5. Black box arc modelling

Circuit-breaker's performance in power system is analysed by representing the circuit-breaker characteristics by a function of electrical parameters such as current/voltage, and combining with, though complicated, power system circuit. For such purposes, so-called "Black-box modelling" is applied, in which, despite of actual circuit-breaker hard-ware such as contact shape, gas pressure, number of breaking point, etc., a mathematical function of electrical parameters is introduced. In the chapter, as being popularly used equations, Mayr arc model and Cassie arc model are taken up.

5.1 Mayr arc model

In Mayr's arc modelling, assuming constant arc diameter, constant arc power loss, Saha's expression of arc conductivity, etc. the following expression is deduced.:

$$\frac{1}{G}\frac{dG}{dt} = \frac{1}{\theta}\left(\frac{EI}{N_0} - 1\right)$$

where, G: Arc conductivity θ: Arc time constant E: Arc voltage I: Arc current N_0: Arc loss constant

Introducing Laplace operator "s" the equation is rewritten as,

$$G_0 = I^2 / N_0 \qquad G = G_0/(1+\theta s)$$

These equations are easily introduced to TACS in ATP-EMTP, and the result G can be the arc conductance, the reciprocal of which is introduced as the circuit-breaker into the system circuit. For details, see the attached data files.

Mayr arc model is suitably applied to low current (< several tens A) of arc, or even post arc current arc.

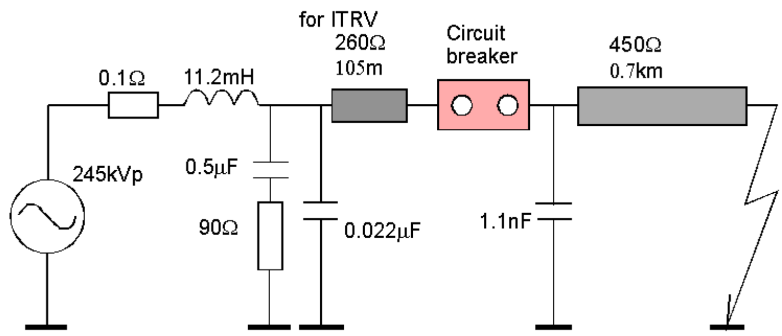


Fig. 5.1 Short line fault breaking circuit 300kV, 50kA, L90 condition

Though fault current of a circuit-breaker is very high, current interrupting is phenomena around current zero, so Mayr arc model is suitably applicable. Also the model is applicable to "arc", i.e. high temperature gas predominant time region, therefore, so called "Inter-action interval" is a typical application.

Note:

- After the Inter-action interval, the time interval is called as "High-voltage interval", where dielectric phenomena are significant, so another model(s) is to be applied.

As the first example, short line fault current breaking is taken up. Fig. 5.1 shows basic (simplified) circuit according to IEC standard for 300kV, 50kA circuit-breaker's L90 (SLF current is 90% of terminal fault one) rated condition. For the circuit-breaker, Mayer arc model is applied,

where, θ(time constant) = 1 μs, N_0(arc loss) = 293kW

The main part of current breaking phenomena in this case lasts several micro seconds, and, also very short length of distributed parameter line for ITRV is involved. Therefore very short step time

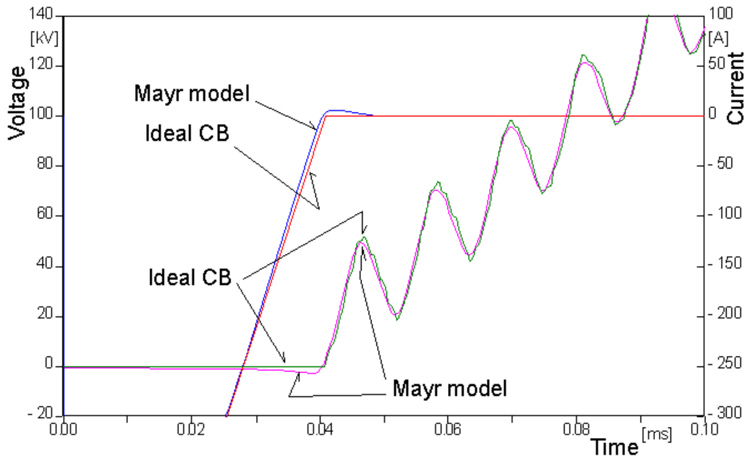
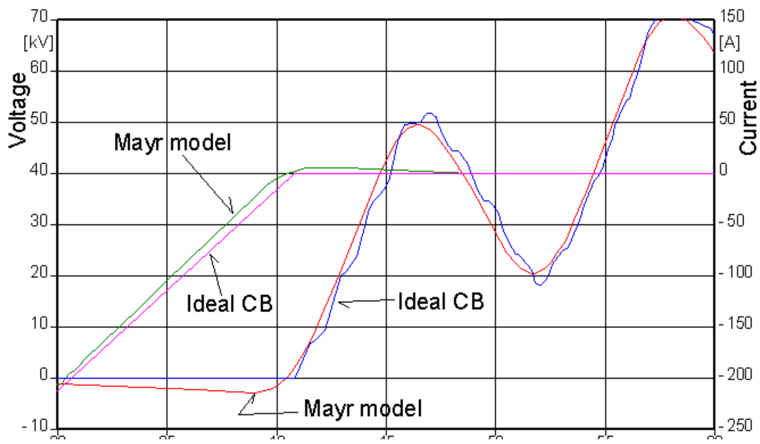


Fig. 5.2 Breaking current and TRV by Mayr model arc and Ideal circuit-breaker

is required in EMTP. For shorter TMAX (total time), suitable TACS initialisation is recommended. For details, see the attached data file. The calculations in this case were done for 100 μseconds around current zero (current interruption).

Fig. 5.2 shows breaking current and TRV in comparison with by ideal circuit-breaker (without arc voltage, infinitive dielectric recovery after current interruption). The main part is zoomed in Fig. 5.3. The above shown Mayr arc parameters θ and N_0 are critical one, i.e. higher. θ and/or lower N_0 bring failure in current breaking. These values seem to be typical of SF_6 gas circuit-breaker.



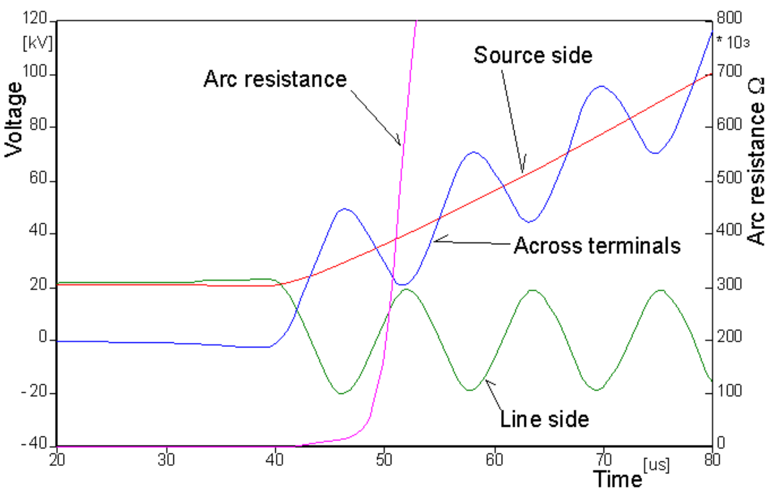


Fig. 5.4 Voltages and arc resistance

Compared to by ideal circuit-breaker, current zero, i.e. interruption is made, though by a little, earlier due to the arc voltage. After current zero, inverse direction of current, called as “post-arc current” flows, the magnitude of which is in the order of several A.

As for TRV by the circuit-breaker, ITRV oscillation is entirely damped and smooth wave shape appears.

In Fig. 5.4, the arc resistance variation is shown. Up to the current zero, the resistance is very low. Then, gradually it increases and after the first peak of the TRV, it quite rapidly enhances up to quasi infinitive. So, around the current zero, the relatively low arc resistance damps ITRV oscillation.

From these, the energy balance just after the current zero is understood, i.e. by the comparison of injecting energy by TRV and the energy loss, breaking success/failure is determined. In very critical failure state, i.e. by a little higher θ or lower N_0, the current recovers at several micro seconds after the current zero. You should try. !!

Fig. 5.5 shows an alternative circuit, which is approved in IEC standard as equivalent to Fig. 5.1, main purpose of which is making easier the breaking test. For details, see IEC standard 62271-100.

In the circuit, ITRV circuit is excluded and, instead, the ramp capacitance at the line side terminal is lowered. Then the TRV across terminals is mostly equivalent to the original one.

By the circuit, introducing

θ= 1.0 μs

N_0= 300kW

critical condition is obtained. Much fortunately by quasi equal arc parameters, the critical condition appears and both circuits are evaluated to be equivalent. Nevertheless, in Fig. 5.6, some differences in post arc current and TRV damping are observed. The circuit in Fig. 5.5 produces much post arc current and much damping of TRV.

By circuit-breakers with another arc parameters (θ, N_0), the results may be different.

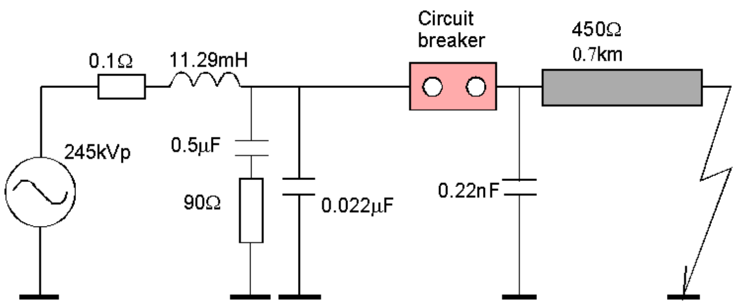


Fig. 5.5 Alternative circuit to Fig. 5.1

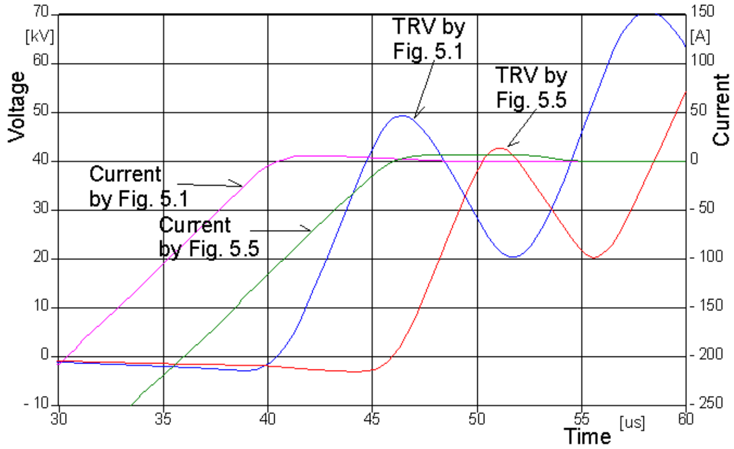


Fig. 5.6 Breaking currents and TRVs by Fig. 5.1 and 5.5

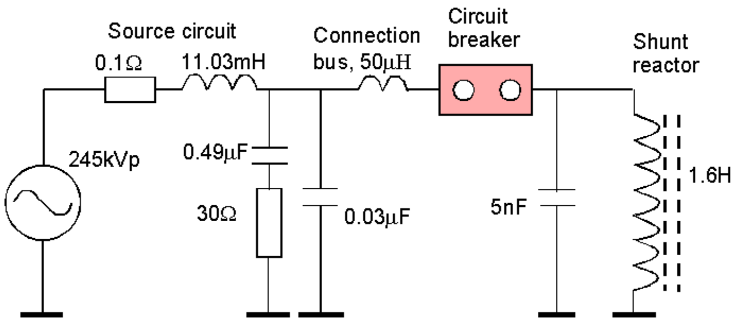


Fig. 5.7 Shunt reactor switching circuit
300kV, 150MVA, Single phase representation

As the next example, shunt reactor switching is taken up. When shunt reactor magnetising current is switched off by a circuit-breaker, while the current approaching the relevant current zero, oscillation is initiated. Especially for smaller current region, circuit-breaker arc exhibits negative V-I characteristic. By Mayr arc equation above shown, for (quasi) steady state, i.e. d/dt=0, EI = Const. i.e. negative characteristic appears. Inserting a negative resistor into a L-C circuit, oscillation is created. Actually in the primary state of radio technology, arc was applied to oscillator.

In Fig. 5.7, 300kV, 150MVA shunt reactor switching circuit (single phase representation) is shown. Shunt reactor inductive current is easily interrupted, so generally the interruption occurs in relatively shorter arcing time, i.e. smaller contact gap and lower blasting gas pressure. As for the arc parameter, lower arc loss seems to be suitable. Lets introduce the following parameters.

θ(time constant) = 0.5 μs, N_0(arc loss) = 15kW

The values are arbitrary ones, but at least from the following results, seems to be suitable for modern SF_6 gas circuit-breaker. For detailed modelling, also see the attached data file.

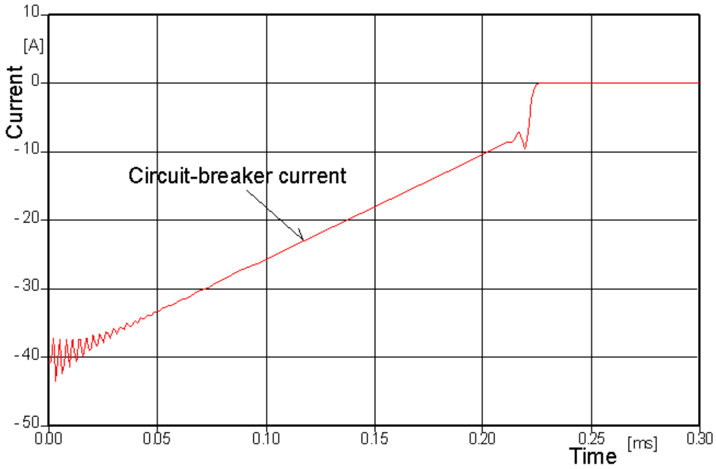


Fig. 5.8 Current chopping by shunt reactor current breaking

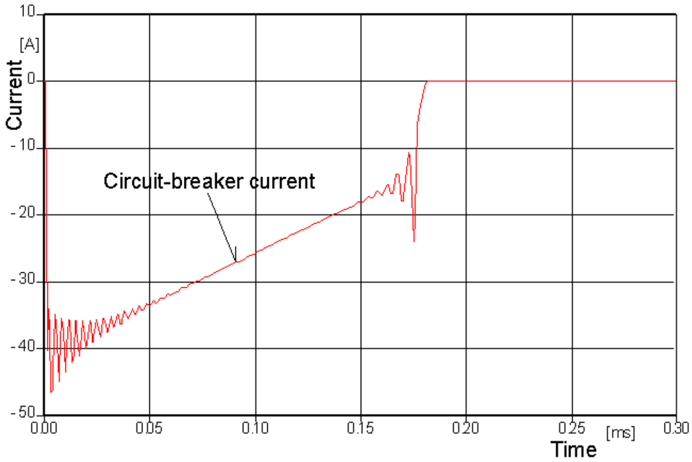


Fig. 5.9 Ditto, but doubled N_0

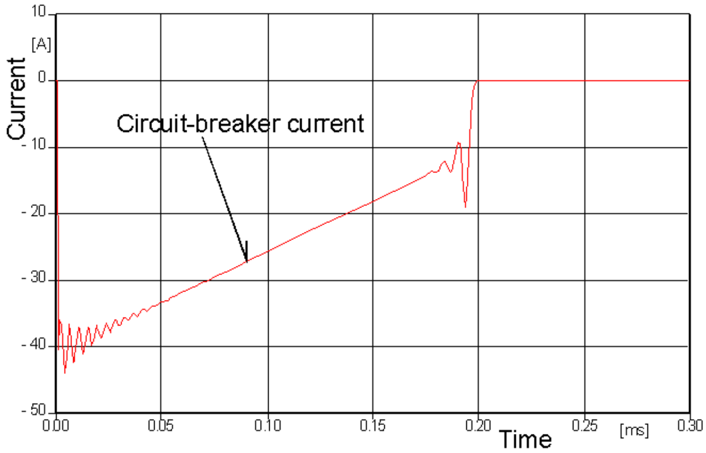


Fig. 5.10 Same as Fig. 5.8, but doubled reactor parallel capacitor from 5nF to 10nF

Calculated circuit-breaker current is shown in Fig. 5.8. Before approaching the prospective current zero, at ca. 8A, oscillation begins and by the oscillating current zero, i.e. before the prospective interruption time, the current is interrupted. Roughly looking, the current is chopped at ca. 8A. Therefore the phenomena is called as current chopping.

In the figure, the first part oscillation is created by switching for the calculation purpose This may help to introduce disturbance to create oscillation.

By doubling N_0, corresponding to longer arcing time (longer contact gap), higher gas pressure, or multi-break circuit-breaker, the calculated result is shown in Fig. 5.9, where oscillation initiating current is almost doubled from the above case. Such phenomena is know, i.e. by stronger quenching force, chopping current is higher.

In some literatures, chopping current is reported as approximately proportional to square root of breaking point number. Factor other than N_0 may be dominant by increasing breaking point.

The next example, shown in Fig. 5.10, is by doubled parallel capacitance to the reactor winding. In the relevant oscillation circuit, i.e. 0.03 μ F, 50 μ H, circuit-breaker and the relevant capacitor, which is called as “second parallel oscillation circuit,” actually the capacitance value is doubled. Then as mentioned in some literatures, the chopping current is enhanced approximately proportional to the capacitance value.

5.2 Cassie arc model

In Cassie arc modelling, the assumptions are:

- Heat loss depends on the arc flow (convection loss).
- Heat loss, stored heat, and electrical conductance are proportional to the cross section area.

Then, as the result, the following is obtained.

$$\frac{1}{G}\frac{dG}{dt}=\frac{1}{\theta}\left(\frac{E^2}{E_0^{\ 2}}-1\right)$$

where, E = Arc voltage, E_0 = Constant, θ= Arc time constant, G = Arc conductance.

The above assumptions correspond to relatively high current of arc, such as higher than several hundred A, so Cassie arc model is applicable to higher current of arc.

Introducing to EMTP-TACS, following rewriting is useful.

$$G_0=G^2 \quad \left(G=\sqrt{G_0}\right) \qquad G=I/E \qquad G_0=\frac{I^2}{E_0^{\ 2}}\frac{1}{1+\theta s} \qquad R=1/G$$

These equations are, likewise as Mayr model easily introduced to TACS. For details, see the attached data file.

For steady state, i.e. d/dt = 0, arc voltage E equal constant E_0. Therefore, as the equation is to be applied to relatively long time interval of high current region, to introduce just appropriate E_0 value is important. As an example, so called zero skipping current breaking near a synchronous generator is taken up.

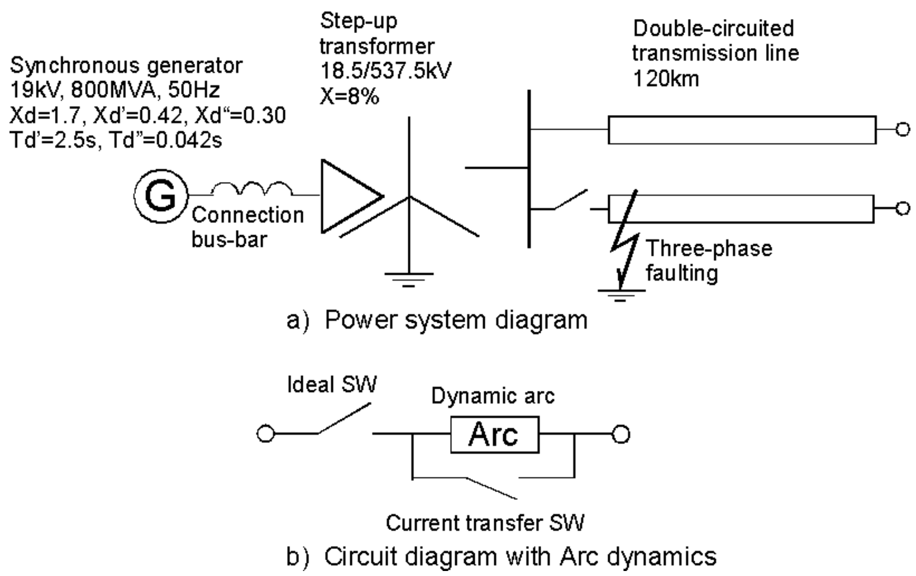


Fig. 5.11 Circuit for zero skipping current breaking calculation

In Fig. 5.11 a), the generator is supplying transmission line charging current via the step-up transformer. Close to the 550kV bus bar, three-phase grounding faults occurs in one of the two circuits. Non simultaneous faulting is introduced, i.e. three-phase point on wave individual timing of faulting to create max of current zero skipping. Actually, the faulting timing is, 14ms, 8.3ms and 8.3ms for phase A, B and C respectively from the voltage crest in phase A. The timing was gotten by trial and error procedure. Therefore such high rate of zero skipping of current could seldom be created.

For introducing circuit-breaker's dynamic arc characteristics calculated by TACS, circuit diagram in Fig. 5.11 b) is used. The main reason is TACS is active only after time 0, so for initialisation purpose, i.e. for t < 0, the switch connected in parallel is required. For more details, see the attached data files. Some important generator parameters applied are shown in the figure. Also for other details of modelling synchronous generator, see the following chapter(s).

In Fig. 5.12, three-phase short circuit current is shown, where in phases A and C apparently no

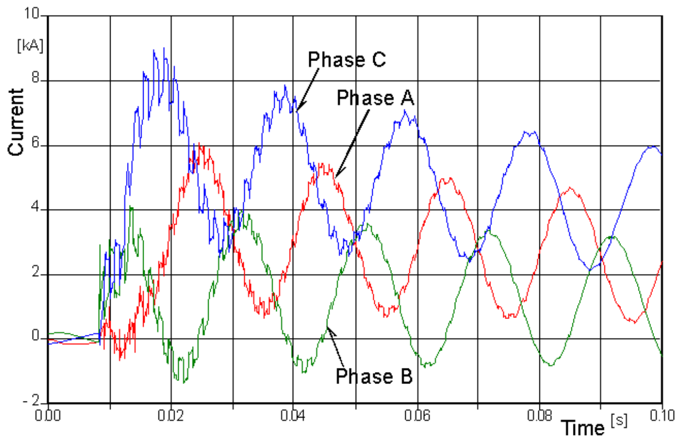


Fig. 5.12 Zero skipping short-circuit current without influence of circuit-breaker arc

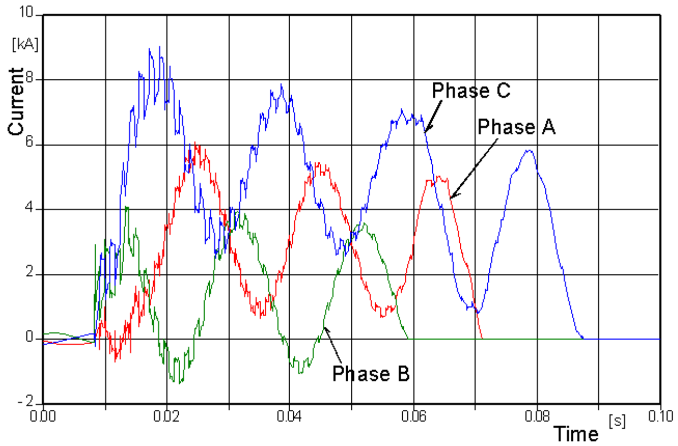


Fig. 5.13 Breaking by ideal circuit-breaker

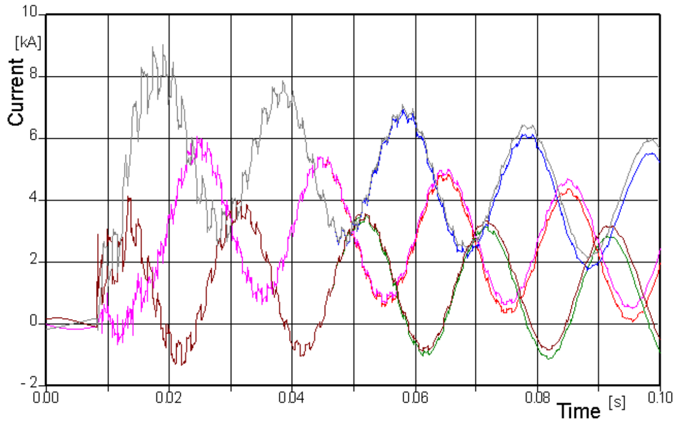


Fig. 5.14 Three-phase fault currents with and without arc voltages

current zero exists. Though the fault initiating timing truly seldom occurs, and practically not necessary to consider from statistical point of view, here the phenomenon is taken up as the base.

In Fig. 5.13, introducing an ideal circuit breaker which has zero arc voltage and can interrupt current at the first current zero, the three-phase fault currents are tried to be interrupted. The contact opening time is set to 0.048s. In phase B current zeros exist, so at the first current zero, it is interrupted. Introducing zero sequence components due to asymmetry of the circuit by one phase of interruption, dc components in phase A and C are much damped very soon current zeros appear. Then the currents in the rest two phases are interrupted.

Introducing Cassie dynamic arc, i.e. inserting arc voltage to the circuit, dc components in three-phases' currents are expected to be much damped. So assuming N_0 = 1000Volt, i.e. as the mean arc voltage, three-phase fault current were calculated. In Fig. 5.14, in comparison with the case without arc voltage in Fig. 5.12, current wave shapes are shown. The difference is very small. This is thought to be the fact that the arc voltage is so small comparing to the system voltage.

Inserting an ideal circuit-breaker in series to the arc model as shown in Fig. 5.11 b), so as to interrupt current at the first current zero, the three-phases' currents calculated are shown in Fig. 5.15. Due to small difference between with and without arc voltage as shown in Fig. 5.14, the current interruption phenomena is not so different from that in Fig. 5.13. Therefore, it can be said that arc voltage of in the order of 1000V does not introduce significant effect on zero skipping current interruption in 500kV system.

The next trial is, though un-realistic, to introduce 10000V of arc voltage.

Due to the higher damping effect on dc component, current zero in skipping phase(s) appears earlier, so the total fault time interval is significantly shortened. See Fig. 5.16.

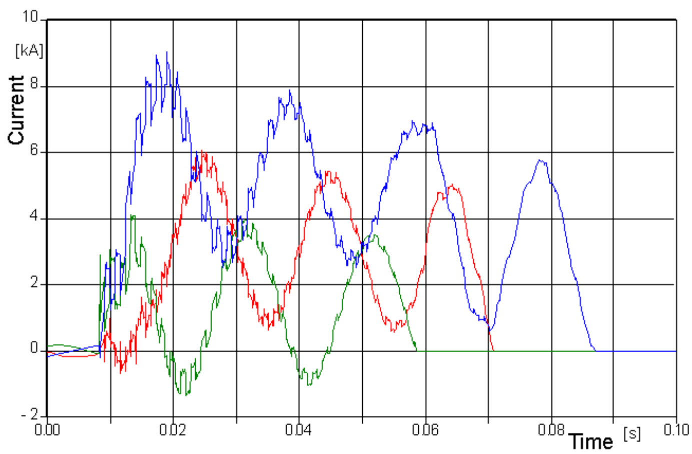


Fig. 5.15 Fault current interruption by a circuit-breaker with Cassie arc model ------ N_0 = 1000 Volt

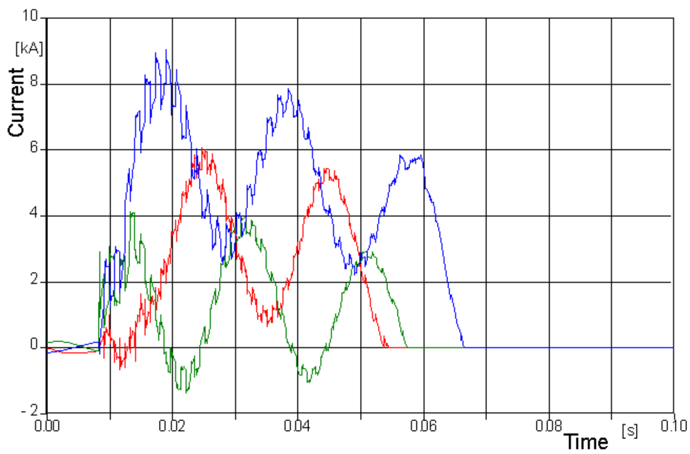


Fig. 5.16 Ditto, but N_0 = 10000 Volt

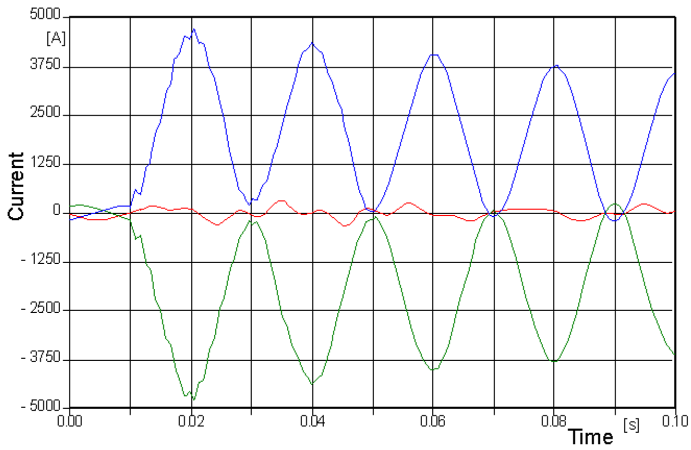


Fig. 5.17 Two phase isolated fault case

What can be said in the section are,

- Significant current zero skipping is of rare occurrence by quite special fault timing of fault initiation.
- Even though of such case, at least one phase current has current zero, so the phase current can be interrupted by usual ac circuit-breaker. After at least one phase of fault current interruption, the other phase's current zero(s) comes soon due to inserting zero sequence parameter (resistance) to the circuit. Then three-phase fault current can be interrupted by usual ac circuit-breaker.
- For introducing significant effect on sooner current zero coming, in the order of 10000V of arc voltage is necessary in 500kV system.

In two phase isolated fault case, due to non-insertion of zero sequence parameter to the circuit, much complicated phenomena is foreseen. But due to the less damping of ac component, sooner current zero coming appears, see Fig. 5.17.

Care should be taken that, in this section, considering high voltage ac circuit-breaker arc, current zero skipping only in high voltage system circuit is taken up. Other current zero skipping such as in shunt reactor making current superimposing on capacitive current, or that in generator circuit is to be surveyed separately.

Attached data files

- Data5-00.dat Short-line-fault (SLF) current breaking according to IEC 62271-100, 300kV, 50kA, 50Hz, L90 (Current interruption by ideal circuit-breaker)
- Data5-01.dat Ditto, but by CB with Mayr arc characteristics, θ=1 μs, N_0=293kW
- Data5-02.dat Ditto, but by alternative test circuit according to IEC 62271-100 (without T_{dl}, without ITRV), N_0=300kW
- Data5-03.dat Current chopping in shunt reactor current interruption, 300kV, 150MVA reactor,

CB with Mayr arc characteristics, θ=0.5 μs, N_0=15kW
- Data5-04.dat Ditto, but N_0 is increased to 30kW
- Data5-05.dat Same as previous but one, with increased parallel capacitance from 5nF to 10nF.
- Data5-11.dat Current zero skipping in HV side of generator step-up transformer, without arc voltage (system circuit prospective).
- Data5-12.dat Ditto, fault current is interrupted by ideal circuit-breaker without arc voltage. Three-phase fault currents are interrupted phase by phase.
- Data5-13.dat Same as previous but one, but inserting Cassie model arc characteristics (arc voltage).
- Data5-14.dat Ditto and also inserting ideal circuit-breaker in series to the arc model to interrupt current at the first current zero.
- Data5-1Z.dat Ditto but the arc voltage is enhanced to 10 times of the previous one to bring significant effect of the circuit-breaker arc.
- Data5-16.dat Two-phase isolated fault case.