DELAYED CURRENT ZEROS DUE TO OUT-OF-PHASE SYNCHRONIZING

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***Abstract*—Out-of-phase synchronizing occasionally occurs in power stations. The resulting fault current may exhibit delayed current zeros. These delayed current zeros have totally different causes and are quite dissimilar in comparison with the well-known delayed current zeros associated with generator terminal faults. The rapid movement of the rotor from initial out-of-phase angle δ_0 to $\delta = 0$ results in a very small a.c. component and a dominant d.c. component when $\delta = 0$ is reached. The various parameters influencing the extent of the delayed current zeros have been analyzed and are discussed. The most influential parameter is the initial out-of-phase angle δ_0. Other important parameters are inertia constant of the turbo set and initial deviation from synchronous speed. The influence of incorrect generator modelling on the result has also been demonstrated. The effect of circuit-breaker arc voltages on delayed current zeros has been examined and a comparison made between generator voltage and HV-side circuit-breakers. From this comparison follows that while circuit-breakers on both sides of the step-up transformer are necessary from a protection point of view, the generator circuit-breaker should preferably be used for synchronizing operations.**

I. INTRODUCTION

Out-of-phase synchronizing occasionally occurs in power stations, one of the main reasons being wiring errors made during maintenance of the synchronizing equipment. The resulting fault current may exhibit delayed current zeros. These delayed current zeros have totally different causes are quite dissimilar in comparison with the well-known layed current zeros associated with generator terminal f

Depending on generator data and moment of fault init tion [1-3], short-circuits close to a generator's terminals lead to delayed current zeros. In the case of three-phase faults this usually applies to the phase current exhibiting maximum asymmetry. However, if the current is interru in one of the phases, the d.c. component is immediately duced by ¼, resulting in current zeros in the remaining phases (Fig. 1) [4]. This allows fast current interruption all three phases. Since the d.c. time constant T_a is alway smaller than the transient time constant T_d', delayed cur zeros due to short-circuits are caused only by the subtran current component and its fast decay. Based on this shor description it is evident, that this problem is significant generators with a high subtransient current component (x_d'/x_d'' high and T_d'' very small) and a large d.c. time co stant T_a (i.e. r_a very small). The interruption of currents delayed zeros is made easier by the influence of the arc v age which reduces T_a and forces new current zeros.

During an out-of-phase synchronization, the currents i armature windings may also exhibit delayed zeros. The layed current zeros in this case, are caused primarily by fast movement of the rotor from an initial angle δ_0 to $\delta =$ For this reason, the inertia constant H_{tot} of the generator turbine set may have a decisive influence on this phenom non. Further, similar circuit-breakers in two power statio equipped with similar generators may be differently stres if the inertia constants of the turbines differ substantially This effect makes the phenomena more complex and con cated. Obviously, whether or not delayed current zeros d ing out-of-phase synchronizing would lead to a problem the circuit-breaker depends also on the type and setting o protection relays. In some plants circuit-breaker tripping substantially delayed or even locked out in the event of a out-of-phase synchronization. In this paper it has been as

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PE-596-EC-0-05-1997 A paper recommended and approved by the IEEE Electric Machinery Committee of the IEEE Power Engineering Society for publication in the IEEE Transactions on Energy Conversion. Manuscript submitted August 6, 1996; made available for printing May 15, 1997.

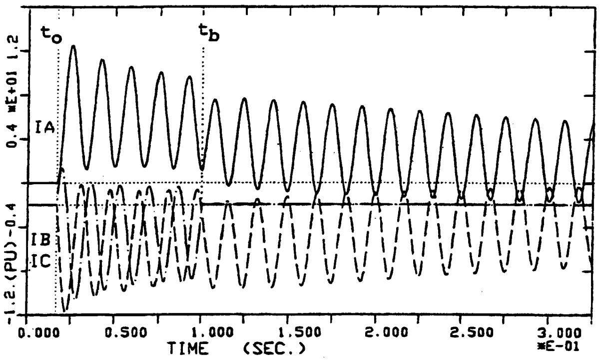

Fig. 1. **Generator current at L-L-L terminal short-circuit, u = 1pu, u_f (excitation voltage) = constant (note the displaced zero-line for phases B and C)**

sumed that fast tripping of the circuit-breaker is in the interest of the operating utility.

The relevant standards [7] make no mention of delayed current zeros due to out-of-phase synchronizing.

II. OUT-OF-PHASE SYNCHRONIZATION, PARAMETERS

The conditions resulting from out-of-phase synchronizing at $\delta_0 = +120°$ (generator voltage u_G leading network voltage u_N by 120°) and at maximum asymmetry in phase A are shown in Fig. 2a. The current components are:

$$i_{dc} \approx \frac{2u_G}{x_d'' + x_{Tr} + x_N} \sin(\delta_0 / 2) \exp(-t / T_{atot}) \quad (1)$$

$$i_{ac} \approx \frac{2u_G}{x_d' + x_{Tr} + x_N} \sin(\delta / 2) \quad (2)$$

The total d.c. time constant T_{atot} with $x_2 = 1/2(x_d'' + x_q'')$ is:

$$T_{atot} = (x_2 + x_{Tr} + x_N) / (r_a + r_{Tr} + r_N) 2\pi f_n \quad (3)$$

Finally, the equation for the rotor movement (angle δ) is:

$$-4 H_{tot} \pi f_n \frac{d^2\delta}{dt^2} = \frac{u_G u_N}{x_d' + x_{Tr} + x_N} \sin(\delta) + T_{asyn} \quad (4)$$

For the sake of simplicity, it has been assumed that $u_G = u_N$ for (1) and (2).

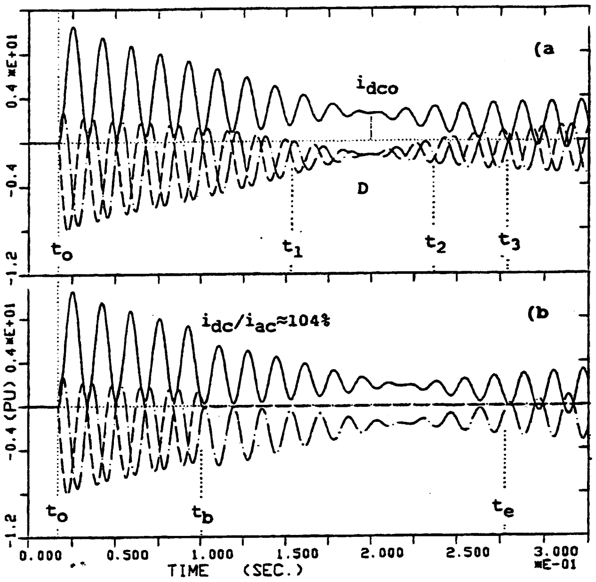

Fig. 2. **Out-of-phase synchronizing at $\delta_0 = +120°$, phase A fully asymmetric (turbogenerator, slip = 0, u_f = constant)**

a) without tripping of circuit-breaker

b) current interruption after about 80ms in phase B only

The a.c. component i_{ac} is quickly reduced by the change in rotor angle δ and hence there are no current zeros in phase A from t_0 to t_3 (Fig. 2a):

$$i_{ac} < i_{dc} \quad \text{for} \quad t_0 < t < t_3$$

When the generator circuit-breaker or the circuit-breaker on the HV-side of the step-up transformer opens, e.g. after about 80 ms, the current in phase B is interrupted at its natural current zero (t_b). The d.c. component is instantaneously reduced to ¾, but nevertheless there are no natural current zeros in the other two phases until t_e (Fig. 2b):

$$i_{ac} < i_{dc} \quad \text{for} \quad t_b < t < t_e$$

If the setting of the tripping delay of the protection relay is relatively high and the circuit-breaker opens only after about 150 ms, then the situation worsens, since there are no current zeros in any phase from 160 to 240 ms (Fig. 2a).

Some of the questions can be answered qualitatively by a short computer program written on the basis of (1) to (4). However, reliable results are best obtained by detailed simulation procedures. The equations show that the following groups of parameters influence the occurrence of delayed current zeros due to out-of-phase synchronizing:

- characteristic data of the generator:
  all reactances x_d, x_d'.....x_2, time constants T_d', T_d''.....and d.c. armature resistance r_a

- rotor angle δ:
  initial out-of-phase angle δ_0, differences in frequency and voltage, inertia constant H_{tot}, asynchronous braking torque of the generator (solid poles)
- data of the generator step-up transformer and of the connected system:
  x_{Tr}, r_{Tr}, short-circuit power and equivalent d.c. resistance
- closing instant, i.e. distribution of d.c. asymmetry in the three phases.

As a first step, these parameters and their influence are discussed in the immediately following sections. The effect of the arc voltages of generator circuit-breaker and high-voltage circuit-breaker will then be analyzed and compared. Large discrepancies in the closing times of the circuit-breaker poles may result in somewhat higher d.c. components. However, this effect has been ignored as all circuit-breakers must fulfill the rigorous requirements imposed by the relevant technical standards.

III. SYSTEM CONFIGURATION AND DATA

The analysis has been based on the configuration shown in Fig. 3, which is simple, but contains all relevant components. The voltage and power ratings assumed ensure that it can be considered as a typical example.

The generator, transformer and system parameters chosen are intentionally unfavorable:

- turbo-generator:

$x_d = 1.78$ pu $x_d' = 0.215$ pu $x_d'' = 0.145$ pu
 $T_d' = 0.69$ s $T_d'' = 0.015$ s
$x_q = 1.75$ pu $x_q' = 0.36$ pu $x_q'' = 0.145$ pu
 $T_q' = 0.148$ s $T_q'' = 0.015$ s
$r_a = 0.0012$ pu $x_a = 0.12$ pu $x_c = 0.138$ pu
$f_n = 60$ Hz $H_{tot} = 5.82$ s

- step-up transformer:

$x_{Tr} = 0.14$ pu $r_{Tr(d.c.)} = 0.0012$ pu

- system equivalent:

$x_N = 0.02$ pu $r_{N(d.c.)} = 0.00133$ pu

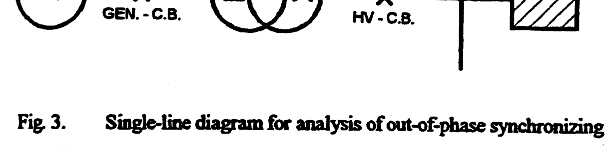

Fig. 3. Single-line diagram for analysis of out-of-phase synchronizing

For those cases where a generator with solid salient po has been examined, the relevant machine parameters ar given below, all other p.u. data remain unchanged.

- generator with solid salient poles:

$x_d = 1.58$ pu $x_d' = 0.274$ pu $x_d'' = 0.165$ p
 $T_d' = 2.13$ s $T_d'' = 0.0245$
$x_q = 0.99$ pu $x_q' = 0.396$ pu $x_q'' = 0.148$ p
 $T_q' = 0.239$ s $T_q'' = 0.013$ s
$r_a = 0.002$ pu $x_a = 0.115$ pu $x_c = 0.106$ pu
$f_n = 50$ Hz $H_{tot} = 2.8$ s

IV. INFLUENCE OF CLOSING INSTANT

D.C. asymmetry in the armature currents depends on a α between d.c. field axis and one of the phase axes. The a periodicity of 60°.

Case 1: one phase shows full asymmetry.
 i.e. $\alpha = 0°, 60°, \ldots$ as in Fig. 1 and 2
Case 2: one phase is symmetrical
 i.e. $\alpha = 30°, 90°, \ldots$

Fig. 4 shows out-of-phase synchronizing at $\delta_0 = +120°$ full symmetry in phase B (Case 2).

For the breaking capability of a circuit-breaker the rati

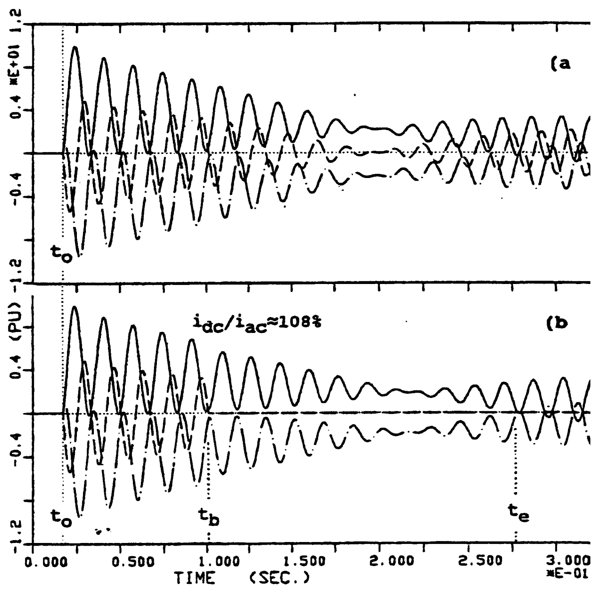

Fig. 4. Out-of-phase synchronizing at $\delta_0 = +120°$, phase B symmetric (turbogenerator, slip = 0, u_f = constant)
a) without tripping of circuit-breaker
b) current interruption after about 80ms in phase B only

i_{dc}/i_{ac} immediately after current interruption in one phase (instant t_b) is very important. In Fig. 2b (case 1) this ratio is $i_{dc}/i_{ac} \approx 104\%$. This means that small arc voltages, which result in only a modest reduction of the d.c. component, can cause immediate current zeros in the other phases.

Full symmetry in one phase according to Fig. 4b leads to $i_{dc}/i_{ac} = 108\%$. This case results in conditions slightly more severe for the circuit-breaker than Case 1. The results of a considerable number of simulations indicate that this is a general a trend. In critical cases, it is therefore recommended that both Cases 1 and 2 be investigated.

V. INFLUENCE OF OUT-OF-PHASE ANGLE δ_0

Out-of-phase synchronization starts at δ_0. If the total d.c. time constant T_{atot} is in the range of the time required to reach angle $\delta = 0$, then at $\delta = 0$ there is a significant residual d.c. component i_{dc0} (see Fig. 2a, instant D). The ratio i_{dc0} / i_{dcmax} with $i_{dcmax} \approx u_G / x_d''$ (maximum d.c. component of three-phase terminal short-circuit current of the generator)

$$i_{dc0} / i_{dcmax} \approx x_d''\, i_{dc0} \qquad (u_G = 1) \qquad (5)$$

may be considered as a qualitative measure of the d.c. component at out-of-phase synchronization.This statement is termed qualitative, because a different d.c. component will result when the circuit-breaker opens at an instant earlier than at $\delta = 0$.

In Fig. 5 this ratio is shown in relation to the out-of-phase angle δ_0. It can be seen that the highest relative d.c. component at $\delta = 0$ (D in Fig. 2a) occurs at an out-of-phase angle of $\delta_0 = +120°$ and amounts to about 35% of i_{dcmax}. The time required for the rotor to reach $\delta = 0$ is somewhat less than 200 ms. The highest d.c. components are related to $\delta_0 \approx +120°$. For synchronizing at $\delta_0 \approx -120°$ (u_G is lagging 120° network voltage u_N), the d.c. component is slightly lower. The reason for the asymmetry of the curves at $+\delta_0$ and $-\delta_0$ is the asynchronous braking torque T_{asyn}

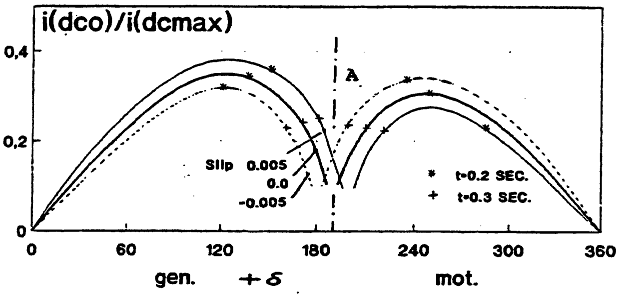

Fig. 5. Relative value of the d.c. current i_{dc0}/i_{dcmax} at $\delta = 0$ as a function of out-of-phase angle δ_0.

$$T_{asyn} \approx u^2 \left[A\left(T_d', T_q'\right) + A\left(T_d'', T_q''\right) + A\left(T_d''', T_q'''\right) \right] \qquad (6)$$

with

$$u \approx u_G \sin(\delta / 2)$$

$$A(T_d', T_q') = \pi f_n \left[\frac{\left(1/x_d' - 1/x_d\right) T_d'}{1 + \left(2\pi f_n T_d'\right)^2} + \frac{\left(1/x_q' - 1/x_q\right) T_q'}{1 + \left(2\pi f_n T_q'\right)^2} \right]$$

$$A\left(T_d'', T_q''\right) = ...$$

and so on.

This braking torque accelerates the backward movement of the rotor in the domain of positive δ_0 and decelerates the forward movement at negative δ_0. Hence the rotor reaches the instant $\delta = 0$ earlier for synchronizing at $+\delta_0$ than at $-\delta_0$. Consequently the d.c. component i_{dc0} is slightly higher for positive δ_0.

For generators with solid salient poles T_{asyn} is significantly higher than for turbo-generators or generators with laminated salient poles. Therefore, the asymmetry of the curves at $+\delta_0$ and $-\delta_0$ is even higher and the axis A in Fig. 5 is shifted to the right. For the computation of realistic magnitudes of T_{asyn} for generators with solid salient poles, sub-subtransient generator data must be taken into account [5].

VI. INFLUENCE OF DIFFERENCES IN SPEED AND VOLTAGE

During out-of-phase synchronizing there may be a comparatively small difference in frequencies. This deviation from the synchronous speed (as initial condition) influences the period of time until $\delta = 0$ is reached and hence the ratio i_{dc0} / i_{dcmax} at $\delta = 0$. Curves 2 and 3 in Fig. 5 show the extent of this influence. Curve 2 corresponds to generator speed 0.5% below and curve 3 to 0.5% above synchronous speed. It can be seen, that a lower generator speed increases the dissimilarity between the ranges $+\delta_0$ and $-\delta_0$. On the other hand, deviations in voltage of up to 5% at the simulation point have not exercised any substantial influence on the results of the computations. This applies equally to voltage changes due to automatic voltage regulators.

VII. INFLUENCE OF INERTIA CONSTANT H

The curves of Fig. 5 also indicate the period of time which elapses before $\delta = 0$ is reached, e.g. when synchronizing at $\delta_0 = +120°$ and 0.5% above synchronous speed the d.c. component at $\delta = 0$ (point D in Fig. 2a) is 32% of $1/x_d''$ and the time to reach $\delta = 0$ is about 200 ms. It is obvious that point D (a.c. component is negligibly small) is extremely important for a circuit-breaker which is required to open at this point in time. For such a circuit-breaker synchronizing at $\delta_0 = +120°$ would be the worst case.

It must be noted however, that these conclusions are case dependent and as such are not generally valid. If the total inertia constant of the generator is smaller than 5.82s, point D would be reached much earlier and the d.c. component i_{dc0} / i_{dcmax} would be even higher. Fig. 6 shows the influence of H_{tot}. It has been assumed that due to a different turbine, the inertia constant is now 2.81s. In this case, synchronizing at $\delta_0 = +120°$ leads to an elapsed time of only 130 ms before $\delta = 0$ is reached. The ratio i_{dc0} / i_{dcmax} equals 0.45, i.e. it is 25% higher than for H_{tot} = 5.82s.

Salient pole machines often have small inertia constants and hence require special attention.

VIII. OUT-OF-PHASE SYNCHRONIZING L-L-0 AND L-0

Out-of-phase synchronization often occurs in practice after maintenance of the synchronizing equipment. It can be shown, that certain wiring errors in the synchronizing a ratus may lead to out-of-phase synchronizing at δ_0 = 18 ±120° or ±60°. Synchronizing at δ_0 = 180° is very simil a terminal fault L-L-L. However, L-L-L synchronizing a = +120° results in the highest d.c. component at point D Moreover, in very rare cases, circuit-breaker closure ma occur only in two phases L-L-0 or in one phase L-0 (HV side). These three variants are compared in Fig. 2a and 7a, b. For the purposes of the simulations, it has been assumed that the step-up transformer has a vector group Y and that the transformer and system neutrals are ground

Obviously the time to point D increases for two- and si phase out-of-phase synchronizing. This was to be expect since the electrical torque is smaller for L-L-0 and L-0 t for L-L-L synchronizing. Conditions for a L-L-L synchr ing may be more severe in the case of an undelayed open operation of a circuit-breaker than L-L-0 or L-0. On the other hand, the case L-0 may cause substantial difficulti a circuit-breaker opening after 250 ÷ 300 ms.

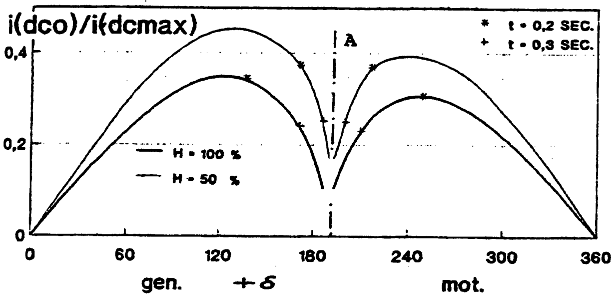

Fig. 6. Influence of the total inertia constant H_{tot} on the relative value of the d.c. current i_{dc0}/i_{dcmax} at $\delta = 0$

IX. INFLUENCE OF GENERATOR MODELLING

Correct modelling of the generator is very important fo investigatory procedure. Some national standards do not mention q-axis transient reactances and time constants a leave these parameters undefined. Further, many analyse the relevant literature disregard x_q' and T_q'. This approa

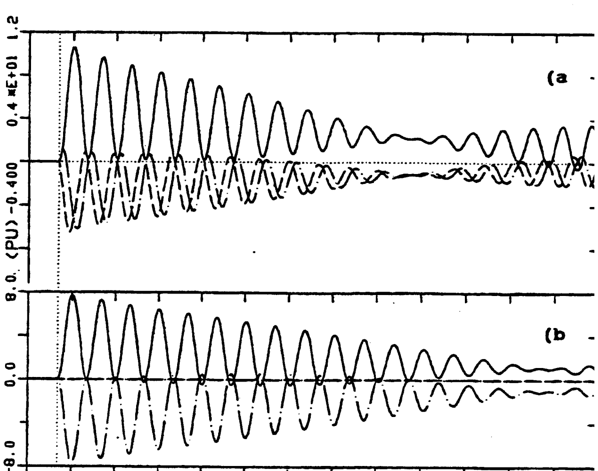

Fig. 7. L-L-0 and L-0 out-of-phase synchronizing at $\delta_0 = +120°$ with ful asymmetry in phase A (turbogenerator, slip = 0, u_f = constant)

a) L-L-0

b) L-0

can not be justified by physics, however in practice the characteristic q-axis data is not readily found nor easily determined. Disregarding the transient q-axis data of the turbo generator in our case results in a pseudo-aggravated situation for the circuit-breaker, i.e. i_{dc}/i_{ac} = 125% against an actual 108%.

The synchronizing of a generator with solid salient poles and H_{tot} = 2.8s at δ_0 = +120 is demonstrated in Fig. 8. Figure 8a corresponds to a simulation taking into account transient and subtransient data only. Actually the rotor movement from δ_0 to $\delta = 0$ is more rapid because of the solid poles and this requires the simulation of the machine using transient, subtransient and sub-subtransient data [5]. The result of a such simulation is given in Fig. 8b. In this case, the d.c. asymmetry i_{dc}/i_{ac} is increased e.g. 157% after 80 ms compared to 135% when sub-subtransient data are disregarded.

X. SPECIAL ASPECTS WHEN SYNCHRONIZING AT δ_0 = +60°

Synchronizing at δ_0 = +60° would appear to be far less critical considering the ratio i_{dc0}/i_{dcmax} as shown in Fig. 5. However, since $\delta = 0$ is reached sooner, the d.c. asymmetry i_{dc}/i_{ac} is higher for a substantial period of time. This is clearly visible from Fig. 9, where current interruption in one phase after 80 ms has been assumed. The ratio i_{dc}/i_{ac} after current interruption in one phase amounts to 178% i.e. the current is predominantly d.c.. Automatic voltage regulation which would immediately increase the excitation voltage reduces this ratio only very modestly i.e. to 175%. Disregarding the transient q-axis data would result in an increased i_{dc}/i_{ac} to 263%. Ratios of similar magnitude would apply to generators with salient poles.

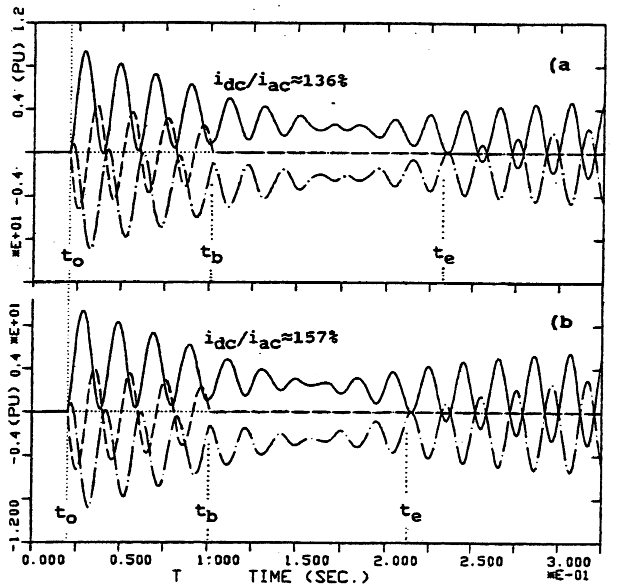

Fig. 8. Out-of-phase synchronizing at δ_0 = +120° on a generator with salient solid poles (phase B symmetric, slip = 0, u_f = constant, system frequency = 50Hz)

a) modelling without sub-subtransient data

b) modelling with sub-subtransient data

Synchronizing at δ_0 = +60° may therefore be very demanding on the circuit-breaker if it is tripped at an unfavorable instant. However, in this case the initial current is not very high, corresponding to a terminal fault at 50% - 60% u_G only.

XI. GENERATOR CIRCUIT-BREAKER VERSUS HIGH-VOLTAGE CIRCUIT-BREAKER

In the simulations shown above the circuit-breaker has been modelled as an ideal switch i.e. interrupting at current zero and exercising no influence on the flow of current. The arc voltage of a practical circuit-breaker - representing a nonlinear resistance - can reduce the d.c. time constant T_a of the circuit by a decisive amount and hence force current zeros.

Circuit-breaker arc voltages depend to a certain extent on the medium of arc extinction. For the widely used SF_6 circuit-breakers, typical magnitudes and shapes of arc voltage have been determined from a number of interrupting tests. It seems noteworthy, that only marginal differences have been found in this respect between a breaking unit of a generator circuit-breaker and a breaking unit of a high-voltage circuit-breaker, provided both use SF_6 at about the same pressure. A major difference may be the number of breaking units per phase, but a typical modern 245 kV- SF_6 circuit-breaker has only one breaking unit per phase. Hence for our case study it

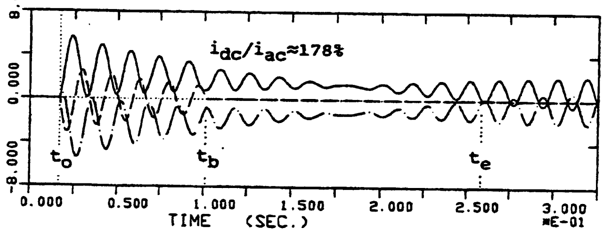

Fig. 9. Out-of-phase synchronizing at δ = +60°, phase B symmetric (turbogenerator, slip = 0, u_f = constant)

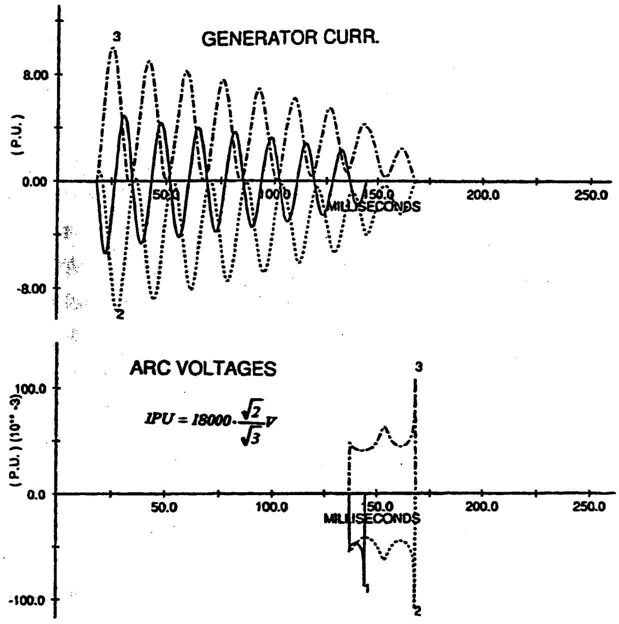

Fig. 10. Synchronizing at $\delta_0 = +120°$ and opening of generator circuit-breaker 120ms later

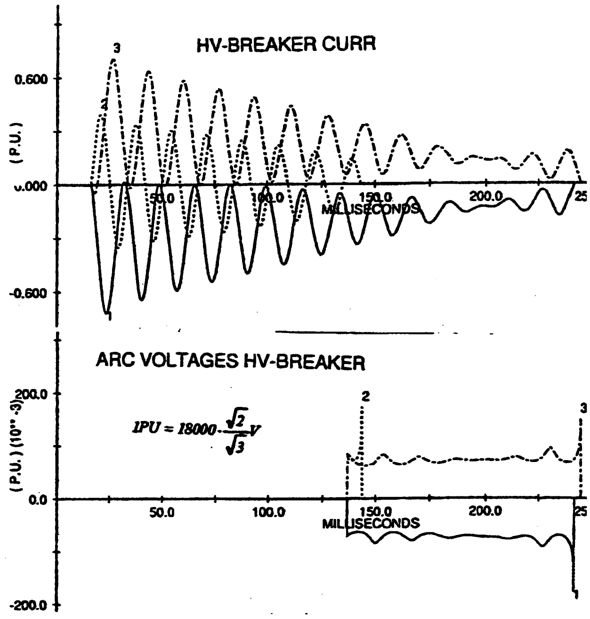

Fig. 11. Synchronizing at $\delta_0 = +120°$ and opening of HV-side circuit-br 120ms later

has been assumed that both the generator voltage and the high-voltage circuit-breakers have the same arc voltage characteristic. For our purposes, this may be approximated by

$$u_{arc} \approx sign(i)\cdot 3500\cdot(|i|)^{-\frac{1}{6}} \qquad (7)$$

which corresponds to an arc voltage of about 750V at 10 kA.

The essential question is whether or not, this arc voltage will be sufficient to force current zeros in all phases during the period of time, during which the circuit-breaker is able to interrupt i.e. about 40 ms from contact separation for a modern SF_6 self-extinguishing circuit-breaker.

The case used as the basis for Fig. 4, i.e. sychronizing at $\delta_0 = +120°$ in combination with a very unfavorable instant of operation of the generator circuit-breaker, i.e. contact separation after 120 ms, has been chosen to demonstrate the influence of the arc voltage. Fig. 10 shows the results of a simulation made by means of the Alternative Transients Program (ATP) [6]. Due to the arc voltages, the d.c. component decays quickly and the maximum arcing time is 35 ms, i.e. successful interruption.

If the circuit-breaker on the HV-side of the step-up transformer should be required to open under the same conditions, the result would be completely different (Fig. 11). Altho the arc voltage of the high-voltage circuit-breaker is the same, its generator side value is reduced by the transfor turns ratio and obviously has practically no affect on the time constant and the operation would result in failure t interrupt in two phases.

Fig. 12 has been obtained by varying the time to conta separation of the circuit-breaker (sum of relay time and opening time of the circuit-breaker) by regular intervals the period from 50 to 200 ms and for synchronizing at δ +120°. The curves show the maximum arcing times of t generator and high-voltage circuit-breakers against time contact separation. At short times to contact separation about 80 ms the high-voltage breaker is able to interrupt since there are current zeros in all three phases. Howeve curve is discontinuous at about 80 ms and arc duration j to about 140 ms, it then decreases steadily with increasi time. In contrast the generator circuit-breaker is able to rupt over the whole range of times to contact separation, showing only slightly increased arcing times for contact separation at times of between 110 and 180 ms.

It must be emphasized that the results of Fig. 12 are va for the specific case data listed and that widely differing

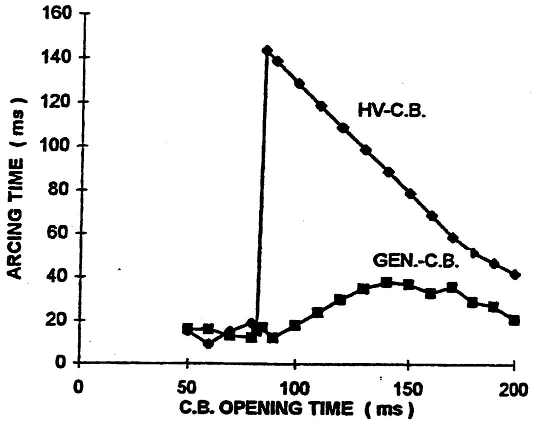

Fig. 12. Circuit-breaker opening after synchronizing at $\delta_0 = +120°$. Maximum arcing times versus time to contact separation

may lead to differing results. However, the statement that the arc voltage of a high-voltage circuit-breaker has only marginal influence on the total dc time constant under out-of-phase synchronizing conditions is generally valid.

XII. CONCLUSIONS

The following conclusions may be drawn from theoretical considerations and a multitude of simulations:

- Delayed current zeros at out-of-phase synchronizing are caused by fast movement of the rotor from δ_0 to $\delta = 0$. They are characterized by fast decaying ac components having their minimum values at $\delta = 0$. Predominantly d.c. currents may flow for some periods in the armature windings. This phenomenon is basically different from the delayed current zeros resulting from generator terminal faults.
- Regarding the distribution of d.c. asymmetry between phases i.e. at instant of closing, two cases have to be considered:
  - current in one phase fully asymmetrical
  - current in one phase symmetrical,

  the latter case being slightly more unfavorable.
- The d.c. component at $\delta = 0$ (ac component minimum) may be considered as a measure of the severity of current interruption by the circuit-breaker in the circuit. It exhibits a maximum for $\delta_0 \approx +120°$ and $\delta_0 \approx -120°$. However, it is highest for $\delta_0 = +120°$. The reason for this asymmetry is the asynchronous braking torque.
- An initial speed lower than synchronous speed will shorten the time to reach $\delta = 0$ for positive δ_0, i.e. will result in a higher d.c. component at $\delta = 0$.
- Initial voltage differences (amount) and automatic voltage regulation have little influence on i_{dc} at $\delta = 0$.
- A smaller total inertia constant H reduces the time to $\delta = 0$, producing a higher d.c. component at $\delta = 0$.
- Out-of-phase synchronizing in one phase (HV-side) or two phases lengthens the time to $\delta = 0$, due to the smaller electrical torque. Attention should be paid to its influence when circuit-breaker tripping is delayed.
- Correct modelling of the generator is essential. Disregarding transient q-axis data leads to pessimistic results, disregarding sub-subtransient data of generators with salient solid poles to excessively optimistic results.
- The phenomenon is highly dependent on electrical as well as on mechanical data. Hence variations of up to 10 % and more in characteristic generator data may influence the phenomenon decisively and consequently the values for the investigation should be chosen conservatively.
- If the circuit-breaker on the HV-side of the step-up transformer is required to interrupt out-of-phase synchronizing currents, there is a time domain where it is difficult or impossible to force current zeros. The arc voltage of the high voltage circuit-breaker is reduced by the turn ratio of the step-up transformer to an ineffective value. This fact has to be taken into account when the setting of the protection relays (i.e. the tripping delay) is determined.
- In contrast, the generator circuit-breaker has a considerable potential for forcing current zeros over the whole range of times to contact separation. Arc voltage data of an actual SF_6 generator circuit-breaker lead to maximum arcing times of 40 ms i.e. successful interruption even under extremely unfavorable conditions.
- From the above follows that while circuit-breakers on both sides of the step-up transformer are necessary from a protection point of view, the generator circuit-breaker should preferably be used for synchronizing operations.

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