Equipment Life Extension and Modernization of Generator Circuit Breakers

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Abstract

Many hydro-electric generating facilities (**Figure 1**) built from the 1930's to 1970's have power circuit breakers installed between the generators and generator step up transformers that are well beyond their expected service life. Generator circuits also have unique characteristics that require circuit breakers specifically designed and tested for these conditions. To meet this need, the Switchgear Committee of the Institute of Electrical and Electronics Engineers (IEEE) developed and published a special industry standard to address these unique characteristics.

Existing circuit breakers applied on generator circuits may use oil, compressed air, air-magnetic or SF_6 technology for arc interruption. Some circuit breaker designs require more and more maintenance over time and if genuine replacement parts are not available, this can result in improper circuit breaker function that can cause catastrophic failure.

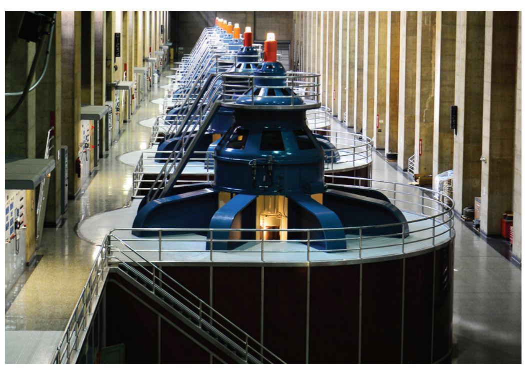

Figure 1. Typical Hydro Generators

This paper discusses these issues and suggests possible improvements associated with modernization and conversions of various types of older circuit breakers used to protect generator circuits. These conversions include generator class circuit breakers with vacuum interrupting technology that complies with IEEE Standard C37.013. The resulting conversions have simpler design, fewer components, reduced maintenance, and readily available replacement parts. They also provide higher reliability, extended insulation life, and often provide safer operation for personnel. Many conversions upgrade the original fixed mounted circuit breakers to drawout designs. Several examples and applications will be presented.

Introduction

In the early days of electrical power generation, alternating current (ac) flow was interrupted by separating the electrical contacts to a suitable distance in air until the plasma could no longer sustain the flow of the arc current. Various techniques were employed to achieve interruption at higher current and voltage levels. The continuing increases in demand for higher current and voltage interruption gave rise to new devices called ***circuit breakers***.

Credit for the development of the first commercial oil circuit breaker in the US was given to Joseph Kelman of California back in 1902; it was made from two wooden barrels filled with mixtures of water and oil.

For nearly the next twenty years, circuit breakers were designed to fulfill the needs of specific applications and were typically developed on a local basis. The shortcomings of existing circuit breaker designs led to better understanding of the basic principles of arc physics, the discovery of new and better arc interrupting technologies and a worldwide increase in circuit breaker development. Generating systems continued to expand, became more demanding and often outpaced the circuit breaker's capability to protect the circuit.

Powering Business Worldwide

Generator Circuit Breakers

It is important to recognize the differences and special requirements posed by generator circuits, compared with those for protection of typical power distribution circuits. Current switching requirements for most generator circuits are more demanding than those associated with typical distribution circuits. Generator circuits have unique characteristics that may require circuit breakers that are specifically designed and tested for those conditions. To meet this need, the Switchgear Committee of the Institute of Electrical and Electronic Engineers (IEEE) developed and issued a special industry standard to address these unique characteristics. The IEEE Standard is C37.013-1997, entitled "IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis". [1]

The first editions of C37.013 focused on the needs of large central-station generator circuits (rated 100 MVA and above) where the ratings were much greater than those required for typical distribution-class circuit breakers. For example, the lowest continuous current rating for generator circuit breakers was 6300 Amperes, more than twice the value of the highest rating of standard distribution class circuit breakers. In 2007 the supplement, C37.013a [2], was published to focus on the needs of smaller generator circuits from 100 MVA down to about 10 MVA. Many of the new ratings appear to be similar to and even overlap the ratings of typical distribution class circuit breakers. However, even though some of the ratings assigned are the same in the "overlap region", other critical performance requirements imposed by generator circuits, such as the transient recovery voltage (TRV) and degree of asymmetry make those applications much more demanding than those normally imposed by typical distribution class circuits.

Demanding performance and versatility are required of generator circuit breakers when applied under certain system conditions. Application possibilities continue to grow 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
- Paper, Chemical, and Process Industries with on-site generation

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

- Generator circuit configuration
    - Generator Characteristics
    - Generator Step-up Transformer Characteristics
- High Continuous Current Levels
- Unique Fault Current Conditions
    - System-Source (Transformer-fed) Faults
    - Generator-Source (Generator-fed) Faults
    - Very high degrees of asymmetry (of the fault current)
- Unique voltage conditions
    - Very Fast Rate of Rise of Recovery Voltage (RRRV)
    - Out-of-Phase Switching

Demanding performance and versatility are required of generator circuit breakers when applied under certain system conditions. Application possibilities continue to grow as a result of the de-regulation of the utility industry, and the construction of smaller packaged power plants. Typical applications includeThe demanding service duty requirements for generator circuit breakers are discussed in the following paragraphs. Finally, a parameter-by-parameter comparison is made between the capabilities required of the generator class circuit breakers and those of the distribution class circuit breakers, as specified in applicable C37 standards. Ruoss and Kolarik [6] discussed the reasons for the development of the first industry standard for Generator Circuit Breakers in 1993.

Generator Circuit Configuration

Figure 2 presents the single line diagram typical of some generator circuits. Although this circuit appears to be 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 close to both the generator and 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 as well as the operational characteristics of generator circuits can present special voltage and current conditions that have to be considered carefully when selecting circuit breakers for such applications.

High Continuous Current Levels

Generator circuit breakers must be able to carry high continuous current levels for extended periods of time. The early editions of the generator circuit breaker standard focused on large generators. For example, they specified a minimum continuous current rating of 6,300 A, and going up to 16 kA or 20 kA. This would obviously require some form of a continuous cooling system for the conductors, and the upper part of this range would be considered "fault current" levels in most distribution circuits. Typical continuous current requirements for standard distribution circuits are usually between 1200 A and 3000 A, or less. Traditionally these circuit breakers are cooled by natural convection of the ambient air. Fan cooling has long been an accepted practice with power transformers, and has become a popular solution in certain distribution 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 of switchgear even for short periods is not preferred. The possible loss of cooling can be unacceptable because of increased maintenance requirements, reduced reliability and limited output in the event the cooling system fails.

Unique Fault Current Conditions

The two key fault current conditions encountered by generator circuit breakers are shown in **Figure 2**.

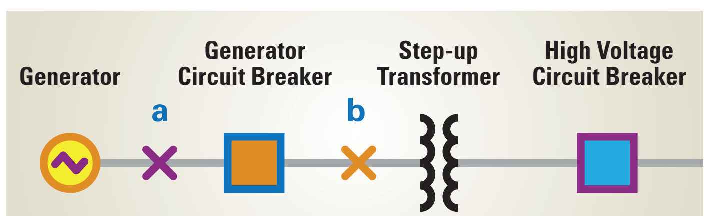

Figure 2. General Circuit Diagram of a Power Station

- 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 current for system-source faults can be extraordinarily 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 impedances. To clear these kinds of faults, generator circuit breakers must be tested and proven capable of interrupting not only the high symmetrical fault currents, but also those with the higher degrees of asymmetry up to 75%, resulting from extremely long dc time constants. (See section 5.8 of IEEE C37.013.)

The currents for generator-source faults are more complicated. Because they are generally lower in magnitude than the system-source faults, some applications can be covered with just the one fault-current rating. However, most generator circuit breakers have a second fault-current rating, for generator-source faults. Because distribution circuit breakers have just one short-circuit current rating, this can be confusing, especially because the generator-source short-circuit current rating is usually less than the system-source short circuit current rating.

However, both ratings can be important, because while lower in magnitude, generator- source faults can produce another very demanding condition called "*Delayed Current Zeroes*," which does not ever occur in typical distribution circuits. This unique characteristic of the generator-source fault current is due to the combination of the very high X/R (inductive reactance to resistance) ratio of the circuit that results in a long dc time constant, coupled with operating conditions of the generator that can produce an ac component of the fault current that decays more rapidly than the dc component! (See the first three cycles of current in **Figure 3**.) When these conditions occur, the current may have an extremely high degree of asymmetry exceeding 100% for many cycles. This condition can manifest itself, for example, when generators are connected in close proximity to step-up transformers by low-resistance conductors, such as over- sized bus runs. This means the asymmetrical fault current peak becomes so high, and its decay time becomes so long, that the first current zero can be delayed for several cycles. (See **Figure 3**) So it is really not sufficient to consider only the magnitude of the symmetrical current, but it is also necessary to consider the degree of asymmetry at contact separation. If the degree of asymmetry is > 100%, then delayed current zeroes can be expected and the circuit breaker has to be tested to prove it has the needed capability.

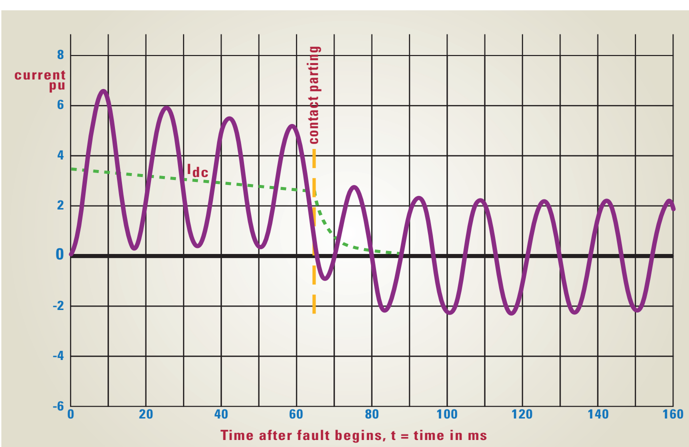

Figure 3. "Delayed Current Zeroes"

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. 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. In the original version of the standard C37.013, the assumption was that each generator circuit breaker would be designed and tested for each specific power station. Depending on the specific conditions of the generator, the generator circuit breaker is tested to demonstrate the ability to withstand the long arcing time and still be able to interrupt the current.

Kulicke and Schramm [7] were among the first to recognize the importance of the ability of the interrupter to withstand long arcing times during the delayed current zero condition. In particular, they demonstrated that vacuum interrupters are well suited to this requirement because unlike some other interrupting technologies, vacuum circuit breakers retain the ability to interrupt, even after the contact motion has ceased.

Since each generator at each power station can have different operating conditions at different moments in time, the standard cannot specify preferred values for generator- source short-circuit current ratings. Therefore manufacturers that provide "off-the-shelf" generator circuit breakers must assign generator-source short-circuit current ratings and appropriate degrees of asymmetry, and subject the circuit breaker to prove that it can interrupt three-phase fault currents with delayed current zeroes. The standard suggests testing at two different conditions as follows:

- Rated generator-source short-circuit current with 110% asymmetry (see 7.3.5.3.4 of C37.013)
- 74% of the rated generator-source current 130% asymmetry (see 7.3.5.3.5 of C37.013)

Although these two proven ratings cannot be used directly to show whether the proposed generator circuit breaker has the capability needed for the defined worst-case generator fault current switching condition, they are intended to be used as reference points from which a skilled short-circuit analyst can determine by analysis that the proposed circuit breaker is suitable.

Unique Voltage Conditions

As previously mentioned, in the generator circuit configuration utilizing a close connected step-up transformer (**Figure 2**) the two large and expensive components, each with highly inductive impedances are connected through the generator circuit breaker with short conductors of minimal resistance. Consequently, the resistance and stray capacitance of the generator circuit are usually much less than those found in typical distribution circuits. These characteristics combine to produce very high natural frequencies of the circuit and in turn result in extreme *Transient Recovery Voltages (TRV) parameters with high Rates of Rise of Recovery Voltage (RRRV)*.

This means that during the interruption, just after the interrupter has been subjected to a high temperature arc, it must re-establish dielectric strength across the open gap rapidly in order to withstand this fast-rising TRV. In the first phase to clear, the peak value of this TRV is 1.84 times (nearly double) the line-to-line voltage of the circuit and the circuit produces that peak voltage within about 10 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, but the rates of rise (RRRV) 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, or 3 to 10 times faster. Smith [8] was one of the first to demonstrate that vacuum interrupters can clear high fault currents against these very fast RRRV values, without adding capacitors to reduce the rate-of-rise. Of course, 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. And even if are surge protective device fails and cannot slow the rate-of-rise of the voltage, the circuit breaker is still able to clear.

These TRV conditions are so severe that even the world's best high-power laboratories cannot usually construct direct test circuits to prove these capabilities. The only way to prove this capability is by high power testing 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 complicated, owing to the need to control the precise operation of two very large power sources, as well as the test object, and 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 desired 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 precisely at the intended moment in time, the result is an invalid test. [It is not a "failure" but just did not demonstrate the required "most severe" condition.] Even invalid tests take time and cause contact wear. Therefore the synthetic tests required for generator circuit breakers are much more difficult to perform and cost more compared to the direct tests required for certification of standard distribution circuit breakers. Initially, synthetic testing was limited to single-phase operations. Recently however, Dufournet and Montillet [9] were among the first to demonstrate a practical, three-phase synthetic test procedure that can apply the appropriate stresses correctly to both the first pole to clear, and the last poles to clear during a single test.

Another unique voltage condition to be considered is the out-of-phase voltage condition, which can occur during normal start-up. Initially, the generator is off and the generator circuit breaker is in the open position with the power system operating. 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. 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 an out-of-phase voltage across the open contacts of the circuit breaker. 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. Section 6.2.9 of IEEE C37.013 requires testing to demonstrate that the circuit breaker can safely perform switching operations under specified out-of- phase voltage conditions. This can occur in the case of accidental closing, when the voltages are not in-phase, and an immediate opening operation is required

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 standard generator class circuit breaker requirements are specified in IEEE C37.013 [1] with its included Amendment, C37.013a [2], for generator circuits rated 10 MVA and above. However, the actual circuit configuration and the system characteristics will determine where these requirements become appropriate.

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]. Field experience has shown that the performance capabilities of some of these vacuum circuit breakers may well be adequate for the protection of smaller machines, rated below 10 MVA.

Table 1. Comparison of Requirements for Generator-Class 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	4.76, 8.25, 15, 27, 38
		1.05 x Gen. Volt.	
Voltage range factor (**K**)		**K** is not used, but effectively, **K** = 1 ③	**K** = 1 ③
Normal frequency	Hz	50 or 60	60
Rated continuous current	kA	1.2, 1.6, 2, 2,5, 3.15, 4, 5, 6.3, 8, 10, 12, 16, …	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	60, 75, 95, 110, 125, 150	60, 95, 110, 125, 150
Power frequency withstand voltage	kV rms	20, 28, 38, 50, 60, 80	19, 36, 50, 60, 80
Short-Circuit Parameters			
Rated system-source short-circuit current (**I**)	kA	20, 25, 31.5, 40, 50, 63, 80, 100, 120,160, ..	16, 20, 25, 31.5, 40, 50, 63
System source % asym (minimum contact parting time)		*75%* ④⑤	*43%* ④⑤
Rated generator-source short-circuit current ⑥	kA	With 110 % asymmetry	N/A
74% rated generator-source short-circuit current ⑥	kA	With 130 % asymmetry	N/A
Close-and-latch (making) current	kA pk	2.74 x **I**	2.6 x **I** ⑦
Rated short-circuit duty cycle		**CO**–30 min–**CO**	**O**–15s–**CO**–3m–**CO** ⑧
Rated interrupting time	ms	Approximate 60 to 90	83 maximum
	(cycles)	(4 to 6)	(5)
Rated permissible tripping delay (**Y**)	s	0.25 (but not used)	2
Duration of short-time current	s	1	2
Rated closing time		Required, but no preferred values	Not required
Rated reclosing time		30 min ⑨	0.3 s or 15 s
(Basis of rating) X/R ratio of circuit		50	17
(Basis of rating) DC 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
System source fault required degree of asymmetry =		075% ④⑤	43% ④⑤
(ref. only) asymmetry factor, **S** =		1.46 ⑥	1.2 ⑥
Rate of rise of recovery voltage [RRRV] (uc/t3)	kV / µs	3.2 to 3.5	0.2 to 0.55
Short-circuit TRV peak voltage uc (E2)	kV pk	1.84 x **V**	1.88 x **V**
Short-circuit TRV rise time t3	µs	0.53 x **V** to 0.58 x **V**	44 to 109
(ref) short-circuit TRV time to peak T2	µs	0.62 x **V** to 0.68 x **V**	50 to 125
Generator-source fault RRRV (uc/t3)	kV / µs	1.5 to 1.6	N/A
Generator-source fault TRV peak voltage uc (E2)	kV pk	1.84 x **V**	N/A
Generator-source fault TRV rise time *t*3	µs	1.35 x **V** to 1.44 x **V**	N/A
(ref) generator-source fault TRV time to peak T2	µs	1.68 x **V** to 1.80 x **V**	N/A

① From generator circuit breaker standard C37.013 1997 (R2008) [includes amendment 1 C37.013a-2007].

② From ANSI/IEEE Standards C37.04-1999, C37.06-2000, and C3709-1999.

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 based on **K** =1.

④ Since 1999, required asymmetrical current interrupting capability $\mathbf{I}_t$ has been determined by: $\mathbf{I}_t$ = Sqrt (2 x %dc x %dc +1) x **I**, where "%dc" = degree of asymmetry at contact separation.

⑤ Prior to 1999, the required asymmetrical interrupting capability was determined by $\mathbf{I}_{ASYM}$ = **S** x **I**, where S = Sqrt (2 x %dc x %dc +1), where "%dc" = degree of asymmetry at contact separation.

⑥ Rated values for generator-source short-circuit current are not always required. And when values are required, they depend on both the characteristics and the operating conditions of the generator. Therefore, it is not possible to choose preferred values for generator-source short-circuit current ratings.

⑦ Prior to 1999, the standard peak close-and-latch current was 2.7 x **K** x **I**.

⑧ An alternate short-circuit duty cycle for distribution class circuit breakers is **O**–0.3s–**CO**–3m–**CO**. Prior to 1999, the standard short-circuit duty cycle was **CO**–15 sec–**CO**.

⑨ Rapid reclosing is not applicable for generator CBs because both generators and transformers contain non-self-restoring insulation, and it is highly unlikely that any fault in a generator circuit would recover its dielectric withstand capability after the fault is cleared.

Extending a Power Circuit Breaker's Useful Life

Circuit breakers used in generator applications can have various types of interrupting technologies, require special operating parameters and may have exceeded their original design life. The circuit breaker's performance and longevity depend on:

- Switching rates
- Number of switching operations and current magnitudes
- Maintenance costs
- Availability and cost of renewal parts
- Maintenance intervals
- Maintenance outage times
- Environmental concerns (oil, PCBs, asbestos, and possibly SF_6)

These parameters not only affect the system availability and reliability, but also impact the ongoing financial viability of the generating station. When considering when to modernize power circuit breakers used in generator circuits, there are a number of options involving available technology upgrades to consider. In most scenarios, there will be some type of "conversion" involved.

IEEE Standard Requirements for Conversion of Power Switchgear Equipment C37.59- 2007 is a process standard that provides guidance and testing methodology for power circuit breakers, including those that are designed to meet the requirements of IEEE C37.013. The original version of C37.59 was approved in December of 1991, but not published until June 8, 1992. The current version of C37.59-2007 defines important conversion terms that should be noted and included in specifications that outline customer requirements for Equipment Life Extension and Modernization. There is an old cliché that says you hope you "get what you paid for", but it may be more important to "get what you asked for". So be sure you ask correctly and insist on getting what you asked for. Some of the C37.59-2007 definitions of conversion terms are reproduced in part from IEEE C37.59-2007, modified to add Std C37.013 and referenced in the conversion process:

3.2 Conversion: The process of altering existing power switchgear equipment from any qualified design.

3.3 Compartment adapter: A removable device designed for insertion into a switchgear circuit breaker compartment that provides mechanical support and interlocking plus the primary and secondary electrical connections to allow insertion of a drawout circuit breaker that differs mechanically from that which originally occupied that circuit breaker compartment.

3.4 Design verification: The process of design qualification, in accordance with all appropriate standards, of any conversion by means of design testing and/or evaluation, supported by justified technical evaluation and documentation.

3.5 Modular assembly: A circuit breaker element, including interrupters, operating mechanism, and connecting terminals, or an alternating current (ac) contactor element, including interrupters, operating mechanism, and connecting terminals, that has been tested and qualified to the appropriate industry standards.

3.6 Qualified design: Any power switchgear equipment that has been tested and certified to appropriate industry standards.

3.7 Racking: The act of moving a removable element physically between the connected position and the disconnected position in its compartment.

3.8 Reconditioning: The process of maintaining existing power switchgear equipment in operating condition as recommended by the manufacturer's instructions, using only qualified design parts. Reverse engineered parts (designs copied from existing parts by other manufacturers) are not considered to be "qualified design parts" unless specifically design verified.

3.9 Replacement interchangeable circuit breaker: A circuit breaker that utilizes all new parts, has been design tested to IEEE Std C37.09 or to ANSI C37.50-1989 or IEEE Std C37.14-2002 ① as required, and requires no conversion of existing switchgear to maintain proper operation.

3.10 Replacement non-interchangeable circuit breaker: A circuit breaker that utilizes all new parts, has been design tested to IEEE Std C37.09 or to ANSI C37.50-1989 or IEEE Std C37.14-2002 * as required but requires conversion of existing switchgear to maintain proper operation.

3.11 Retrofill: A conversion process that includes replacement of the circuit breaker and circuit breaker compartment functional components of a qualified design within a vertical section or compartment of a vertical section with functional components of a different qualified design.

** Circuit breakers used for generator service should also be design tested to Standard C37.013.*

Note: The term "retrofit" is not defined and is no longer used in the IEEE C37.59-2007 Standard.

These conversion solutions are readily available from a number of sources. Site performance and financial requirements will drive the selection process. It is important to note that the "right" solution should provide the best long-range performance. Look for cost estimates and proposals from a number of sources. Typical solutions can be categorized as follows:

- **Reconditioning:** If OEM parts are available, outage time is not an issue, the circuit parameters are less than or equal to the circuit breaker's rating and the switching rate is low, then reconditioning of the existing circuit breaker may suffice for at least 3-5 years. If OEM parts are not available for a rebuild, then the circuit breaker's performance will be affected and a failure can occur. Reconditioning using third-party reverse engineered parts, as cautioned by the IEEE C37.59-2007, can be dangerous. Reconditioning does nothing to update technology or increase the circuit breaker's capabilities. However, this is the lowest cost solution.
- **New replacement circuit breakers:** These will either fit directly into a drawout arrangement or require minor structure or control wiring modifications to complete their interface. Complete standalone designs can be manufactured to replace existing fixed mounted oil circuit breakers. In many instances, the fixed mounted design can be replaced with a drawout configuration to enhance reliability and reduce maintenance outage time. The new design would be tested to the appropriate IEEE Standards.
- **Retrofill conversions of existing installations:** Retrofill Conversions are often good solutions, provided the existing enclosure has the capability and room to accommodate the conversion components. Newer technology and circuit breakers with increased capabilities can be interfaced into the existing enclosures. IEEE "Design Qualification Testing" is required to IEEE C37.59- 2007 and can be costly, but is less expensive than installing new switchgear. Conversions of fixed mounted circuit breakers to drawout construction improve uptime and reliability of the installation. When installations are unique, a Retrofill Conversion is often the best solution. The cost is usually between that of New Replacement Circuit Breakers and Complete Replacement.
- **Complete replacement:** New switchgear with current technology circuit breakers is always an option. Often extensive site preparation and reconfiguration is required to accommodate a different dimensional layout and new cabling is required. In addition, outage time, available space, conductor interfaces and total installed cost may rule out this option. This is usually the highest cost solution.

Hydro-Generating Case History

Gaston Hydro Station (Figure 4) is located in the small town of Thelma, North Carolina along the banks of the Roanoke River. The station is integral with the Gaston Dam that backs up water from the river into the Lake Gaston reservoir. When water is routed through the powerhouse turbines, the station's four generators can produce up to 55 megawatts each, for a total capacity of 220 megawatts.

Figure 4. Gaston Hydro Station

The powerhouse contains one adjustable and three fixed-blade propeller type turbines and generators originally manufactured by Westinghouse Electric Corporation. The turbines generate 70,000 horsepower from a 67-foot head at 100 rpm.

Commercial operation of the power house dates back to 1963. Today the power house is used for continuous, peaking, or black start power for other generating plants on the Dominion Energy Grid. For reference, the estimated lost revenue per day for one of the generators at Gaston Hydro Station at 80% base load based on a consumer average rate of $.115/kwh is:

- $110,000/day
- $554,400/man-week

Original Circuit Breakers

The original four circuit breakers installed at the Gaston Hydro Station in 1963 used oil as an interrupting medium (Figure 5). They were referred to as bulk oil circuit breakers (OCB) and were not designed to the new generator circuit breaker standard; the original C37.013 Standard was not written until 1989 and did not address characteristics for circuit breakers of this size. The circuit breakers were outdoor, fixed mounted designs that were located in a switchyard with overhead air switches for isolation and were connected via overhead porcelain bushings. Bulk oil circuit breakers utilize the formation of the gas bubbles created by the arc; the bubbles increase pressure and push the arc through the arc grids. When the arc passes through the next current zero it is extinguished. The byproducts of the arcing process (such as carbon) as well as temperature and pressure fluctuations that cause air intrusions tend to contaminate the oil. Contaminated oil was replaced or filtered on a regular basis.

Figure 5. Typical Oil Circuit Breaker

Porcelain bushings provided a high dielectric path for the current leads to enter the grounded metal tank. Oil immersed ring-type current transformers were sufficiently insulated for higher dielectric levels. Maintenance required a complete outage as well as isolation and grounding of the fixed mounted bulk oil circuit breaker conductors.

The circuit breakers also required de-tanking to access the contacts. This was expensive and required an outage of up to a week for one substation team. Spare parts were becoming difficult to obtain and their cost was increasing. Additionally, oil spills that could occur during maintenance outages would cause environmental issues.

The circuit breakers at the Gaston Hydro Station were maintained on a regular eight year schedule and had an in-service life of about 29 years. By the early 1990s their service life was about over.

Ratings for the original oil circuit breakers installed at the Gaston Hydro Station:

- 15.5 kV maximum voltage
- 110 kV BIL
- 3000A continuous current
- 1500 MVA (63 kA) interrupting at 13.8 kV
- Outdoor OCB with six bushing-mounted current transformers
- Three-tank design provided phase isolation of the internal conductors

First Conversion December 1991

In December 1991, the four OCBs were replaced with conversions (**Figure 6**) that used fixed-mounted vacuum circuit breaker elements rated and manufactured to distribution circuit breaker standards. The circuit breakers were mounted in a ferrous- steel enclosure with a stainless-steel top and the final assembly was painted. The stainless-steel top prevented circulating currents from melting the steel between the bushing mountings. The enclosure mountings and termination locations were designed to interface with the original bulk oil circuit breakers to reduce total installation costs. Since C37-59-1992 had not been published at the time the conversion circuit breakers were manufactured, there was no IEEE Standard to cover their design and test. The manufacturer supplied a standard factory production test report similar to the requirements of C37.09, Section 5. An IEEE Certification of Performance was not available since no standard existed. A total of five conversion circuit breakers were furnished so the utility would have one spare unit (**Figure 7**).

Figure 6. First Gaston Circuit Breaker Conversion

Converted Circuit Breaker Ratings and Features:

- 15 kV maximum voltage
- 95 kV BIL
- 3000A continuous current
- 1000 MVA short-circuit (48 kA)
- Outdoor enclosure—six bushing mounted CTs
- Vented openings with replaceable HVAC filters
- Open bus configuration with phase barriers
- Vacuum interrupters were not isolated from bus
- Standard distribution-class circuit breaker modular assembly

The circuit breakers perform satisfactorily, but some of the maintenance issues of the original bulk oil circuit breakers remained and a few new issues came with the vacuum conversions.

Figure 7. Spare Conversion Circuit Breaker

- Since they were fixed mounted designs, they still required long outages for maintenance and repair
- Substantial rigging was required for removal and transport to a maintenance area
- Filters needed attention and changing, also requiring an outage
- Moisture from blowing rain and snow was an issue
- Touch-up painting for rust prevention required an outage
- Paint would not stick to stainless-steel top, so it would flake off
- In-service life of 19 years and would have lasted longer, but maintenance costs were increasing
- The complete assembly was not designed or tested to any IEEE standard
- If a fault occurred anywhere in the circuit breaker enclosure, it would propagate to both line and load on all three phases
- Operating mechanisms became unreliable with several improper operations

Second Conversion December 2010

In 2010, Dominion Energy decided to replace the first vacuum breaker conversions with new replacement vacuum circuit breakers. Our replacement project would benefit from the following "wish list" since the transmission grid had gotten stronger and the breaker duty rating had exceeded 100%:

- Reduce maintenance cost
- Improved overall system reliability and uptime
- Reduce maintenance outage time
- Increase short-circuit capability back to 63 kA
- Designed and tested to C37.59-2007 with an IEEE Test Certificate
- Circuit breaker modular assembly designed and tested to C37.013 Generator Standard
- Provided drawout construction with a spare circuit breaker element
- Eliminate painting and rusting
- An isolated phase bus compartment
- Metal-clad circuit breaker compartment
- Eliminate bus torqueing and cleaning
- Eliminate filters and moisture issues
- Maintain bushing termination locations

- Provide standard instruction manual for the circuit breaker and supplemental interactive digital video with support for maintenance and testing of the new circuit breakers

The only way to meet the requirements of the utility's "wish list" was to manufacture a unique circuit breaker enclosure. The multiple requirements were not covered by any IEEE Standard, but various parts of different IEEE Standards were grouped under the blanket of IEEE C37.59-2007 Conversion Standard. This provided a qualified design and established certification testing to ensure the circuit breaker would perform as required. The wish list required a number of new design approaches.

1. Enclosure—304 non-magnetic stainless steel with stainless-steel hardware to eliminate enclosure maintenance and painting (see **Figure 8**)

Figure 8. Second Conversion Circuit Breaker and First Conversion Circuit Breaker

2. Double-louvered venting with sandwiched stainless-steel wire mesh to prevent the entry of blowing rain, snow, and insects without the need of separate filters (see **Figure 9**)

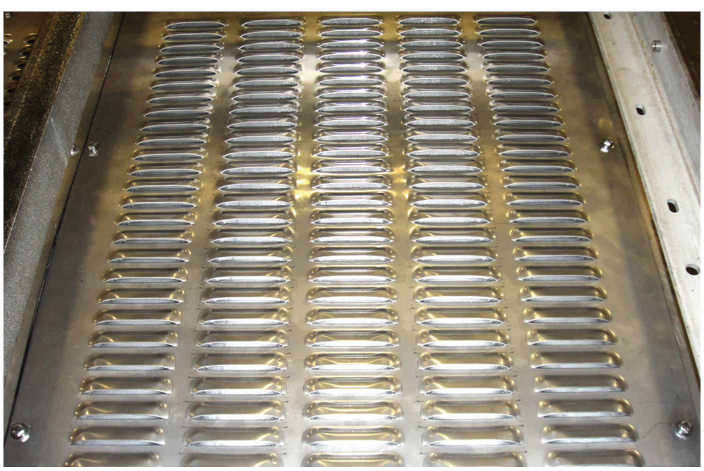

Figure 9. Double Louvers with Wire Mesh

3. Oversized space heaters with thermostatic controls
4. Thermally compensating porcelain roof bushings to prevent conductor movement resulting from load and temperature fluctuation. Bushing terminations to match the existing locations and termination methods
5. Belleville compression washers at all bus connection joints to eliminate bus re-torquing
6. Semi-station class main bus compartments to provide phase isolation (see **Figure 10**)

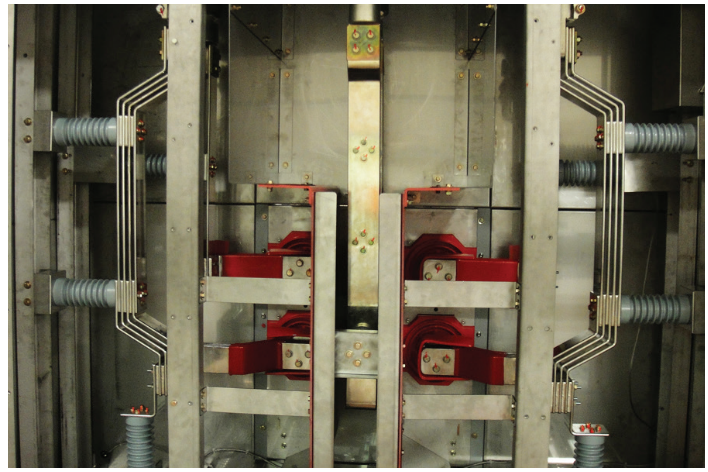

Figure 10. Station-Class Bus Design

7. Drawout construction for the circuit breaker with metal-clad isolation between the circuit breaker and bus compartments (see **Figure 11**)

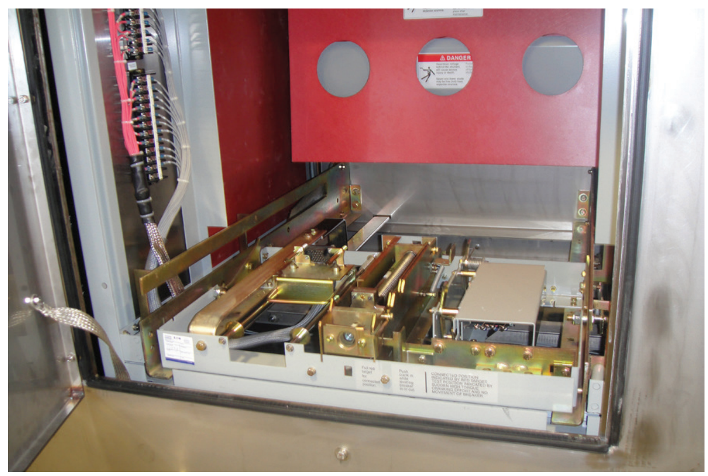

Figure 11. Metal-Clad Drawout Breaker Compartment

8. IEEE Certificate for Qualification Testing required

Second Conversion Circuit Breaker Ratings

- 15 kV maximum voltage
- 95 kV BIL
- 3000A continuous current
- 1500 MVA nominal short-circuit (63 kA)
- Generator class circuit breaker

IEEE Design Testing

Qualification or design testing is the most important facet of completing a new circuit breaker system design. C37.59-2007 provides guidance on test procedures and references additional IEEE Standards germane to the type circuit breakers used in the conversion design. Some of the certification test parameters can be conducted on the circuit breaker modular assembly and sub-assemblies, but others require testing of simulations or duplications of the actual conductor system, components and enclosures as a complete assembly. The generator circuit breaker modular assembly requires complete qualification testing to IEEE C37.09 and IEEE C37.013 at rated voltage and current and must be supported by a design test certificate. This verifies the modular assembly conforms to the ratings stated on the circuit breaker nameplate.

A part of the new assembly is a "mini-module." The mini-module consists of a structural steel frame, primary stationary conductors to interface with the removal generator circuit breaker modular assembly, secondary control contacts, interlocks, MOC (mechanism operated contacts) and TOC (truck operated contacts) switches, rejection code plates, and a racking system to lever the circuit breaker in and out of the fully connected positions. The mini-module also passed design testing per IEEE C37.20.2 and specific test methods and parameters are contained in the standard.

Since the generator circuit breaker modular assembly and its associated mini-module previously passed design testing to IEEE C37.09, IEEE C37.013 and C37.20.2, it is not necessary to repeat all the test sequences. However, IEEE C37.59-2007 requires specific design tests to confirm design qualification of changes in the conductor system and enclosure and to verify the complete system will perform as required.

The second conversion circuit breaker's enclosure is a combination of a metal-clad construction for the generator circuit breaker modular assembly and a semi-station class arrangement for the bus compartment. Major test parameters in IEEE C37.20.2 and C37.013 were used for design testing.

- Dielectric withstand tests of all primary conductors
  - 36 kV power frequency for one minute
  - 95 kV BIL
- Continuous current test at 3000A
- Short time current test for 2 seconds at 63 kA
- 15 cycle momentary test at 63 kA x 2.74 = 173 kA
- Louvers subjected to water spray tests
- Complete production tests were performed before and after the design tests

All design tests were performed successfully and the four replacement units were installed by the end of March 2011. Since installation, there have been numerous rain and snowstorms, several hurricanes, and one earthquake. No generator circuit breaker outages have been reported and no unscheduled maintenance has been required.

The drawout spare generator circuit breaker can be rotated with the other four circuit breakers to enable extremely short outages for scheduled maintenance; this reduces the required outage to change circuit breakers from several days to 3-4 hours. If an in- service circuit breaker needs an unscheduled outage, it can be exchanged with the spare circuit breaker in a matter of hours and the generator can be put back on line.

Since the enclosure is all stainless steel, no maintenance is required for painting. The louvers and screens have prevented the intrusion of water and insects.

The new generator vacuum circuit breakers have been in service about three years at the writing of this paper. They need at least 10-15 more years of service before providing a serious service log. Based on their capabilities and the rugged design of the switchgear system, a service life of 25-35 years should be feasible.

Interactive Digital Video Training Module

The hydro generation and utility industry has an aging workforce, which is creating a 15-20 year knowledge gap that requires training and time to bridge. To facilitate education and help address the "knowledge gap" and address different learning techniques that are more familiar to the younger employees, an interactive video training module was provided to teach the basics of circuit breaker maintenance and testing (**Figure 12**). The module, designated VIBE (Visual Instruction Book Essentials) is in PDF format and does not require any special software to operate. Numerous test procedures are detailed along with active animations and illustrations to guide personnel through the maintenance and testing process. VIBE contains videos with step-by-step instructions on replacing coils and charging motors as well as mechanism lubrication (**Figure 13**). The vacuum circuit breakers incorporated in the Lake Gaston circuit breakers can have a *CloSure™* test performed to determine the health of the circuit breaker mechanism. The digital system also contains a 3D model of the new circuit breaker with an indented bill-of-material (**Figure 14**) and individual parts identification. It allows the digital disassembly of the circuit breaker. The user can rotate, zoom, and remove parts with the click of a mouse button on a standard laptop computer without needing special software. Everything is contained in a standard PDF format.

It is anticipated that the interactive digital training video will greatly accelerate the learning curve.

Figure 12. VIBE

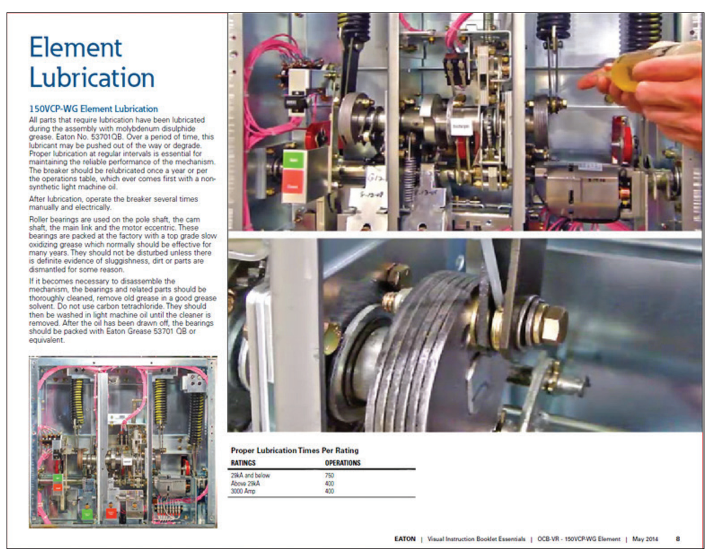

Figure 13. Lubrication Video

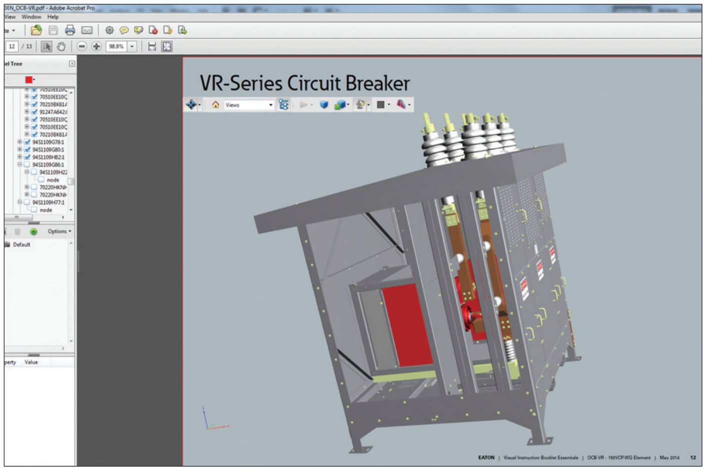

Figure 14. 3D Model and Bill-of-Material

Conclusions

- Generator circuits may present special requirements for the circuit breakers intended to protect them. Excellent industry standards are available to identify the requirements and demonstrate the required capabilities
- Standard distribution circuit breakers are not designed and tested for conditions identified in C37.013 and PC37.013a. However, field experience has shown that some vacuum circuit breakers have capabilities sufficient to protect smaller generator circuits
- Both small and large generator circuits can experience the unique phenomena discussed here
- Suffering a transformer fault is very unfortunate; however, losing the generator in addition would be far worse. With a generator circuit breaker, properly rated and tested to the appropriate industry standard, one can protect the generator from damage, or even complete failure that could occur when it is feeding the faulted transformer
- Similarly, suffering a fault in a generator is very unfortunate; however, losing the transformer in addition would be far worse. With a generator circuit breaker, properly rated and tested to the appropriate industry standard, one can protect the transformer from damage, or even complete failure that could occur when it is feeding the faulted generator
- There are various methods available to extend the useful life of generator circuit breaker systems using reconditioning and conversions. Conversions also make ti possible to modernize the system to current generator class circuit breakers. By incorporating newer interrupting technologies and other enhancements, a reduction in maintenance costs and reliability improvement can be realized
- Interactive digital video training accelerates the learning curve for maintenance personnel on new technology and existing testing techniques that are specific to generator class power circuit breakers

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