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ANALYSIS OF FAULTS INTERRUPTED BY GENERATOR CIRCUIT BREAKER SF_6

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Abstract: *This article describes the analysis of faults interrupted by generator circuit breaker (SF_6). This work is focused on the analysis of all types of faults that occur in three phase network. There is derived the whole spectrum of network parameters: voltage, nominal short fault currents, maximal value of recovery voltage as well as the RRRV. There are introduced valuable experiments of interrupting time interval for each individual standardised discipline. The comparison of network parameters to circuit breaker interrupting capability determines circuit breaker's limited interrupting characteristics and thus reliable fault's interruption. This analysis includes also an asymmetrical fault with respect to longer arcing time. These results will serve for design as well as testing of quenching chambers of circuit breakers.*

Key words: *Generator circuit- breaker, SF_6, Recovery voltage, Arc voltage, System fed fault.*

INTRODUCTION

Generator circuit breaker is located between generator and step-up transformer in power networks and its ratings usually range from 1000MVA to 1300MVA. Owing to the potentially high asymmetrical fault levels at relatively low voltage near the terminals of generator, the current interruption requirements of GenCB are significantly higher than in the distribution networks at similar voltages.

The CB has to withstand extreme stresses due to the conduction of rated current and interruption of very large short fault current – the range is from 50 kA to 200kA. CB must interrupt in all situations that may occur in 3-phase net, independently on sequence of current zero and tripping impulse initiated mechanical function. Moreover, after interruption current appear very severe transient recovery voltages across the breaker. One of the most important parameters characterises interruption capability is ITI – Interrupting Time Interval.

Because of these high current rating properties, testing of GenCB is very expensive and time demanding.

1 GENERATOR CIRCUIT BREAKER

With use references [2], [3], [4], [5], [6]

Generator circuit breaker is located between generator and step-up transformer (*Fig 1.*) in power networks and its ratings usually range from 1000MVA to 1300MVA. Owing to the potentially high asymmetrical fault levels at relatively low voltage near the terminals of generator, the current interruption requirements of GenCB are significantly higher than in the distribution networks at similar voltages.

Modern GenCBs are using self-blast interrupting principles in order to reduce the operating energy of the circuit breaker. With this special design, the GenCBs are capable of interrupting also short circuit currents with high asymmetries.

During a breaking operation by an SF_6 GenCB, the arc voltage modifies the behaviours of the short circuit current. Therefore, GenCBs usually exhibit significant arc voltages with short arcing times.

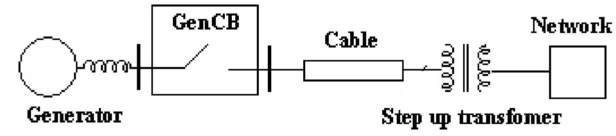


Fig.1: System-source fault of generator circuit breaker

There exists a few number of different mathematical circuit breaker models and are mostly characterized by experimentally measured parameters to describe the dielectric properties of different phenomena taking place in the breaker opening process. At the moment there is no existing precise universal arc model - because of the complexity of the arc physics. On the other hand, most of the models mainly focus on describing the breaker behaviours during the current zero periods and ignore the importance of arc voltage.

This work is focused on the comparison of network parameters with interrupting circuit breakers parameters included an asymmetrical fault. There are derived characteristics of the whole spectrum of parameters: voltage, nominal short currents, maximal value of recovery voltage as well as the rate of rise of recovery voltage (RRRV). The analysis results in time-current interrupting characteristics that will serve for a reliable design of the quenching chamber of circuit breakers.

The interrupting process could be described in four main stages of the breakers' operating processes:

- closed contacts
- arc burning
- arc extinguishing
- opened contacts

Thus, not only the dynamic conductance during current zero has been considered but also the effects of arc voltage on the arcing times have been included.

The critical parameters determining the reliability of interrupting are external network parameters are:
rated voltage U_N, rated breaking current I_{BN} and derived transient phenomena parameters.

Internal limiting parameters of GenCB are derived:

- in interaction interval from power supply and power losses and they could be represented by:
  $Q_i = du/dt * di/dt$ (1)
- In dielectric interval breakdown voltage represented by:
  $Q_u = U_{BD} / U_{network}$ (2)

These limiting parameters the GenCB must be above network parameters in the whole spectrum of disciplines (including asymmetrical fault) in so-called ITI.

2 INTERRUPTING TIME INTERVAL

With use references [3], [6]

Interrupting capability of GenCB is limited within the "interrupting time interval" – ITI in that GenCB is able to interrupt. It is related to the design of GenCB. In publications is also used the term "arcing window" in that arc burn. But arc can burn even if GenCB failures and therefore it seems more accrued to use the term ITI. The GenCB must interrupt all faults that may occur in three phase network with respect to its mechanical function by accidental contact separation independent on current zero. The GenCB must be designed and tested to prove sufficient interrupting capability within interrupting time interval (ITI) in the whole broad spectrum of electrical and mechanical parameters that can occur. ITI of GenCB is also dependent on the value of current and non-simultaneity contact separation between quenching chamber in a pole and between poles and power frequency.

2.1 Arcing time

The GenCB exploiting the thermal energy of the arc combined with a puffer action, high breaking capacity can be realized with low operating energy. The CBs using this technology are so-called self-blast CBs.

$$ITI = t_w = t_{amax} - t_{amin} \quad (3)$$

The minimal arcing time t_{amin} is influenced only by interrupted parameters (voltage, current, the first TRV peak etc.) The maximal arcing time t_{amax} is limited by interrupting capability – sufficient pressure gradient that provides gas flow thereby arc cooling.

The arcing window has to be long enough to ensure safe interruption. On the other hand it's extending leads to over-designing of quenching chamber and thereby increase in price of circuit breaker.

Experimental results shown on Fig 2. can be considered generally valid for the same principle of SF_6 CB i.e. also for GenCB.

2.2 Generator circuit breaker testing

The GenCB has to be adequately tested. In most cases the available short-circuit power sources of test laboratories are insufficient to perform those tests in a direct circuit and therefore synthetic test methods have to be applied. The three phase GenCB cannot tested by interrupting the three phase fault because of power insufficiency of HV testing station. Thus the GenCB is being tested in one phase testing circuit and experimental conditions are set to correspond to three phase interrupting.

The very beginning of interrupting process starts by tripping impulse to the CB and following movement of contacts. The origin of interrupting is considered the contact disconnection and arc burning. The end of interrupting is the moment when the arc extinguishes and current is broken.

The interrupting impulse is not synchronised with current zero and therefore the contact disconnection is independent on current zero and may occur in any moment of course of alternating current.

The parameters of asymmetrical fault, fault in earthed/insulated network must be taken into account as well as different conditions of one/two/three phase fault interrupting.

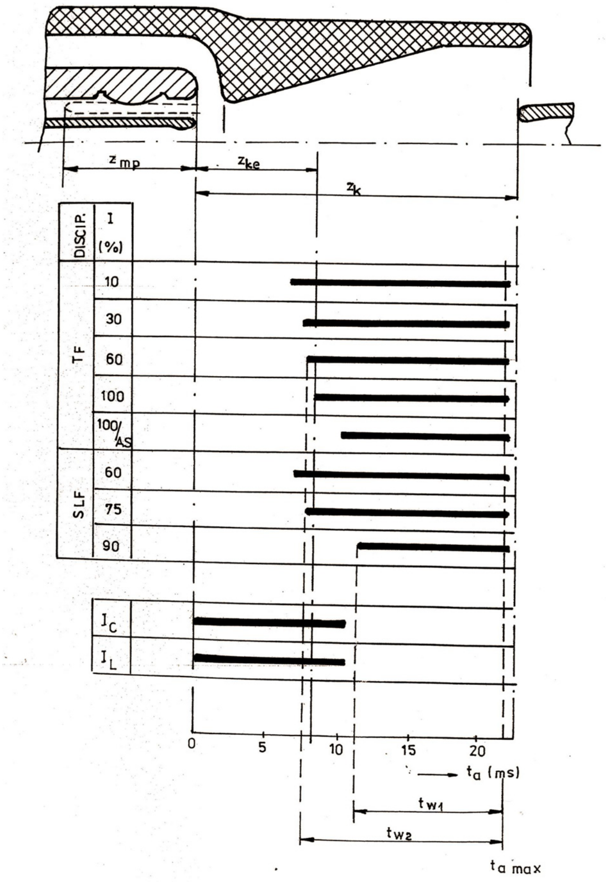


Fig.2: result of tests a SF$_6$ CB, 123kV and 40kA for the interrupting stresses according IEC. ITI for individual interrupting discipline is represented by horizontal black line.

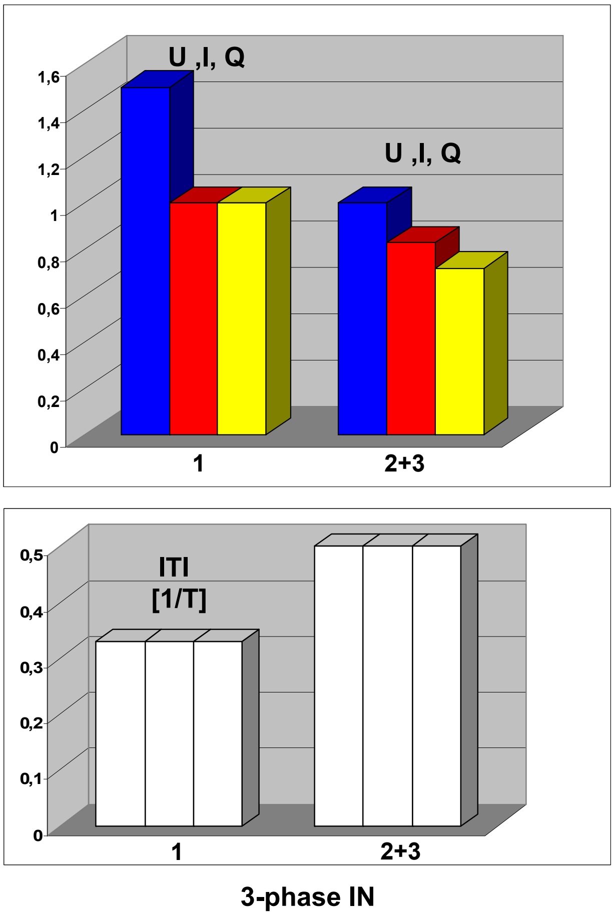
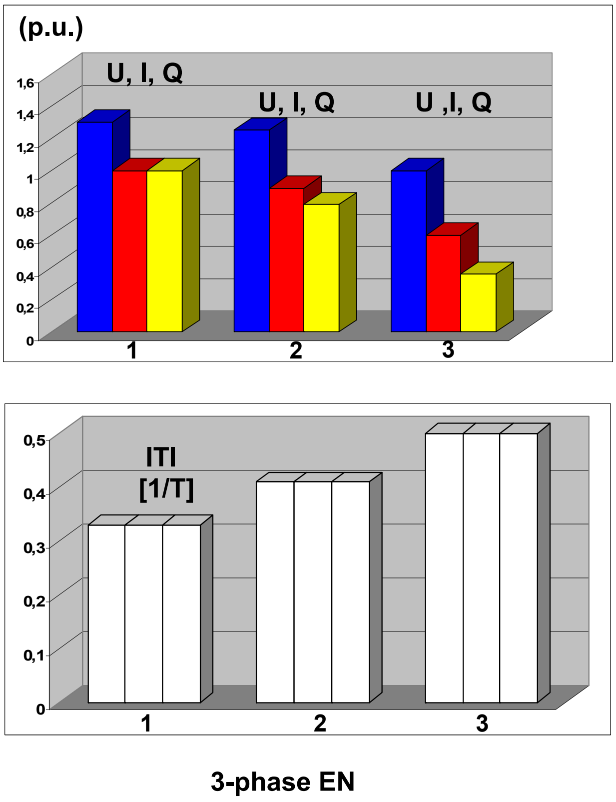


Fig.3: Stresses of CB (p.u.) in related ITI under various network's faults and non-simultaneity of contact separation N=O



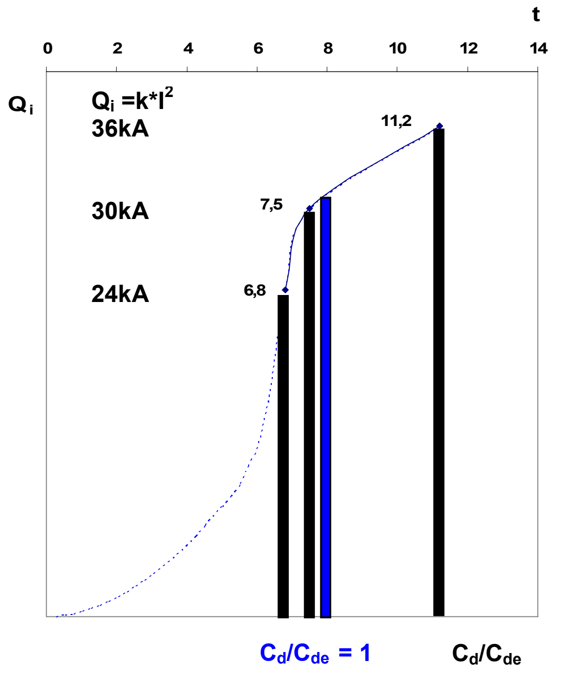


Fig.4: Qi vs. Contact distance – C_d (p.u.) for short line fault (SLF) derived from fig 2. The amplitude of RRRV, (du/dt), in 50Hz network is equal to $0,2I_k$ (kV/μs).

3 INTERRUPTING PROCESSES

With use references [1], [3], [6], [7]

3.1 One phase fault interrupting

One phase fault is the most frequent case of fault during interrupting. The fault is interrupted only by one phase of GenCB, in earthed neutral networks there is no need to be concerned with the influence of intact phases.

In insulated neutral networks the fault current flows through two phases and after interruption of one phase the current is interrupted also in second phase.

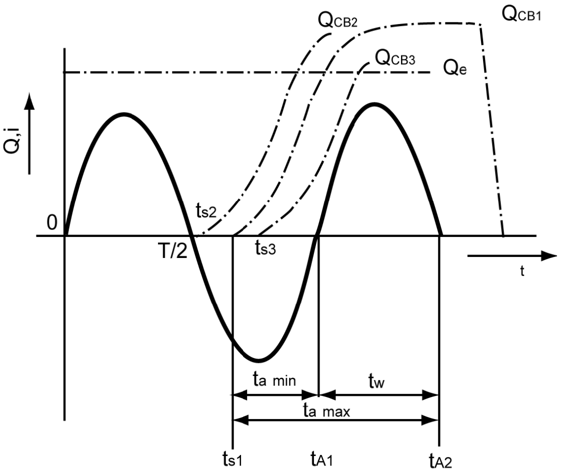


Fig.5: Interrupting of one phase fault

Figure 5 shows the symmetrical fault current curve. The Q_e level is featuring demanded interrupting capability given by parameters of external network. In time t_s the contacts are separated and the interrupting capability of GenCB is function of moving contacts distance.

If the GenCB reaches demanded interrupting capability before current zero the GenCB interrupt (e.g. Q_{CB2} curve). If the current zero is passed without sufficient interrupting capability the arcing continues and next chance for interrupting is in next current zero in time t_{A2}. The arcing window should be than longer than T/2 i.e. with 50Hz $t_w \geq 10$ms

The interrupting of asymmetrical fault current is influenced by direct current component and thus two following current zeros do not have to be at T/2 distance. This must be taken into account. For common interrupting time of 30ms the unbalance is approximately 50% and the time of arcing window approximately 0,75T

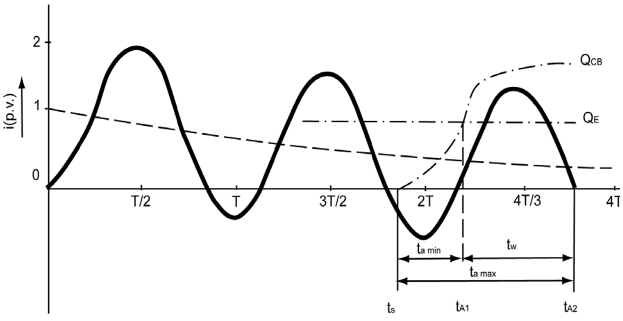


Fig 6: One phase asymmetrical fault

This is from the point of view of energy balance of the arc (with respect to lower di/dt and du/dt) less difficult in comparison with symmetrical fault. But this is essential because of longer time of arcing and hence failure possibility.

3.2 Interrupting of three phase fault in network with earthed neutral

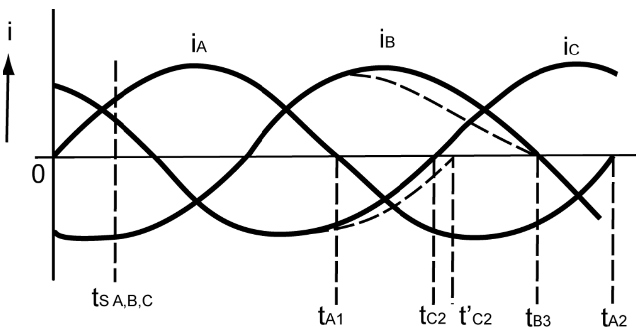


Fig 7: Interrupting of three phase fault

During interrupting of the three phase earthed fault the current zero goes progressively throw all phases and according to interrupting the fault is continuously turning into two phase fault and finally to one phase fault.

We assume simultaneous separation of contacts in all three phases in t_{SA} as shown in figure 7. The first possible chance to interrupt is in phase A in time t_{A1}, if this do not interrupt next current zero is in phase C in time t_{C2}. The same way the interruption continues in phase B in time t_{B3}. Successful interruption of phase is possible only if the quenching chamber has/reaches sufficient interrupting capability.

3.3 Interrupting of three phase fault in network with isolated neutral

The conditions of three phase interrupting are similar to interrupting of three phase fault in network with earthed neutral. After the current in phase one is interrupted current in two remaining phases is deformed as shown in figure 8. Conditions for interrupting of two phase fault in network with isolated neutral are similar to interrupting of one phase fault in network with earthed neutral. Both poles interrupt at the same moment, because after interruption in one phase the current extinguish also in second phase. Both poles are in fact sequenced in series

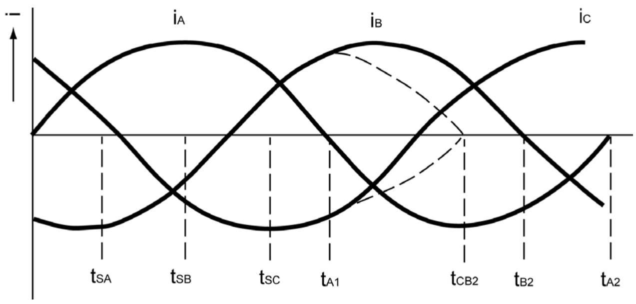


Fig 8: Interrupting of three phase fault in network with insulated neutral

4 CURRENT INTERRUPTION REQUIREMENTS AND STANDARDS

With use references [2], [5], [6]

Generator circuit breaker is located between generator and step-up transformer in power networks and its ratings usually range from 1000MVA to 1300MVA. Owing to the potentially high asymmetrical fault levels at relatively low voltage near the terminals of generator, the current interruption requirements of GenCB are significantly higher than in the distribution networks at similar voltages.

The CB has to withstand extreme stresses due to the conduction of rated current and interruption of very large short fault current – the range is from 50 kA to 200kA. CB must interrupt in all situations that may occur in 3-phase net, independently on sequence of current zero and tripping impulse initiated mechanical function. Moreover, after interruption current appear very severe transient recovery voltages across the breaker.

GenCBs are usually designed as single phase integrated into the bus duct connecting generator and step-up transformer. The location of GenCB puts special requirements to the stress, which are these devices, exposed to: thermal, electrical and mechanical.

The high power flow and the vicinity of the current and voltage generating main components at either side of the GenCB cause the severity of the fault current interruption to be significantly higher than in distribution networks oa similar voltage, both from current and voltage point of view. In the past the interruption of current in GenCBs was accomplished in pressurized air arc extinction chambers assisted by a high-pressure air blast. But pressurized air as an arc extinguishing medium has a relatively long time constant to recover to its non conducting state. Therefore special means has to be applied to reduce RRRV in order to facilitate the interruption. Very often there is mounted a parallel resistor (in order of 1Ω). The disadvantage of this principle is that we need second interrupting chamber to interrupt the resistor current.

A new generation of GenCBs using SF_6 as the arc extinction medium as well as for internal insulation came on the market in 1980s. Exploiting the thermal energy of an arc combined with a puffer action, high breaking capacity can now be realized with low operating energy the so-called self-blast technology. Reduction of the TRV severity by capacitors parallel to the interrupting chamber is sufficient for successful current interruption.

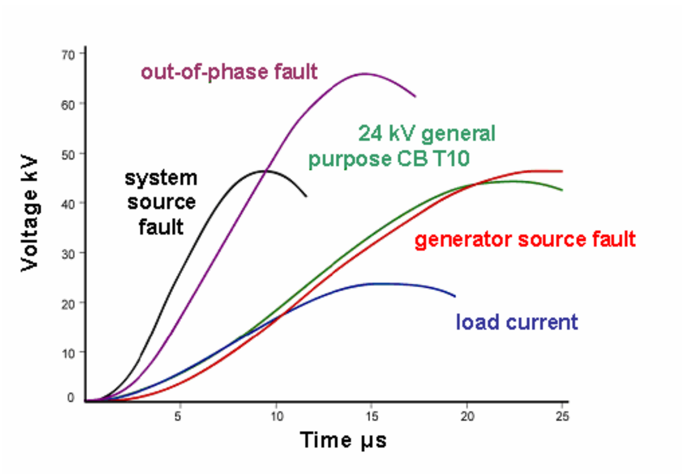


Fig.9: TRVs wave shapes for generator circuit breakers >1000 MVA compared to T10 TRV of a general purpose

Figure 9 shows TRV wave shapes based on various interruption duties. As can be seen the TRV requirements of GenCB are far more severe than for general purpose circuit breakers.

4.1 *Load current switching*

Load current for large generation unit can rise up to 50kA. This value often demands forced cooling. After interrupting of load current the two circuits at both sides of the GenCB oscillate independently. This is creating a TRV that is a sum of two wave shapes. At the generator side a wave shape appears with relatively low RRRV because both the distributed capacitances and the ac impedance is high compared to the values at transformer side where the higher RRRV originates.

4.2 *System-source faults*

In this situation the source of fault current the step-up transformer that supplies the energy from the network (system fed). The magnitude of this current has the highest value of all the possible fault situations because the short circuit the short circuit reactance of transformer is usually smaller than the GenCB reactance. Unlike the conventional HV circuit breakers the maximum voltage (TRV) stress for GenCBs coincides with the maximum short circuit current stress. The very high RRRV value originates from the small-distributed capacitance of the step-up transformer.

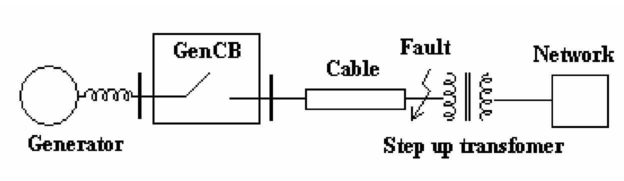


Fig.10: System-source fault of generator circuit breaker

Figure 10 shows the simulation network of a system fed fault. There is usually a cable connected between the GenCB and the step up transformer, hence the demonstration circuit comprises a voltage source, a GenCB, a cable and a fault initiated at the end of the cable.

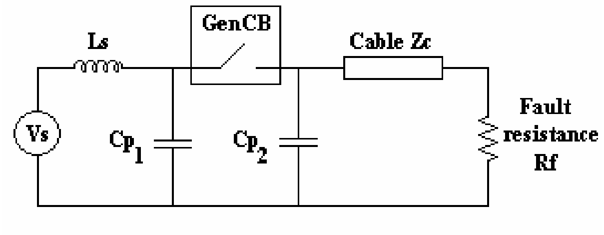


Fig.11: Demonstration circuit of system-source fault

Immediately after current interruption at about 8ms, the voltage oscillates at a high frequency. This oscillation is a result of interaction between the source inductance Ls and the parasitic capacitance to ground C_{P1}. The frequency is given by:

$$f = \frac{1}{2\pi\sqrt{L_S C_{P_1}}} \approx 40kHz \qquad (4)$$

The first TRV peak of oscillation reaches the value of 40kV and the rate of rise of recovery voltage is about 5kV/µs. Following the decay of the transient, the voltage oscillates at 50Hz with $20kV_P$.

4.3 Generator-source faults

In this case the generator supplies the fault current. This may cause a big dc component and thus very high asymmetries and delayed current zero. However, thanks to fault and eventually circuit breaker arc the arc time constant reduced by the effective arc series resistance to the circuit resistance. The effect of these additional series resistances is acceleration in decay of the dc component.

The value of the generator reactance limits the short circuit current to values below the system source case and same can be of the TRV associated stress. Because of the relatively large inherent capacitance of the generator the TRV rate of rise (RRRV) has about half value of the system source fault.

4.4 Out of phase switching

The characteristics of this interruption can be compared with the load current interruption. Only the amplitude of TRV is significantly higher. The difficultness of this interruption depends on the out-of-phase angle δ. Taken into account that the generator is in risk at values of δ>90° this situation must be excluded by protective relaying.

For the out-of-phase angle δ = 90° the current has about half value of the system fed fault current. On the voltage side the RRRV is approximately almost in the same order as in the system source fault case, but with a peak value being approximately 2-times higher.

5 CONCLUSION

This paper dealt with an analysis of the whole spectrum of network parameters: voltage, nominal short fault currents, maximal value of recovery voltage as well as the RRRV with the respect to relevant interrupting time intervals. There are introduced valuable experiments of interrupting time interval for each individual standardised discipline. The comparison of network parameters to circuit breaker interrupting capability determines circuit breaker's limited interrupting characteristics and thus reliable fault's interruption. This analysis includes also an asymmetrical fault with respect to longer arcing time. These results will serve for design as well as testing of quenching chambers of circuit breakers.

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