Generator Circuit Breakers

General Review

Why ?

GCB Standards and

How they apply to GCB's

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Generator Circuit-Breakers
Why / Benefits

Generator Circuit Breakers were used in multi-unit stations where a number of relatively small generators were connected to a common bus. The rapid increase in generator size and system fault current levels soon exceeded the interrupting capabilities of this type of switchgear. The unit concept was then adopted where each generator had a separate steam supply *[and]* auxiliary systems *[are]* directly connected step-up transformer and high side breaker(s).

. . . . advances in circuit breaker design(s) have made the generator circuit breaker concept a viable alternative even at the 250 kilo-ampere level required for some applications.

A major advantage of the generator circuit breaker is that fault current contributions from the generator can be interrupted in 5 to 7cycles (*now it's 3 - 5 cycles)* for faults in the isolated phase bus or on the high side of the generator step up transformer.

Other advantages include the elimination of transfer of auxiliary loads (auxiliary transformer remains connected to the system), and improved reliability when the generator is synchronized with the system.

(IEEE Transactions on Power Apparatus and Systems, Vol. PAS-I02, No.9, September 1983)

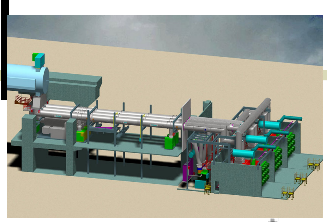
GCB Standards
C37.013

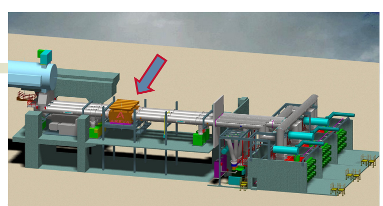
Generator circuits experience conditions that are not common and are certainly more demanding than those experienced in normal distribution circuits. These unique characteristics require breakers that have been specifically designed and tested. IEEE has developed the only standard known world wide specifically addressing the requirements for this application

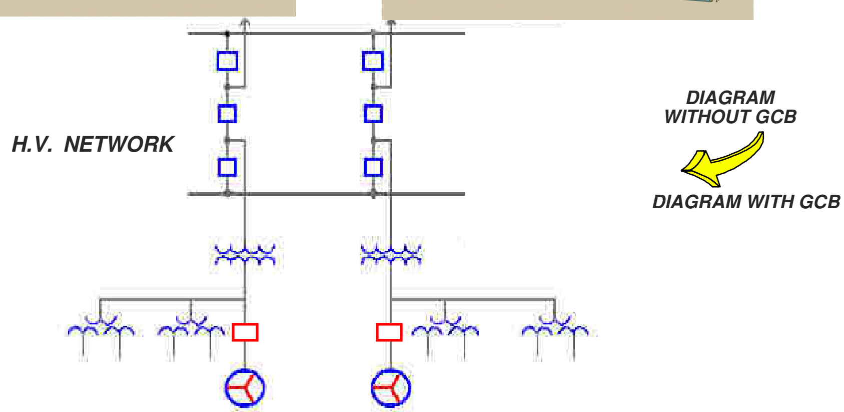
The first editions of the standard, C37.013, focused on large power stations. Later revisions included applications on smaller generation plants and today, the standard is being revised to include comments from the international community.

(Are All Circuit Breakers Created Equal? Certainly NOT When it Comes to Generator Circuit
William Long and Dr. Kirkland Smith: Eaton Technology and Eaton Cutler-Hammer Business, respectively)

Generator Circuit-Breakers
Why / Benefits

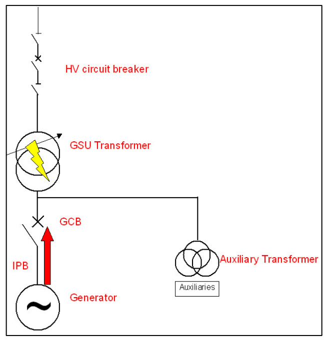






Generator Circuit-Breakers
Why / Benefits

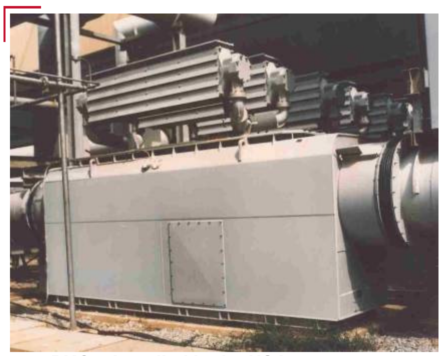
- A GCB is a protection device for the transformer . . . . . .
  - Protection of the GSU transformer against generator-fed short-circuit currents



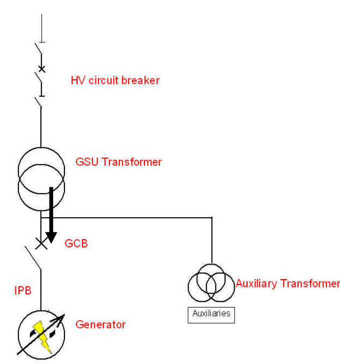
Generator Circuit-Breakers
Why / Benefits

Protection of the Generator against system-fed short-circuit currents

PKG2R, 24 kV, 275 kA, installed in 1977 : **interrupted a 250 KA fault in 1995.**



PKG - Installed in the USA



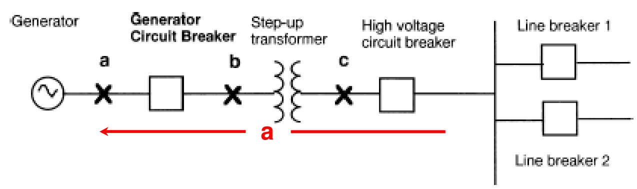
- The GCB is an effective protection device for the transformer and the generator
  - Starting and maintenance stages
  - Synchronization and normal conditions
  - Abnormal conditions including:
    - Overvoltages, un-balanced load
    - Short circuit
      - Step up transformer side
      - Generator side
    - Out of Phase Requirements

- Specific technical constraints :
  - Transient recovery voltage
  - Asymmetrical current
  - Rate of rise recovery voltage in kV/µs
  - Capacitors
  - Out of phase

Definitions that should be understood that are specific to generator circuit breakers.

- *Rated maximum voltage of a generator circuit breaker:*
- *Generator source short circuit current*
- *System source short circuit current*
- *Rated continuous current of a generator circuit breaker*
- *Rated mechanism fluid operating pressure of a generator circuit breaker (if applicable!)*
- *Rated Interrupting time of a generator circuit breaker*

Influence of Station Design Configuration

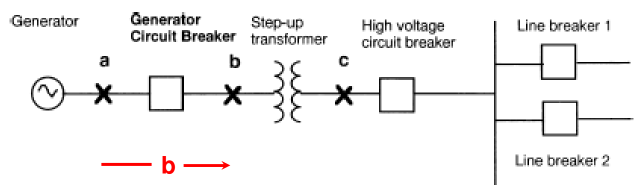


A short circuit current can be initiated at the following points:

- a - Location **a** is called a system source short circuit current.

The transformer-fed fault current can be very high because the full energy of the power system feeds the fault. The low impedance of the transformer and the short, very lowloss buses connecting the generator, generator circuit breaker, and transformer, do little to limit the fault current because of their very low impedance. To clear these kinds of faults, generator circuit breakers must be tested and proven capable of interrupting not only the high symmetrical fault current, but also the higher asymmetrical fault currents resulting from extreme DC components of fault current, up to 75% as required in section 5.8 of IEEE C37.013.

Influence of Station Design Configuration



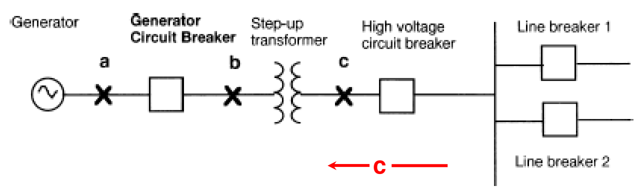
A short circuit current can be initiated at the following points:

- b – Location **b** is called a generator source short circuit current.

Generator-fed fault currents, while lower in magnitude, are subject to another type of very demanding condition called "*Delayed Current Zeroes*". This unique characteristic of the fault current comes from the very high X/R (inductive reactance to resistance) ratio of the circuit and the operating conditions of the generator, which can combine to produce a DC component of the fault current exceeding 100%! This means the asymmetrical fault current peak becomes so high, and its decay becomes so slow, that the first current zero can be delayed for several cycles. Since circuit breakers rely on a current zero crossing in order to interrupt, generator circuit breakers must be able to withstand longer arcing times and greater electrical, thermal, and mechanical stresses when clearing this kind of fault.

Standards – Definitions

Influence of Station Design Configuration



A short circuit current can be initiated at the following points:

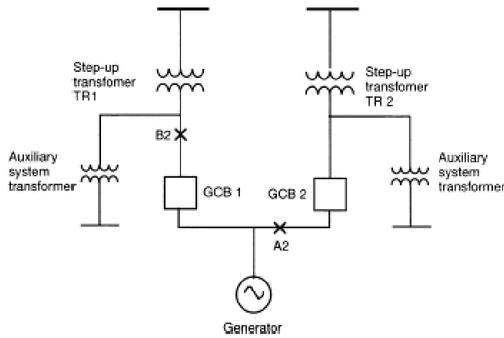
- c – Location **c** is called a high voltage generator source short circuit current, but of a smaller current than location b.

Influence of Station Design Configuration

Different station configurations have different characteristics . . . and therefore, each applicable breaker characteristics should be defined respectively.

Half-Sized TR Configuration

For a system source fed fault (A2) in the adjacent figure, the short circuit current and the TRV parameters seen by the individual circuit breakers are related to each step up transformer's rating.

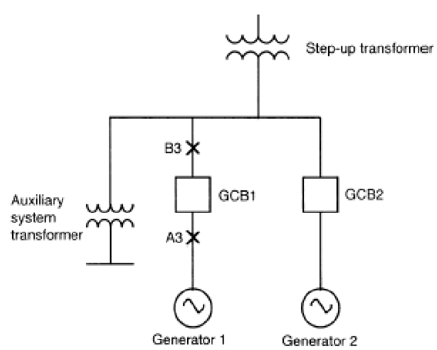


Half-sized transformer unit system

Influence of Station Design Configuration

Half-sized Generators Configuration

For a system source fed fault (A3), the short circuit current is higher because the fault is also fed by the generator, G2. However the TRV rate is lower because of the G2 generator winding's capacitance. If the generator G2 is out of service, the situation is the same as for a fault in A2 of the first figure, except that the generator is half the rating.



Half-sized Generator Configuration

The ratings and required capabilities of a generator circuit breaker are the listed maximum limits of operating characteristics based on well defined service conditions and shall include the following electrical performances, as a minimum:

- A – **Rated Maximum voltage**
- B – Power frequency 50 / 60 Hz
- C – **Rated continuous current**
- D – **Rated dielectric withstand**
- E – **Rated short circuit duty cycle**
- F - **Rated interrupting time**
- G – Rated closing time
- H – **Rated short circuit current**
- I – **Transient recovery voltage (TRV) rating**
- J – Rated load switching capability
- K – Capacitance current switching capability
- L – Out of phase current switching capability
- M – Excitation current switching capability
- N – Rated control voltage
- O – Rated mechanism fluid operating pressure (if applicable)

Rated Maximum Voltage

- **Rated maximum voltage.**

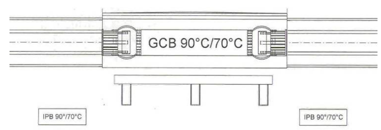
The rated maximum voltage applied to a generator circuit breaker is the highest r.m.s. value for which the circuit breaker is designed and is the upper limit for operation.

The rated maximum voltage is equal to the generator's maximum operating voltage times 1.05.

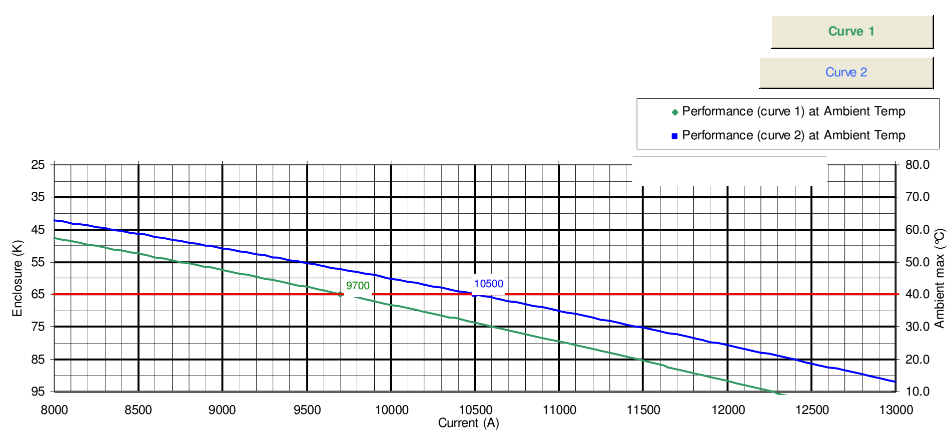
Rated continuous current

The rated continuous current of a generator circuit breaker is the designated limit of current in rms amperes at power frequency, which it shall be required to continuously carry without exceeding any stated limitations

- Continuous Current Limiters
  - Frequency
    - 50 Hz
    - 60 Hz (derated)
  - Site temperature: 40℃ as max. standard
  - Busbar temperature
    - 90 / 70℃ for IEC
    - 105 / 80℃ for ANSI (derated)
  - Installation
    - Outdoors (derated)
    - Indoors
  - IPB Cooling/Ventilation



Rated continuous current – Cont'd



Rated dielectric strength & External insulation

Table 4a – Schedule of dielectric strength for ac generator circuit breakers and external insulation

Line	(Ref. IEC) Rated Voltage (kV, rms)	(Ref. ANSI) Rated Maximum Voltage (kV, rms)	Insulation Withstand Voltages (1) Power Frequency 1-minute, dry (kV, rms)	Lightning Impulse 1.2 x 50 µs wave (kV, peak)
Line	Column 1	Column 2	Column 3	Column 4
1	7.2	5	20	60
2	12	8.25	28	75
3	17.5	8.25 / 15	38	95
4		15.5	50	110
5	24	27	60	125
6	36	38	80	150 (2)

(2) The lightning impulse is still 150 kV peak as there are no generator rated 36 kV with a lightning impulse at 170 kV peak.

The rated dielectric withstand of a generator circuit breaker is it's voltage withstand capability with specified magnitudes and wave shapes. In the event of loss of insulating medium, the generator circuit breaker shall be able to withstand 1.5 times the voltage under the following conditions:

A – In the open position, the phase opposition voltage across the contacts, the phase to ground, and the line to line voltage between phases are to be withstood.

B – In the closed position, the phase to ground and line to line voltage between phases are to be withstood.

Rated Short-Circuit Duty Cycles

The rated short circuit duty cycle of a generator circuit breaker shall be made of two unit of operations with a 30 minutes interval between operations

(duty cycle: CO – 30 minutes – CO)

This means two full short circuit interruptions separated by 30 minutes between each short circuit closing. This is designed to protect power plants and generators in particular, because two close-opens at full short circuit might damage the generator and the step up transformers. These types of short circuit are very unlikely and after a full short circuit, it is very unlikely that the plant manager will try to close again after 30 minutes.

Standards –
Ratings & Required Capabilities

Rated Interrupting Time

- Rated Interrupting Time
  The rated interrupting time of the generator circuit breaker is the maximum permissible interval between the energizing of the trip circuit at rated control voltage and rated fluid pressure of the operating mechanism and the interruption of the main circuit in all poles on an opening operation. Typical values are approximately 60 – 90 ms with the actual time being dependent on the rated short circuit current.

Standards –
Ratings & Required Capabilities

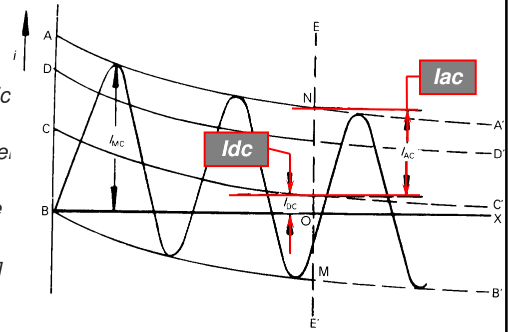
Rated Short-Circuit Current

- The highest rms value of the symmetrical component of the three-phase short circuit current;
- Generally, the rated Isc rms value is derived from the system source side. The GSU's low impedance and the short, low-loss bus connection usually makes this fault the highest rating;
- It is measured from the envelope of the current wave at the instant of primary arcing contact separation, and is the current that the generator circuit breaker shall be required to interrupt at the rated maximum voltage and rated duty cycle. The short circuit current source is from the power system through at least one transformation;
- Establishes also, by ratios defined later in the text, the highest current that the generator circuit breaker shall be required to close and latch against and to carry; and
- Typical values of short circuit current, three-phase system are:
  50 kA, 63 kA, 80 kA, 100 kA, 120 kA, 160 kA, 180 kA, 200 kA, 250 kA, 275 kA.

Rated Asymmetrical Current
System and Generator Source 3-Phase Faults

- *The rated short-circuit current is defined by 2 values:*
  - *the r.m.s value of the symmetric (a.c.) component;*
  - *the percentage of d.c. compone*
- *The a.c. and d.c. components are determined as indicated in the figure*

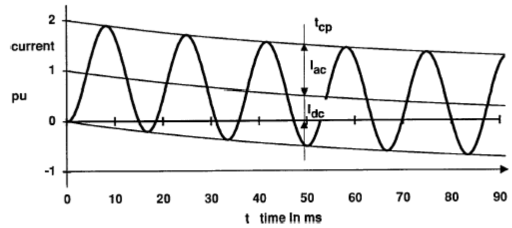
% d.c. = 100 x (I_{DC} / I_{AC}) [I_{AC}=I_{sym}p]



The requirements for asymmetrical system-source interrupting capability of a generator circuit breaker at rated maximum voltage and for the rated duty cycle is composed of the rms symmetrical current and the percentage dc current component.

The value of the dc component is percent of the peak value of the symmetrical short circuit current are given in the standard in the figure below for primary arcing contact parting times in milliseconds.

Rated Asymmetrical Current – Cont'd
System Source 3-Phase Faults

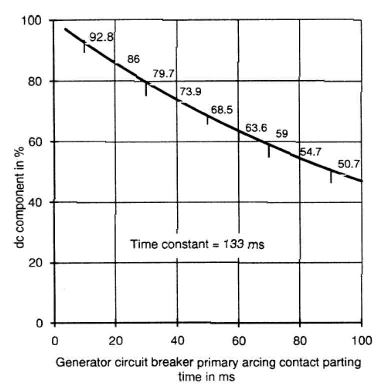


The degree of asymmetry *a* at the time *tcp* is determined by the following equation:
a = *Idc / Iac* = degree of asymmetry
Where the dc component are:

$$I_{dc} = I_{ac} \times \left(e^{-\frac{t_{cp}}{\tau}} \right)$$

Where t = 133 ms.

The asymmetrical interrupting capability: DC component in percentage of the peak value of the symmetrical three-phase system source short-circuit current.



Rated Asymmetrical Current – Cont'd
Generator Source Faults

- **For three phase faults**

The required asymmetrical generator source interrupting capability of a generator circuit breaker at rated maximum voltage and for the rated duty cycle is made of the rms generator source symmetrical current and a dc component.

The ac component of the short circuit current, when the source is from a generator without transformation may decay faster than the dc component. The decay of the ac component is governed by the generator's sub-transient and transient time constants (Td", Td', Tq", Tq') and the decay of the dc component by the short circuit time constant, Ta = Xd" / ωRa where Xd" is the direct axis sub-transient reactance and Ra represents the armature resistance.

Generally, the generator fed source faults will be lower in magnitude but zero current crossings will be greater than those of the system source faults due to the higher X/R ratios. The maximum required degree of asymmetry of the current for the condition of maximum required degree for asymmetry is 130% of the peak value of symmetrical current for the generator fault as opposed to 75% on the system fed fault.

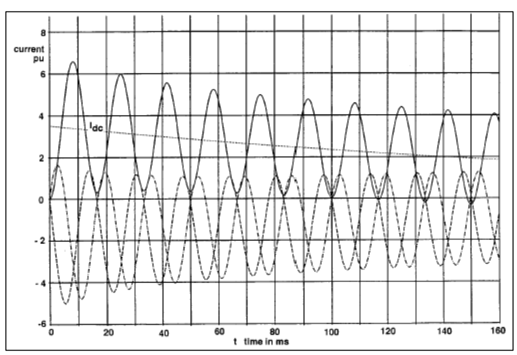
Rated Asymmetrical Current – Cont'd
Generator Source Faults

The highest value of asymmetry occurs when, prior to the fault, the generator is operating in the under-excited mode with a leading power factor.

Under such a condition, the DC component may be higher than the symmetrical component of the short circuit current and may lead to delayed current zero's.

In the case where the generator is carrying load with a lagging power factor prior to the fault, the asymmetry will be lower, and delayed current zeros should not be expected.

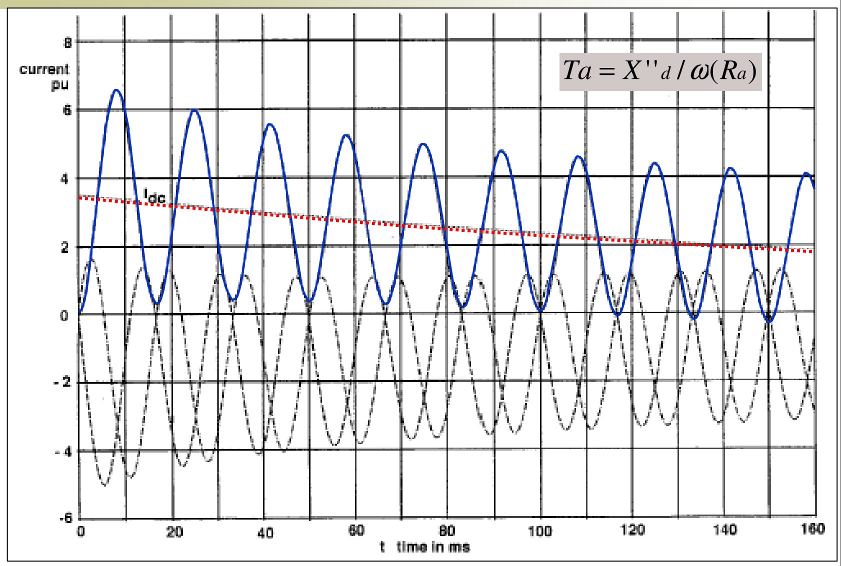
An example of short circuit current for a generator source fed fault.



GCB – Discussions
TECHNICAL

Delayed current Zeros

Interruption - With an Asymmetrical Current

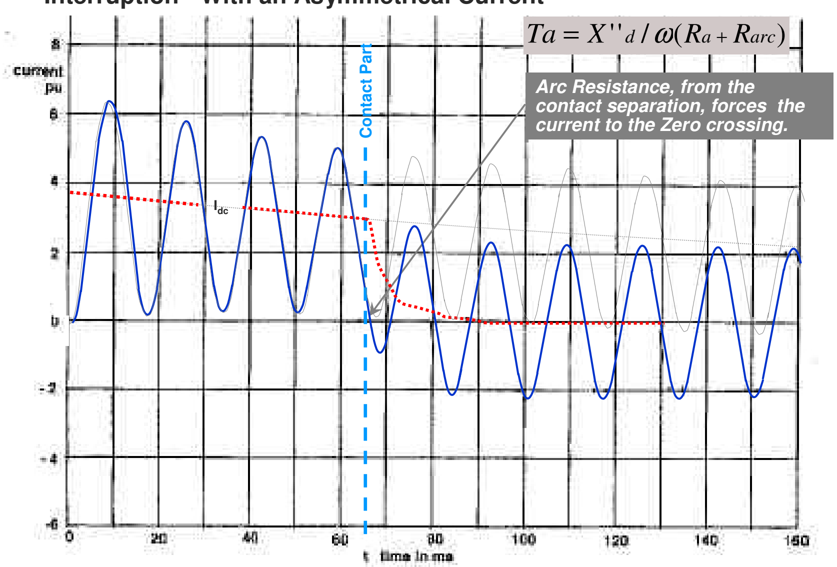


IEEE – Atlanta Chapter

GCB – Discussions
TECHNICAL

Delayed current Zeros

Interruption - With an Asymmetrical Current



IEEE – Atlanta Chapter

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Required Closing, Latching and Carrying capabilities on a short time

- The short circuit current into which the generator circuit breaker must close is determined by the highest value of either the system source short circuit current or the generator.
- Closing and latching any power frequency making current (50 Hz or 60 Hz) whose maximum crest (peak making current) does not exceed 2.74 times the rated symmetrical short circuit current the maximum crest (peak making current) of the generator source short circuit current, whichever is higher.
- The ratio of the maximum asymmetrical short circuit peak current at ½ cycle to the rated short circuit current of the generator circuit breaker is determined by the following formula:

$$\frac{Ipeak}{Isym} = \sqrt{2}(e^{-t/133} + 1) = 2.74$$

- The carrying time on short circuit current is limited to 0.25 second for a generator circuit breaker.

Rated Transient Recovery Voltage [TRV]

The resistance and stray capacitance of the generator circuit is typically very low. These characteristics combine to produce very high natural frequencies of the circuit and in turn result in extreme transient recovery voltages (TRV) with high rates of rise (RRRV).

During the interruption, just after the interrupter has been subjected to the plasma arc, the dielectric strength must be re-established across the contact's open gap in order to withstand this fast-rising TRV. In the first phase to clear, the peak value of this TRV is nearly double the line-to-line voltage of the circuit, and the circuit produces that peak voltage within microseconds following the current zero. If the interrupter is able to withstand that voltage, then the interruption is successful. If not, the gap will break down again, and the fault current will continue to flow until the next current zero, when there will be another opportunity to interrupt.

Here it is important to note that the critical parameter is how fast the TRV rises across the recovering gap after the current zero. This is measured by the RRRV, which is proportional to the peak value of the transient voltage in kV, divided by the time it takes the voltage to reach that peak value in microseconds, so that the RRRV is measured in units of "kV / microsecond".

Standards –
Ratings & Required Capabilities

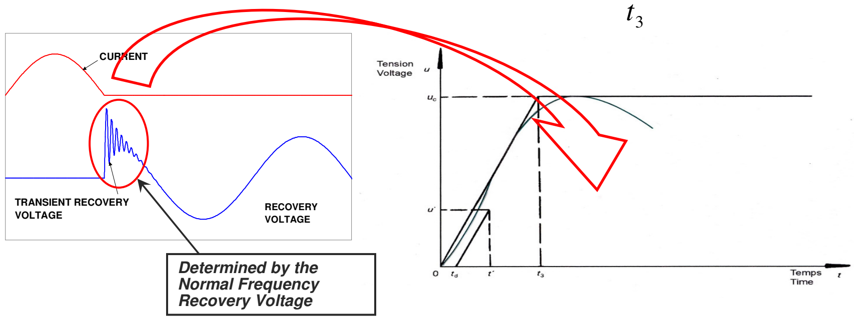
Rated Transient Recovery Voltage (cont'd) [TRV]

The TRV parameters are defined as function of the rated voltage (*Ur*), the first pole to clear factor (*kpp*) and the amplitude factor (*kaf*) as follows; where *kpp and kaf* are equal to 1.5

$$U_c = k_{pp} \times k_{af} \times U_r \frac{\sqrt{2}}{\sqrt{3}}$$

*t*3 is determined from U_c and the rate of rise

$$\frac{U_c}{t_3}$$



Standards –
Ratings & Required Capabilities

Rated Transient Recovery Voltage – Cont'd [TRV]

TRV parameters for system-source faults

Transformer rating MVA	T_2 in µs	Inherent TRV	
		E_2-crest voltage	TRV rate kV/µs
100 or less	0.62 *V*	1.84 *V*	3.5
101–200	0.54 *V*	1.84 *V*	4.0
201–400	0.48 *V*	1.84 *V*	4.5
401–600	0.43 *V*	1.84 *V*	5.0
601–1000	0.39 *V*	1.84 *V*	5.5
1001 or more	0.36 *V*	1.84 *V*	6.0

NOTES
1—Time delay shall be equal to or less than 1 µs.
2—*V* is the rated maximum voltage in kV.

TRV parameters for generator-source faults

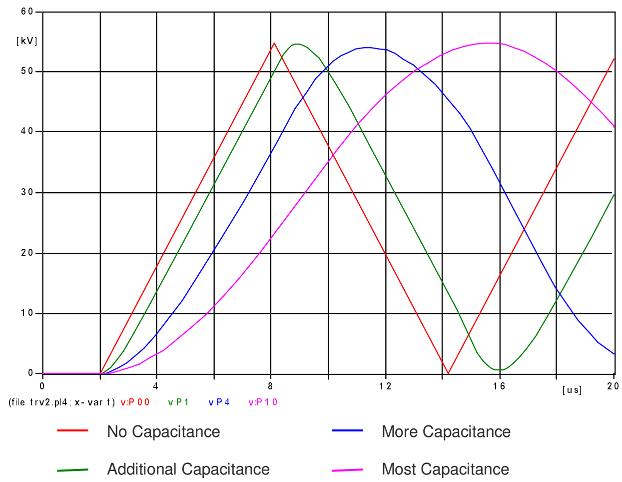
Generator rating MVA	T_2 in µs	Inherent TRV	
		E_2-crest voltage	TRV rate kV/µs
100 or less	1.35 *V*	1.84 *V*	1.6
101–400	1.20 *V*	1.84 *V*	1.8
401–800	1.08 *V*	1.84 *V*	2.0
801 or more	0.98 *V*	1.84 *V*	2.2

NOTES
1—Time delay shall be equal to or less than 0.5 µs.
2—*V* is the rated maximum voltage in kV.

GCB – Discussions
TECHNICAL

Re-visting Transient Recovery Voltage [TRV]

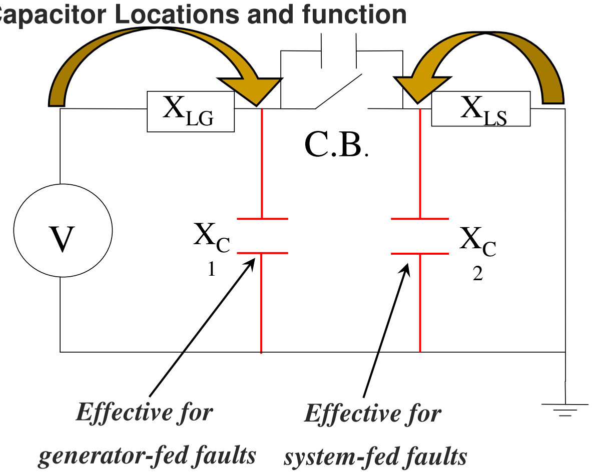
Reduction of TRV slope by increasing Capacitance



GCB – Discussions
TECHNICAL

Applying Capacitors to GCB's

Capacitor Locations and function



7.4 Guide to specification

7.4.1 General

When requesting proposals for a generator circuit breakers, the engineer should furnish to the manufacture(s) a specification containing the information outlined in 7.4.2–7.4.6.

7.4.2 System characteristics

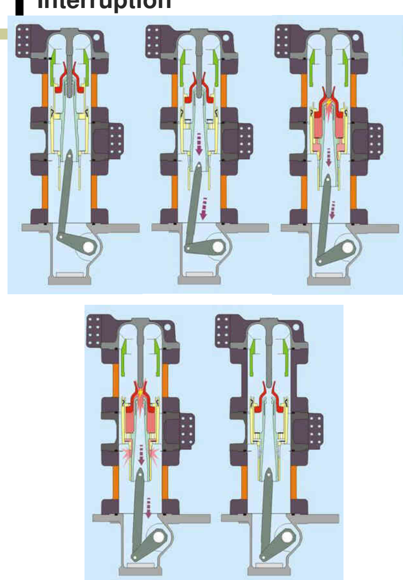
7.4.3 Application

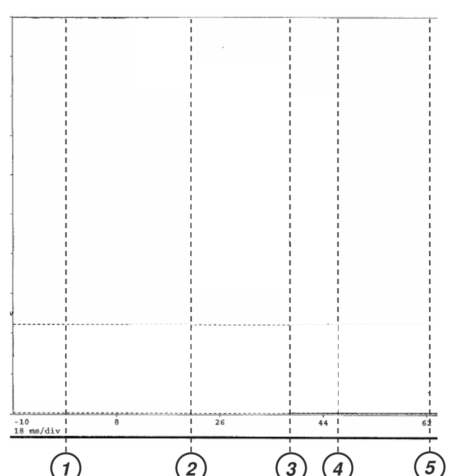
7.4.4 Generator circuit breaker electrical characteristics

7.4.5 Operating mechanism and auxiliaries

7.4.6 Miscellaneous

Interruption

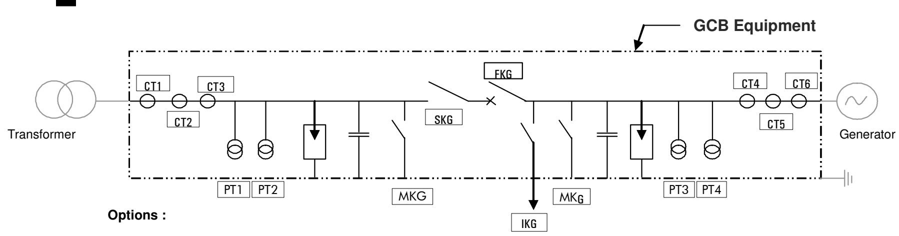




Review – GCB Standards

- Applicable GCB standards
- High Asymmetrical currents
- System source fault:
  - asymmetry: 60 to 80 %
  - du/dt: ..6 kV/µs
  - delay: < 1 µs
  - E2 (Ur): 1.84 x U
- Generator source fault:
  - asymmetry: ..130 %
  - du/dt: ..2.2kV/µs
  - delay: < 0.5 µs
  - E2 (Ur): 1.84 x U

Description		GCB	MV
Out of Phase	[kA]	50%*I	25%*I
Withstand BIL	[kV]	125-150	95
Power Freq	[kV]	60- 80	36
Close & Latch	[kAp]	2.74*I	2.6*I
TRV- TR - GEN (>1000MVA)	[kV] [kV]	1.84*V	1.84*V
RRRV – TR – GEN (>1000 MVA)	[kV/µs] [kV/µs]	6.0 2.2	0.2 - 0.55



Options :

Transformer side
CT : 1,2 or 3 cores
PT : 1 or 2
Surge arrestor
Capacitance
Capacitance } Determined by System variables
Earthing switch

Generator side
CT : 1,2 or 3 cores
PT : 1 or 2
Surge arrestor
Capacitance
Capacitance } Determined by System variables
Earthing switch
Starting switch (connect to SFC)

QUESTIONS?

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