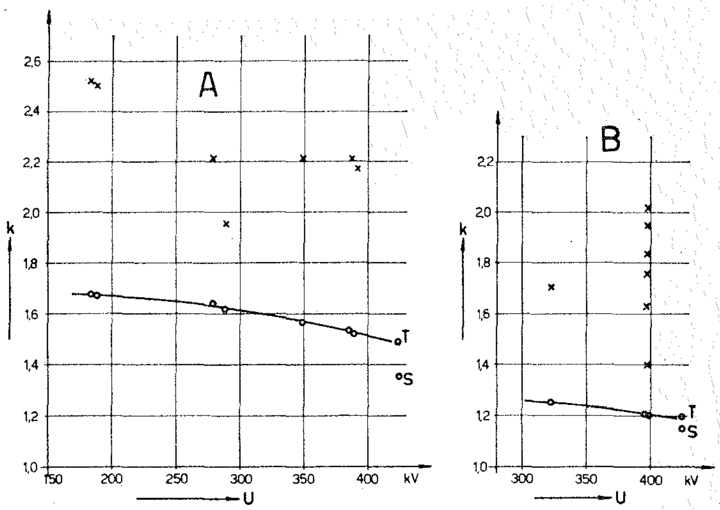

Fig. 2.—Charging the unloaded line Tavanasa-Breite.
A. Fed by 2 generators.—B. Fed by 4 generators.

Measured: — increase of the 50 Hz voltage;
x overvoltage factors;
Calculated: S subtransient increase of the 50 Hz voltage;
T transient increase of 50 Hz voltage.

This increase of the 50 Hz voltage is straightforward. The transient phenomenon beginning immediately after closing of the first breaker contact is less easy to oversee. The following effects are involved here:

—The transients in the generators are damped by the solid iron poles (no damper winding present).

— The three breaker poles do not close simultaneously, hence the three natural modes [1, 2] are excited by the first contact to close. Once all the poles have closed the modes oscillate at their natural frequencies, in particular the zero system mode (mode 3 according to [1]) energized by the staggered closing of the contacts. The probability that these first amplitudes of the oscillations of the various frequencies caused by this uneven closing of the contacts coincide is very slight.

—The damping especially that of the zero system mode must be taken into account. With increasing frequency the ground-return resistance of the line rises almost proportionally with the frequency.

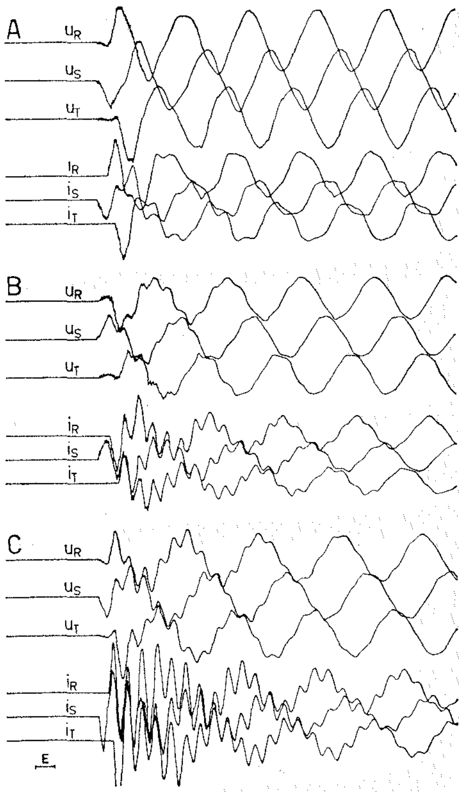

FIG. 3.—Examples of oscillograms taken by charging the unloaded line Tavanasa-Breite in Tavanasa.

A. Fed by 2 generators: $k_T = 2.21$.
B. Fed by 4 generators: $k_R = 1.71$.
C. Fed from 220 kV system: $k_T = 2.0$.

Scale: U_R, U_S, U_T: 300 kV/E; i_R, i_S, i_T: 225 A/E.
E is given as unit on the figure below, left side.

When the line is charged up from two generators a maximum overvoltage factor k of 2.21 was measured meaning that a peak of 760 kV (line to earth) would be obtained if the voltage at the H.V. side of the transformer before closing the breaker is 420 kV (r.m.s.). This value lies well under the sparkover voltage of the lightning arrester of 900 kV (protective level 970 kV) and the withstand level of the transformers of 1 550 kV.

Oscillograms A to C in *Figure* 3 show three examples of oscillograms taken.

(ii) *Dropping the line.* A short discussion should suffice for explaining the general behaviour of the voltage after dropping the line by means of a restrike free circuit-breaker. The measurement with the aid of the potential transformer then requires close attention with regard to the accuracy of its output.

Measurements carried out on a line in Canada [3] revealed that the discharging time constant of an overhead line without potential transformers amounts to several seconds. Since the breaker poles do not open simultaneously the line voltage of the first phase to clear can rise above the peak value of the supply voltage.

In a rough calculation the maximum possible overvoltage factor k when dropping the line can be determined, assuming that each breaker pole interrupts the current at the voltage maximum, or as the current passes through zero. The ratio of the mutual capacitance C_G to the earth capacitance C_E (partial capacitances) of the line needed for this calculation averages 0.25, typical for this line with earth wire.

If the first phase clears at the peak value the sum of the voltages in the two other phases changes by $U' = U \cos 60°$ until the next peak value is reached. The voltage rise ΔU_1 in the first phase coupled through the partial capacitances is then:

$$\Delta U_1 = U' \frac{C_G}{2\,C_G + C_E} = \frac{1}{12}\,U.$$

The voltage in the third phase changes again by $U' = U \cos 60°$ until interrupted. The further voltage increase in the first phase is then:

$$\Delta U_1 = U' \frac{C_G}{C_G + C_E} = \frac{1}{10}\,U.$$

By this theory therefore the total voltage rise in the first phase to clear amounts to:

$$\Delta U_{total} = 0{,}18\ U.$$

Which corresponds to an overvoltage factor of $k = 1.18$.

In the cases evaluated however, this value was not quite attained since the breaker often interrupts the current before the passage through zero, i.e. the voltage does not quite reach the full 50 Hz peak.

If an inductive load is available at some place along the line, e.g. potential or power transformers, then the line capacitance can be discharged. Together with the inductance of the transformer this produces an oscillation of a few cycles. Because of this low frequency the discharge current rises well above the saturation level of the transformer. Since the effective inductance is thus decreased the line voltage changes rapidly as *Figure* 4 shows.

In the test carried out the potential transformer at the sending end of the line which discharges it as described above is also connected to the G.O. The question arises now if the voltage measured by the G.O. is a replica of the line voltage. In order to clarify this point the line voltage was measured in Breite parallel to a potential transformer by means of a capacitive divider and a C.R.O. The measured curves are compared in *Figure* 4, with the following result:

The curve of the low-frequency oscillation is correct as far as the peak value of the voltage is concerned. The fast changeover when the

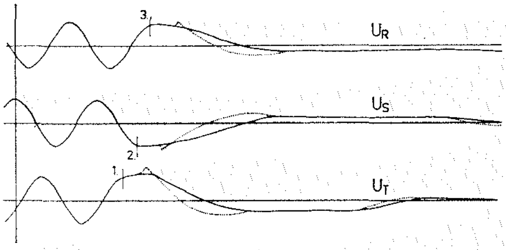

FIG. 4.—Dropping the unloaded line Tavanasa-Breite in Breite.
Comparison: —— measurement by means of a capacitive divider and a C.R.O.
.... measurement by means of a potential transformator and a GO.
1, 2, 3 instants of opening the breaker poles.

saturation of the transformer is reached, i.e. both the sudden increase before and the overshoot after the changeover is not correctly reproduced by the potential transformer. The general behaviour, especially the subsequent decreasing peak voltage values, can be correctly read from the G.O. measurement. As evident from *Figure* 4, the transformer very quickly damps the voltage swings due to its high resistance. The phase T shows the described rise in voltage after interruption of the first phase, the value $k = 1.2$ not being reached.

(iii) *Switching on-off and off-on.*—In an other test the breaker was closed and after 0.1 sec it was opened again. Since the transient phenomenon has already died out after 3 cycles these switching operations do not reveal anything new. These can therefore be regarded as separate on and off sequences.

Switching off-on could be a more serious case if the line is not discharged fast enough. However, the tests showed that the line is practically discharged after 5 cycles as *Figure* 4 shows and hence charging the line anew would not lead to any higher overvoltages.

b. *Voltages at the receiving end of an unloaded line.*—If a voltage at a given frequency is maintained at the sending end of an unloaded line it appears at the receiving end with a higher amplitude. This can easily be calculated from the line equations being referred to in the literature as the Ferranti effect.

This voltage rise for the Tavanasa-Breite line is represented in *Figure* 5 as a function of the frequency. The curve 1 shows the behaviour for an ideally undamped line (line and earth resistance = 0) ; curve 2 takes the earth-return into account being valid for homo-

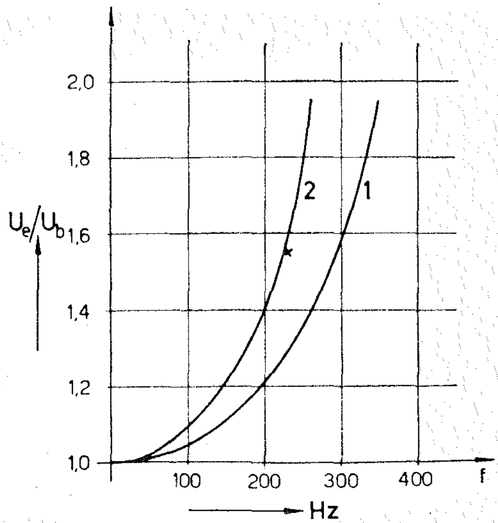

FIG. 5.—Calculated Ferranti effect in function of the frequency for the Tavanasa-Breite line (140 km).

1 increase of the undamped modes (line and earth resistance = 0).
2 increase of the zero mode with earth-return (x measured value).

polar oscillations. The calculation agrees quite well with reality as demonstrated in *Figure* 5. The voltage rise for the transient oscillations of the natural modes of the system should lie between these two curves.

The explanation why the damped system, i.e. taking the ground as the return path has such a pronounced Ferranti effect is due to the higher inductance of the earth-return, hence to the lower speed of wave propagation. This influence is equivalent to having a longer line and appears to be considerably stronger than that of the damping.

Figure 5 shows that the voltage rise (Ferranti effect) for the 50 Hz voltage of the Tavanasa-Breite line is in the order of one percent.

This is however virtually the same as the measurement accuracy of the G.O. reading.

Depending on the type of the feeding system the transient phenomenon has various frequencies, these cause higher overvoltages at the receiving end than were found at the sending end. Details can be taken from Table V.

TABLE V.

Feeding system	$k_{1\,max}$ receiving end	$k_{2\,max}$ sending end	Frequencies f (c/s)		$(k_1/k_2)_{max}$ measured maximum
			Zero-mode	Other (*) modes	
2 generators	2.43	2.21	197	98	1.1
4 generators	2.36	2.02	248	134	1.2
220 kV system	2.18	2	280	—	1.22

It has to be noted that the zero mode due to the higher natural frequency and its lower wave velocity has a higher voltage rise at the receiving end of the line resulting in a higher overvoltage factor.

The lower frequencies when the line is discharged lead to no measurable voltage difference between Tavanasa and Breite.

3. SWITCHING SURGES COMPUTED AND COMPARED WITH THE FIELD TEST

3.1. General remarks.—The field tests carried out in this test series which have been discussed in the foregoing chapters lend themselves to a comparison with computed switching surges. Thus the theories and assumptions employed in the computation can be checked and improved if necessary.

As a test case the charging of the unloaded line Tavanasa-Bonaduz-Breite 140 km in length by four generators of the Tavanasa power station (oscillogram B of *Fig.* 3) has been selected. Neither in the substation Bonaduz nor in the Breite station any additional lines or apparatus besides instrument transformers were connected.

The surges in current and voltages were computed over a length of time of 40 ms and directly compared with the measured results. For this purpose the voltages and the currents from oscillogram B of *Figure* 3 were enlarged and replotted such that a convenient comparison was possible. In the analysis of the computed and measured

(*) Mode 2 and 3 according to [1].

results special emphasis is placed on the agreement of the appearing frequencies, amplitudes and the damping of the various components.

3.2. The fundamentals employed in the computation.— The test case considered can be reduced to a case where one generator feeds an unloaded three phase line if the generators and transformers of the power station are converted into an equivalent generator. The transients in a synchronous machine are most conveniently treated by the two-reaction theory [4] and the transients on a three-phase line by the method of Schnyder-Bergeron [2]. Details of the theoretical background of the computation and the digital program used can be found in appendix A and B.

3.3. Data used for the computation.

Generator data.—See Table III. In the direct axis saturation of the air gap flux has been included.

Transformer data. — From Table II the short circuit reactance between L.V. and H.V. side is equal to 11.8 % referred to 2×60 MVA being valid for the positive and negative sequence system. Due to the delta—star connection the same value applies to the zero sequence system. The magnetizing reactance has been neglected.

Line data.—From Table I the characteristics below can be taken:

	Positive sequence	Zero sequence
Surge impedance	$Z = 298.5\,\Omega$	$Z_0 = 725\,\Omega$
Velocity of wave propagation	$V = 282\,000$ km/s	$V_0 = 211\,000$ km/s

The resistances are as indicated in Table I.

Initial state and sequence of closing of the breaker contacts.—In the test case considered (oscillogram B of *Fig.* 3) the steady state voltage at the H.V. side of the transformer before closing of the breaker contacts equals $323/\sqrt{3}$ kV phase to earth or 0,769 p.u. referred to $420/\sqrt{3}$ kV. The closing of the breaker contact in phase *b* takes place 4,58 ms after the positive crest of the voltage in phase *a* on the generator side of the breaker. The breaker contacts of phase *a* and *c* close 3,35 ms and 5,50 ms later.

3.4. Comparison of measured and computed results.— Both measured and computed line voltages and line currents at the breaker location in Tavanasa are plotted in *Figure* 6.

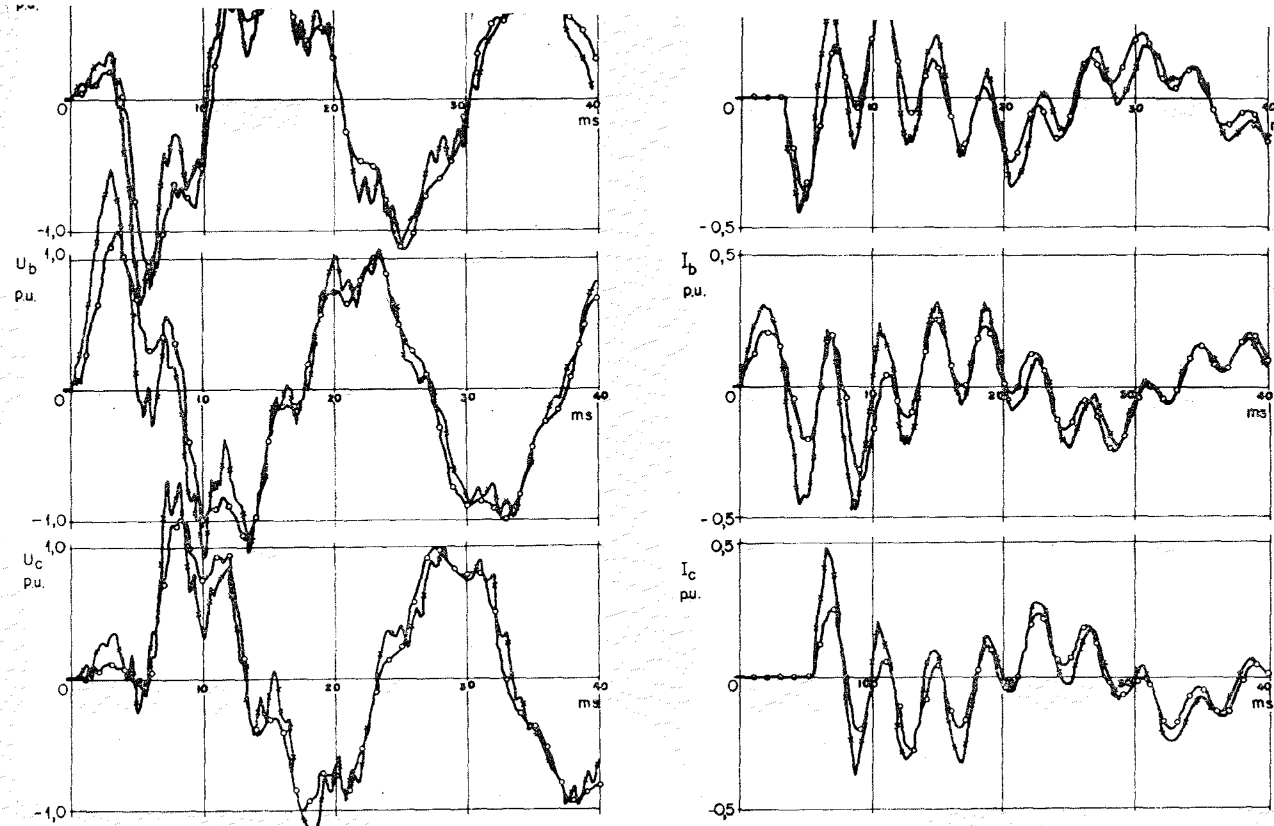

FIG. 6.—Comparison of measured and computed results.
Charging of the unloaded 420 kV line Tavanasa-Breite 140 km in length by 4 × 60 MVA generators of the Tavanasa power station.

There is general agreement between measurement and computation although appreciable deviations can be noticed within the first ten milliseconds. Before going into details for the reasons of the discrepancies the results are discussed from various viewpoints as indicated in Table VI.

TABLE VI.

Agreement of measured and computed results as to various characteristics of the switching surge.

	Agreement
Fundamental component	very good
Frequency of natural modes	very good
Amplitudes of natural modes	poor
Damping of natural modes	good

The fundamental components of voltage and current agree quite well within the time interval under consideration. The same is true for the frequencies of the natural modes. Considerable deviations appear in the amplitudes of the natural modes which are quite noticeable in the currents. In the currents the zero system mode is dominant and it is to say that this mode is excited by the delayed closing of the breaker contacts. Since the ratio of current and voltage amplitudes at the beginning of the surge in the computation and in the test is about the same which means that the line representation is right, the reason for the appearance of these enlarged amplitudes must be sought in the generator representation. As long as not all breaker contacts are closed the generator is unsymmetrically loaded. It has solid iron poles and no damper windings. In the present computer program one equivalent damper winding in the direct axis is used to represent the damping effect of the solid iron. It is quite well known that one equivalent damper winding is not sufficient to reproduce the same effects as the solid iron in the generator especially when a negative sequence component appears as it is the case for the unsymmetrical load. The discrepancies of measurement and computation are probably to a large portion due to this insufficiency of the generator representation and the nonsimultaneous closing of the breaker contacts exciting a zero system mode. It might very well be that other cases where an almost simultaneous closing of the breaker contacts takes place would give better agreement with the same computer program since the unsymmetry in the generator does not appear there.

This observation of the appearance of a dominant zero system is quite important since in the system representation the zero system is quite often neglected or treated with less care.

The damping of the natural modes was reproduced quite well by the computation although the equivalent circuits for the skineffect in the conductors and for the ground return [5] were rather rough. A further improvement can be expected when the equivalent circuits are matched to the exact characteristics.

It has to be noted also that the computation is based on ideal symmetry which is not the case for the Tavanasa-Breite line.

CONCLUSIONS

The tests performed at the 420 kV line Tavanasa-Breite show that transient overvoltages appear practically only when the line is charged. They are highest when 2×60 MVA generators feed the line. A maximum peak voltage of 760 kV corresponding to an overvoltage factor of $k = 2.21$ would be obtained for this case if the voltage before closing the beaker is 420 kV line-to-line. For this case the sparkover voltage of the lightning arrester being 900 kV for the impulse is not reached. Under normal conditions four generators are employed and for this case the power frequency overvoltage during charging the line stays well below the rating of the arrester indicating that the coordination of the insulation is adequate.

The dropping of the line is harmless as long as the breakers do not restrike. Magnetic-type potential transformers very quickly discharge the line after opening the breaker.

It is interesting to note that the transients on the line die out rather quickly and that the voltages and currents with power-frequency being determined by the transient reactance of the generator and the line capacitance are reached a few cycles after closing the breaker.

The computation of the phase voltages and currents for the particular case where the line is charged by four generators of the Tavanasa power station shows reasonable agreement with the field test besides the initial amplitudes of current and voltage. The frequency and the damping of the natural modes are well reproduced. For the damping due to the conductors and the ground-return at higher frequencies equivalent circuits were introduced.

APPENDIX A

Fundamentals for the calculation of transients in synchronous machines and on three phase transmission lines as used in the present computation.

The fundamentals and assumptions for the calculation of transients in systems where a synchronous machine is connected to a three phase transmission line are represented here as they were used in the digital program which served as a means to compute the switching surges shown in this report. The digital program which is also adaptable to compute various fault cases in this machine-line system is described in appendix B.

1. *The synchronous machine.*—For the calculation of transients in the synchronous machine the two-reaction theory is best employed if the flux and ampere-turn distribution in the air-gap can be assumed sinusoidal. For the present case it is assumed that the damping of the solid iron pols as well as that of damper bars can be represented by a single equivalent damper winding in each of the two axes. According to the two-reaction theory the equivalent synchronous machine employed here has three windings in the direct axis and two in the quadrature axis [4]. To take saturation of the air gap flux into account a nonlinear relationship $f_d = f(a_{td})$ (noload characteristic) in the direct axis is introduced where f_d is the flux linkage in the direct axis being common to all three windings and a_{td} are the ampere-turns exciting this flux. A dependence of the reactances on the currents as it was noticed in the tests described in this report has not been considered.

The machine data given in Table 3 are sufficient according to the theory used to calculate all time constants, leakage coefficients, etc., necessary and thus to compute the transients.

2. *The excitation system.*—The dynamic behaviour of the exciter and the voltage regulator is described by a system of differential equations. Nonlinearities and amplitude limits can be present. For the present case the inductance and resistance of the armature of the exciter was taken into account, the voltage regulator was neglected since the exciter electromotive force did not change within the time interval considered here.

3. *The transformers at the sending end.*—The transformer reactance in the positive and negative sequence system was combined with the reactances of the generators such that an equivalent generator was formed. The reactance of the zero sequence system being earthed on one side due to the delta-star connection was considered separately.

4. *The three-phase transmission line.*—The three-phase transmission line as it was treated here has been considered as ideally symmetrical. Hence, the transients can be calculated on three independent equivalent systems corresponding to the natural modes [1, 2] after an appropriate transformation is introduced. Specifically, the line was transformed into its α, β and 0-system. For these systems surge impedances and wave velocities were given. The method of Schnyder-Bergeron [2] was used to compute the transients. This method does not allow to take line resistance, skineffect and ground return into account in a

straightforward manner since lumped elements can be inserted along the line only.

Here these lumped elements were chosen such that their frequency characteristics approximate that of the conductors including the skineffect and that of the ground return [5]. They consist of resistances and inductances in parallel.

The closing of the breaker contacts being non-simultaneous in the three phases can be easily treated in the α, β, 0-system.

APPENDIX B

A digital program to compute transients on a machine-transmission line system.

Since the charging of an unloaded transmission line by a synchronous machine and various disturbances on this system are quite common in practice and hence of particular interest, a digital program was set up to compute the switching surges in this configuration. The digital program is based on the fundamentals in appendix A.

It can be applied to a straight three phase transmission line consisting of five lossless line sections which are connected by lumped circuits. These lumped circuits can be adapted to represent various apparatus, line resistance, damping elements (skineffect), ground return, etc., by subroutines. The transmission line is fed by a synchronous generator over a transformer. To account for saturation in the generator the noload characteristic may be given in a straight line approximation. Allowance is made for the system of differential equations describing the excitation system. Since saturation in the direct axis has been included only this program is mainly valid for salient pole generators but it can be used for round rotor generators as well taking a certain inaccuracy into account.

The following operating and fault conditions can be treated with this program:

(*a*) Charging of an unloaded line which may be precharged. The breaker may be located in any place along the line. The closing of the three breaker contacts may be delayed.

(*b*) Load dropping in any location along the line.

(*c*) Clearing of a three phase short-circuit in any location along the line.

The specialities of this program lie in the fact that the line representation is three phase and that the machine representation in two axes includes damper windings, the excitation system and saturation.

The computational methods employed in the program are the one by Euler-Cauchy for the system of ordinary differential equations and the Bergeron method for the partial differential equations of the transmission line. Lumped elements inserted in the line (resistances, transformers, etc.) are treated by modification [2].

The digital program was set up for the Siemens 2002 computer of the Brown Boveri computation center in Baden.

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