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Generator circuit breakers have special requirements for generator protection

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Abstract

Generator circuits experience conditions that are not common and are certainly more demanding than those experienced in normal distribution circuits. Generator circuits have unique characteristics that require circuit breakers specifically designed and tested for those conditions. To meet this need, the Switchgear Committee of the Institute of Electrical and Electronics Engineers (IEEE®) developed and issued a special industry standard to address these unique characteristics. The specific IEEE Standard is C37.013-1997, entitled "IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis" and C37.013a-2007. [1]

This paper summarizes unique and demanding aspects of protecting generator circuits and compares differences between the requirements for generator circuit breakers and those for standard distribution circuit breakers. The superior performance capabilities of generator circuit breakers are summarized in a detailed, side-by-side comparison with the capabilities required of standard distribution circuit breakers. Finally, it will compare the existing standard against the dual logo standard 62271-37-013 D9.3 draft.

Introduction

Superior performance and versatility are required of generator circuit breakers. Application possibilities continue to grow. The need for generator circuit breakers was first recognized by electric utilities to protect large generating stations, and the first editions of the industry standard were directed to this need. However, many industrial and commercial power systems now include small generators as a local source of power. New applications are arising as a result of the de-regulation of the utility industry, and the construction of smaller packaged power plants. Typical applications include:

- Electric utility "black start" generators
- Packaged power plants
- Combined cycle/combustion turbine plants
- Pumped-storage facilities
- Smaller hydro-generating stations
- Process industries with on-site generation

For most generator circuit applications, consideration must be given to:

- Generator circuit configuration
- High continuous current levels
- Unique fault current conditions
  - System-source (transformer-fed faults)
  - Generator-source (generator-fed) faults
- Unique voltage conditions
  - Very fast rate of rise of recovery voltage
  - Out-of-phase switching

The demanding service duty requirements for generator circuit breakers are discussed in the following paragraphs. Finally, a parameter-by-parameter comparison is made between the generator class circuit breaker and those of the distribution class circuit breaker, as outlined in applicable C37 standards. Ruoss and Kolarik discussed the reasons for the development of the first industry standard for generator circuit breakers in 1993. [6] Finally, the paper will review some of the additional and expected changes that will be required of generator circuit breakers.

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Generator circuit configuration

Figure 1 presents the single-line diagram of a common generator circuit. Although this circuit appears to be very simple, there are a number of critical factors to be considered. For example, generator circuits are typically designed for high efficiency in order to minimize the watts loss of the system. Therefore, the generator circuit breaker may be located very close to both the generator and the transformer, connected by short conductors with a large cross-section, resulting in minimal circuit impedance.

Applications with high continuous current levels require connections with very large conductors of very low impedance for optimum efficiency. This circuit configuration and the operational nature of generator circuits can present special voltage and current conditions that must be addressed when applying circuit breakers in such applications.

High continuous current levels

Generator circuit breakers must be able to carry high continuous current levels for extended periods of time. Up to now, the existing generator circuit breaker standard has focused on larger generators. For example, it specifies a minimum continuous current rating of 6300A, up to 16 or 20 kA. This would obviously require some form of a continuous cooling system for the conductors, and the upper range of these currents would be considered fault current levels in most distribution circuits. In marked contrast, typical continuous current requirements for standard distribution circuits are usually between 3000A and 1200A, or less.

Traditionally these circuit breakers are cooled by natural convection of the ambient air. Fan cooling has been a long accepted practice with power transformers and has become a popular solution in certain switchgear applications where the circuit is expected to carry higher than normal current, for short periods of time when demand is temporarily high. In most instances, however, fan cooling is not preferred. For some applications it is not acceptable, for reasons of increased maintenance, and possibly decreased reliability or availability, due to possible loss of cooling.

Unique fault current conditions

The two key unique fault current conditions encountered by generator circuit breakers are shown in **Figure 1**.

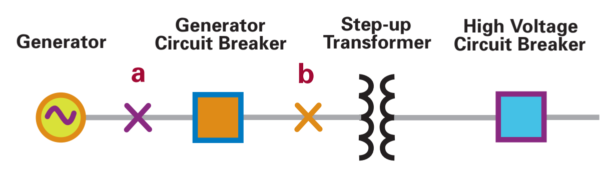

Figure 1. Typical Generator Circuit [1]

- Faults at location "a" are called "System-source Faults" or "Transformer-fed Faults"
- Faults at location "b" are called "Generator-source Faults" or "Generator-fed Faults"

The differences between these two fault conditions become apparent when the important parameters of each are discussed below.

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 low-loss 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.

Generator-fed fault currents, while usually lower in magnitude, are subject to much higher degrees of asymmetry, sometimes resulting in 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 (see **Figure 2**).

Because 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. Sections 5.8.2.3 and 7.3.5.3.5.1 of IEEE Standard C37.013 require verification by test that the circuit breaker can interrupt under these extreme conditions.

Depending on the minimum opening time, the generator circuit breaker must demonstrate the ability to interrupt three-phase fault currents with DC components of 135% at one fault current level and of 110% with a higher fault current level, each time with the related delayed current zero. Kulicke and Schramm [7] were among the first to recognize the importance of the ability of the interrupter to withstand very long arcing times during the delayed current zero condition. In particular, they demonstrated that vacuum interrupters are well suited to this requirement because they retain the ability to interrupt even after the contact motion has ceased.

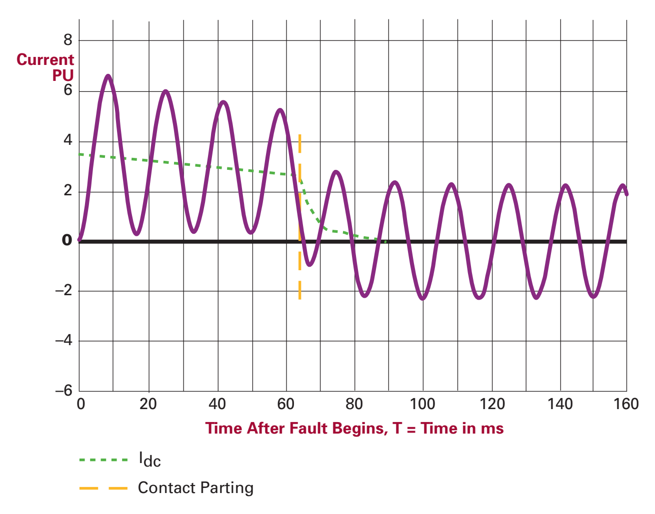

Figure 2. Short-Circuit Current with Delayed Current Zeroes [1]

Unique voltage conditions

As previously mentioned, in the typical generator circuit configuration, two large and very expensive components, each with a highly inductive impedance, are connected through the generator circuit breaker with very short conductors, of minimal resistance. Consequently, the resistance and stray capacitance of the generator circuit is typically much less than in a normal distribution circuit. 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 of Recovery Voltage (RRRV).

This means that during the interruption, just after the interrupter has been subjected to a 50,000 degree plasma arc, it must re-establish dielectric strength across the 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 fast-rising 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".

Although generator circuit breakers and standard distribution circuit breakers are both subjected to TRVs during interruption, the rates of rise are quite different. RRRV values for typical 15 kV standard distribution circuits are in the range of 0.4 to 1 kV / microsecond, while RRRV values for some generator circuits can reach 3.5 kV / microsecond. Smith [8] was one of the first to demonstrate that vacuum interrupters can clear high fault currents against these incredibly fast RRRV values, without adding capacitors to reduce the rate-of-rise. One may prefer to install surge protective devices for many other reasons, but they are not needed to reduce the RRRV in order for the vacuum interrupter to clear.

These TRV conditions are so severe that even the world's best high power laboratories cannot construct direct test circuits to prove this capability. The only way to prove this capability by high power testing is with the synthetic test method, where two separate sources are used—one to provide the required short-circuit current and the other to produce the required transient recovery voltage. These circuits were originally developed to test transmission class circuit breakers, rated 100 kV and above. Although the synthetic test method is not new, it is very complicated, owing to the need to control the precise operation of two very large power sources and the test object, as well as one, or sometimes two, auxiliary circuit breakers, to achieve the necessary "worst case switching conditions".

In the synthetic laboratory, it is not uncommon to have several "invalid tests" for every valid test. Invalid tests occur when one or another of the parameters, necessary to demonstrate the required worst case switching condition, is not achieved. This happens because there is some inherent variability in the operating time of each of the major switching components required to provide the proper stress parameters at the proper instant. If one component of the test circuit does not operate at the right moment in time, the result is an invalid test. Of course even invalid tests take time and cause wear of the contacts. Therefore, the synthetic tests required for generator circuit breakers are much more difficult and much more costly to perform, compared to the direct tests required for standard distribution circuit breakers. Initially, the synthetic testing was limited to single-phase operations. However, recently, Dufournet and Montillet were among the first to present a practical, three-phase synthetic method demonstrating that both the first and last poles to clear can be stressed appropriately [9].

There are other unique voltage conditions to be considered such as the out-of-phase voltage condition, which can occur during normal startup. Initially, the generator is off and the generator circuit breaker is in the open position with the power system operating at normal voltage. The voltage across the open circuit breaker contacts is equal to the normal power system voltage. When additional or emergency power is desired, the generator is started and begins to produce voltage.

As the generator comes up to speed, the generator output voltage and frequency slowly increase. This causes the voltage across the open contacts of the circuit breaker to vary. In some instances when the generator voltage and the power system voltage are nearly in-phase, the voltage across the circuit breaker contacts will be almost zero. However, a little later, there will be instances when the voltages will be out of phase, producing a voltage across the open contacts of the circuit breaker temporarily exceeding the rated voltage. Even though the generator is usually grounded through a grounding resistor, the voltages across the open contacts can still reach 2.5 times the rated line-to-ground voltage of the system, and the dielectric design of the circuit breaker must take this into account. Sections 6.2.2 and 6.2.9 of IEEE C37.013 require demonstration tests to verify these two capabilities:

1. That the generator circuit breaker can withstand these voltages when open.
2. That it can safely perform switching operations under specified out-of-phase voltage conditions. This is the case of accidental closing, followed by opening, when the voltages were not in phase.

Parameter comparison

Table 1 provides a parameter by parameter comparison between the requirements for generator class circuit breakers and the requirements for distribution class circuit breakers. In some instances, there are obvious and major differences.

The generator class circuit breaker requirements are as specified in IEEE C37.013 [1] and its supplement, C37.013a [2], and identifies performance criteria for smaller generators encompassing a range of machines nominally rated between 10 MVA and 100 MVA.

The standard distribution class circuit breaker requirements are as specified in IEEE C37.04 (Rating Structure) [3], C37.06 (Preferred Ratings) [4], and C37.09 (Test Requirements) [5].

Table 1. Main Differences Between Generator Class Circuit Breakers and Distribution Class Circuit Breakers

Parameter	**Units**	**Generator Class ①**	**Distribution Class ②**
Basic design and application philosophy		Custom	Standard
Rated maximum voltage (V)	kV	5, 7.2, 8.25, 15, 15.5, 17.5, 24, 27, 36, 38 ③ 1.05 x generator voltage	4.76, 8.25, 15, 27, 38
Voltage range factor (K)		K = 1 ③	K = 1 ③
Normal frequency	Hz	60	60
Rated continuous current	kA	1.2, 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 7, 8, 10, 12.5…④	1.2, 2, 3
Emergency current if loss of cooling	A	Required as applicable	Not required
Rated dielectric strength			
Lightning impulse withstand voltage	kV pk	95 ④	95
Power frequency withstand voltage	kV rms	38 ④	36
Rated short-circuit current (I)	kA	20 ④ –120,...	16–63
Close-and-latch (making) current	kA pk	2.74 x I	2.6 x I ⑤
Rated short-circuit duty cycle		CO–30 min–CO	O–0.3s–CO–3m–CO
Rated interrupting time	ms (cycles)	Approx. 60 ④ to 90 (4 ④ to 6)	50 and 83 maximum (3 and 5)
Rated permissible tripping delay (Y)	s	0.25	2
Duration of short-time current	s	1	2
Rated closing time		Required	Not required
Rated re-closing time		Not applicable ⑥	0.3s or 15s ⑦
(Reference) X/R ratio of circuit		50	17
(Reference) Time constant of circuit	ms	133	45
Example: asymmetrical fault current			
If minimum opening time	ms	30	30
Then minimum contact parting time	ms	38	38
% DC for minimum contact parting time		75% ⑧	43% ⑧
(Reference) **S**-factor for minimum contact parting time		1.46 ⑨	1.2 ⑨
Rate of rise of recovery voltage	kV/µs	3.5	0.2–0.55
Short-circuit E_2 peak voltage	kV pk	1.84 x V	1.88 x V
Short-circuit T_2 time to peak	µs	0.62 x V	50–125
Generator-fed asymmetrical fault			
Delayed current zeroes		Must demonstrate	Not required
Relevant DC component at contact part		> 100%	
For example above		110% and 135%	
Endurance capabilities: operations			
Required no-load mechanical		1000	5000 or 10,000
Rated load-current switching capability		50	500
Required short-circuit switching capability	kA cum.	None specified	8 x I_t ⑧
Out-of-phase switching capability			
Out-of-phase switching current	kA	50% x I	25% x I
Power frequency recovery voltage	kV rms	Sqrt(2/3) x 1.5 x V 1.22 x V	2.5 / Sqrt(3) x V 1.44 x V
Rate of rise of recovery voltage	kV/µs	3.3	68% of $RRRV_{S\text{-}C}$
Out-of-phase E_2 peak voltage	kV peak	2.6 x V	2.54 x V
Out-of-phase T_2 time to peak	µs	0.89 x V	2 x $T_{2\,S\text{-}C}$
Rated control voltages		Same as C37.06	Standard
Nameplate markings		Special	Standard
Basic design and application philosophy		Custom	Standard

① From IEEE Standard C37.013-1997 and C37.013a-2007.

② From ANSI Standards C37.04-1999, C37.06-2000, and C37.09-1999.

③ Prior to 1999, K-factors were greater than 1 for most indoor circuit breakers. Generator circuit breakers do not have a rated "K-factor," however, in effect are rated with K =1.

④ Lowest rating listed in C37.013; additional ratings for generators rated 10–100 MVA are included in proposed supplement C37.013a. Comparison of PFWV and lighting impulse criteria is for 15 kV.

⑤ Prior to 1999, the peak close-and-latch current was 2.7 x K x I.

⑥ Reclosing is not applicable for generator circuit breakers because it is highly unlikely that any fault in a generator circuit could simply clear itself.

⑦ An alternate short-circuit duty cycle is O–15s–CO–3m–CO. Prior to 1999, the standard short-circuit duty cycle was CO–5 sec–CO.

⑧ Prior to 1999, the required asymmetrical interrupting capability was determined by I ASYM = S x I, where S = Sqrt (2 x $(\%DC)^2$ +1).

⑨ Since 1999, required asymmetrical interrupting capability It has been determined as follows: It = Sqrt (2 x $(\%dc)^2$ +1) x I.

IEEE/IEC Standard 62271-37-03

In April 2013, the joint IEC/IEEE generator circuit breaker working group met to revise the IEEE C37.013 standard to satisfy the needs of both IEC and IEEE users. Assigning a "Dual Logo" standard presented a challenge. Due to existing rules, IEC would not allow letters and periods in identifying the standard. For this reason it was decided and approved by both IEC and IEEE that the new edition will be designated 62271-37-013. The content of the standard increased from 113 pages to 200 pages. **Table 2** lists just a few of the many changes made to the standard. The biggest change is that the manufacturer can build one product to cover both IEEE and IEC markets.

Table 2. C37.013 and Dual Logo 62271-37-013 Draft Comparison

Description	C37.013	62271-37-013
PFWV/LIWV for 15–17.5 kV	38/95 kV	50/100 kV
Continuous current—load switching test requirement	50 times (M1)	At least three three-phase tests or six single-phase tests
	150 times (M2)	
Interrupting classification for generator-source faults	N/A	G1 and G2
Test procedures and test duties for generator-source fault tests	Required, but not clearly specified	If G1: TD-3, -4, -5 If G2: also TD-6A and -6B
Mechanical operation endurance classifications	1000 cycles	M1000 and M3000
Sound test measurement	No	Yes
Close, latch, and carry for 0.25s test	Yes	Included as TD-1A or as part of TD-1
Tolerances for test parameters	No	Yes
Harmonized TRV parameters	No	Yes
Faults in case of three-winding step-up transformers	N/A	Included
Rules for transport, storage, installation, operation, and maintenance	N/A	Included
Guidelines for safety	N/A	Included
Influence of generator circuit breakers on the environment	N/A	Included
Use of mechanical characteristics and related requirements	N/A	Included
Index of symbols and terminology	N/A	Included
Determination of degree of asymmetry for generator-source short-circuit breaking tests	N/A	Included

Note: Yes = mandatory requirement / No = not mandatory

Conclusion

- Generator circuits present special requirements for the circuit breakers intended to protect them, and an excellent industry standard is available to identify the requirements and demonstrate the capabilities needed
- Standard distribution circuit breakers are not designed and tested for these capabilities
- Both small and large generator circuits experience the unique phenomena described here. If the generator, or the transformer, is critical to the function of the installation, is expensive, or would be time consuming to replace, then an appropriately rated and tested generator circuit breaker would be a prudent investment to protect that circuit
- To suffer a transformer fault is very bad; however, to also lose the generator would be far worse. With a generator circuit breaker, properly rated and tested to C37.013, one can protect the generator from damage, or even complete failure that could occur when it is feeding the faulted transformer
- Similarly, to suffer a fault in a generator is very bad; however, to also lose the transformer would be far worse. With a generator circuit breaker, properly rated and tested to C37.013, one can protect the transformer from damage, or even complete failure that could occur when it is feeding the faulted generator

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