

# Replacement of hydro plant generator oil circuit breakers with modern vacuum technology

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## Abstract

Modernization of aging infrastructure is the key to continued reliability and performance of today's power plants. Aging and obsolete medium voltage generator circuit breakers are commonly found throughout hydro, thermal, and other power plants. Many of these breakers are oil or compressed air type breakers that are rapidly approaching their end-of-life, requiring replacement or conversion using practical solutions that minimize outage duration and system downtime.

Until recently, SF<sub>6</sub> insulated generator circuit breakers have been the primary available solution for replacement of new generator circuit breaker applications above 3000A continuous current. These breakers are designed and tested to the special requirements of IEEE® C37.013-1997 [1], which is structured to address much larger central station generator applications with continuous currents from 8000 to 26,000A and interruption ratings from 100 to 160 kA. As a result, these breakers are physically very large because they are designed for connecting to high-ampere iso-phase type bus conductors. In many cases, this makes them impractical with regard to cost and footprint for smaller generators.

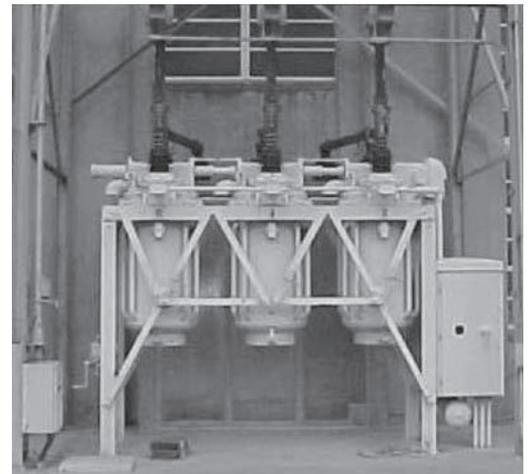
Continual advances in vacuum technology have led to the advent of 5 to 15 kV medium voltage vacuum circuit breakers with continuous current ratings from 1200 to 6000A (convection ambient air cooled) and up to 7000A (with fans) and with interruption ratings from 50 kA up to 75 kA.

The industry has recognized the need for more practical generator circuit breaker solutions. In 2007, the IEEE Switchgear Committee issued a supplement to IEEE C37.013a [2] to address small to medium size generator breaker applications in the 10 to 100 MVA generator unit range.

Testing of these new high-ampere vacuum circuit breakers has confirmed performance to the unique requirements of IEEE C37.013, which far exceeds the requirements of normal power distribution circuits. This has facilitated the use of vacuum circuit breakers, with all their advantages in these applications, while meeting the physical constraints, the available space, and the required connections to the circuit.

## Introduction

After almost 50 years of service, two 15 kV station type outdoor oil-filled generator circuit breakers (shown in **Figure 1**) at a two-unit 160 MW hydro power plant were retired and replaced with modern environmentally friendly vacuum circuit breakers. The existing GE Model FK-339 oil-filled station generator circuit breakers were manufactured in 1959. The circuit breaker electrical ratings were 15.5 kV maximum voltage, 110 kV BIL, 1500 MVA, 5000A continuous current, and 60 kA interrupting.



**Figure 1. Existing Oil Circuit Breaker**  
(Photo Courtesy of Southern Company)

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This paper provides a useful template to follow for replacement generator circuit breaker projects, as well as new generator applications in the 10 to 180 MVA unit generator range. The process of replacing these breakers will be presented, including the environmental, operational, maintenance, and technical considerations. In addition, system calculations and modeling performed to confirm that the critical generator circuit parameters were within the tested capabilities of the generator circuit breaker will be discussed. Finally, the before and after installation configurations, and the associated challenges of the replacement will also be examined.

## Environmental considerations

The hydro plant is located in a popular public recreational lake area; therefore, environmental considerations were important. Replacement of the oil circuit breakers eliminated potential leakage concerns and reduced the inventory of combustible materials on the site.

Vacuum circuit breakers are environmentally friendly because they use solid insulation systems and vacuum interrupters that are free of combustible oil or SF<sub>6</sub> gas. The potential health risk to arced SF<sub>6</sub> gas is eliminated, as well as the special hazardous waste handling equipment and procedures that SF<sub>6</sub> breakers require during routine maintenance or when they are disposed of at the end of life.

Southern Company, the hydro plant owner, is one of 81 utilities who participate in a voluntary collaborative effort with the EPA called the SF<sub>6</sub> Emission Reduction Partnership for Electric Power Systems [3] to identify and implement cost-effective solutions to reduce sulfur hexafluoride (SF<sub>6</sub>) emissions.

## Maintenance consideration

The site operating environment and duty cycle (the number of annual open-close operations) provide for long life of the generator circuit breakers. The environment is clean and free of airborne pollutants with generally mild temperatures, except for the hot and humid summer months. During normal operating conditions, the breakers are continuously on (closed).

The oil circuit breakers were subject to an on-going conditions-based preventative maintenance program. General maintenance was performed every scheduled outage, including oil monitoring and analysis, visual inspection for leaks, inspection and repair of the coating system, and periodic cleaning of the bushings. The leakage of seals, valves, bushings, flanges, gaskets, drain plugs, and so on can be complex repair operations.

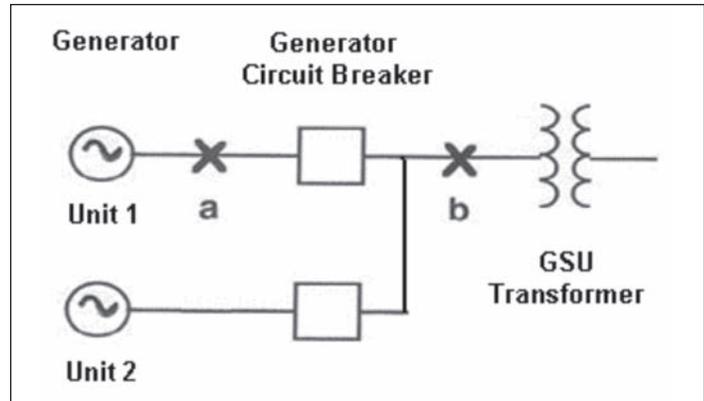
The decision to replace the oil circuit breakers was primarily driven by reliability concerns due to their 50-year age. As the breakers aged, the main concern became replacement parts availability. Parts were often either not available or supported by the original manufacturer. The circuit breakers were indeed obsolete and there were no spare breakers for this application in the Southern Company system.

Upon replacement, the existing oil circuit breakers had approximately 1000 operations (less than six operations per year). In other power plant applications, like pumped storage and peaking plants, generator circuit breakers can be called upon to operate more frequently, and the breaker duty cycle can become a more important factor in the established periodicity of the preventative maintenance program. The replacement vacuum generator circuit breakers selected for this project provide a demonstrated load current switching capability of 10,000 operations, with up to 1000 operations between servicing.

## Generator circuit configuration

A simplified site single-line diagram of the generator circuit configuration is presented in **Figure 2**. The two site generators and generator circuit breakers are connected in parallel, feeding a common bus connected to the GSU transformer that serves both units. The generator circuit breakers serve as the primary switching and protective devices.

Each generator is rated 87.5/100.625 MVA, 60/80 degree C rise, with a 60 Hz operating voltage of 13.8 kV ±5%. During peak operating conditions, the maximum continuous current of the site generators at the minimum rated voltage is 4419A.



**Figure 2. Simplified Site Generator Circuit One-Line (Showing Potential Fault Locations a and b)**

The GSU is a combined transformer and autotransformer rated 114/152/190/212.8 MVA, OA/FA/FOA/FOA, stepping up the 13.8 kV generator voltage to the transmission voltages of 115 and 161 kV.

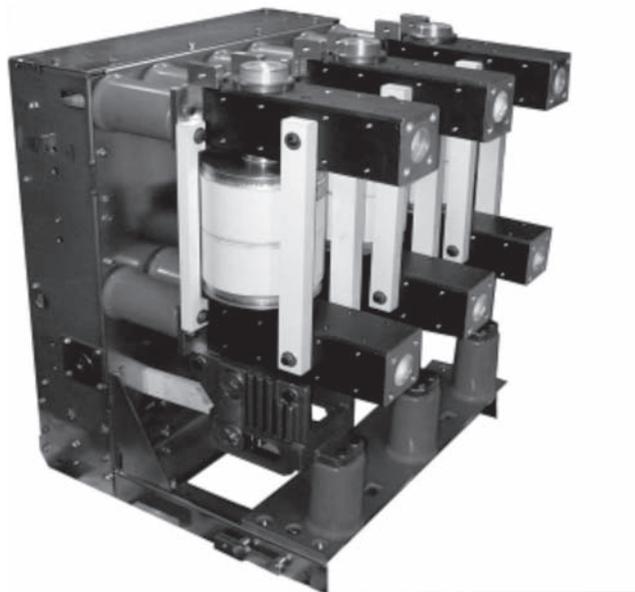
## The special requirements of generator circuit breakers

Generator circuit breakers are a special application, because they experience conditions that are not common and are certainly far more demanding than those experienced in normal power distribution circuits [4]. Generator circuit breakers are commonly connected in close proximity to large inductive generators and step-up transformers by large conductors with low impedance. This maximizes the system operating efficiency and reduces the watts loss of the system. However, this configuration leads to special conditions when the breaker is called upon to switch or interrupt transformer source faults (**Figure 2**, fault location a) and generator-fed faults (**Figure 2**, fault location b).

Special testing to IEEE C37.013 [1] [2] is required to confirm performance of the circuit breaker to these unique characteristics. In addition to high continuous current and interruption ratings, these special conditions include high X/R ratios, high AC asymmetry, delayed current zero, fast transient recovery voltage (TRV) with rapid rate of rise recovery voltage (RRRV), and out-of-phase current switching.

## Vacuum generator circuit breaker ratings and testing

Eaton's Model 150VCP-WRG75 5000 fixed-mounted vacuum generator circuit breaker, rated 15 kV, 75 kA interrupting, and 5000A continuous, was selected for this project. This breaker element, shown in **Figure 3**, employs specially designed 7-inch diameter vacuum interrupters equipped with TMF (transverse magnetic field) contacts and "LR" metal-vapor condensation shields, which are fabricated from special copper-chromium material. The circuit breaker mechanism and bracing has also been enhanced beyond what is typically provided for normal power distribution breakers.



**Figure 3. 150VCP-WRG75 Generator Circuit Breaker**  
(Courtesy of Eaton Corporation)

The breaker was tested as a component mounted in a minimum volume test enclosure to IEEE C37.013, achieving ratings as published in certified test report 3A74981H79 [5]. The published ratings and tested capabilities of this breaker now will be presented in relation to the required critical site parameters.

## Site generator circuit requirements and calculations

Conservative engineering practice always requires a system study to model the actual site electrical circuit conditions. This is essential to establish the critical system parameters and to confirm that the generator circuit breaker is applied within its demonstrated ratings. A review of this process and these critical parameters is now presented.

### X/R ratio

It is expected that the system X/R ratio (ratio of system inductance to resistance) will be much higher for generator circuit applications than normal power distribution circuits. This was confirmed for the actual site conditions, as the calculated system X/R ratio was approximately 39. Typical X/R ratios on normal power distribution systems are typically 17 or less. The higher X/R ratio increases the DC component of the fault current, extends its rate of decay, and under certain circuit conditions can even delay the current zero for several cycles.

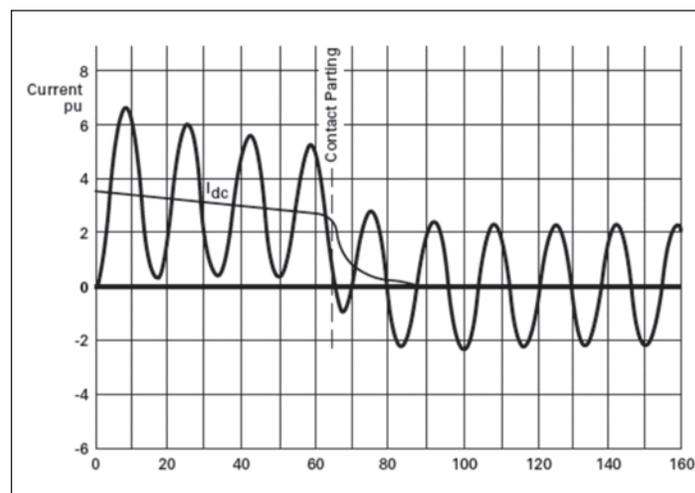
### Transformer source faults

Transformer source faults (**Figure 2**, fault location a) can be very high in magnitude because the full energy of the power system feeds the fault. In addition, the high X/R ratio characteristic of generator circuits increases the DC component of the fault.

The available fault current at the site was calculated to be 41.4 kA rms symmetrical, 65.9 kA rms asymmetrical, and 109.8 kA peak. These ratings are well within the published ratings of the 150VCP-WRG75 vacuum circuit breaker, which achieved system source ratings of 75 kA rms symmetrical and 100.4 kA rms asymmetrical. The demonstrated breaker percent DC component is 63%, and the close and latch rating is 206 kA peak.

### Generator fed faults

Generator fed faults (**Figure 2**, fault location b), while lower in magnitude, can experience a severe condition called delayed current zero. The high X/R ratio along with other conditions of the generator circuit can cause the DC component of the fault current to exceed 100% as shown in **Figure 4**. The asymmetrical fault current ( $I_{dc}$ ) becomes high enough and its decay slow enough that the first current zero can be delayed for several cycles.



**Figure 4. Typical Short Circuit with Delayed Current Zeros**

Circuit breakers require a current zero to interrupt the fault current. As a result, the generator circuit breaker experiences a longer arcing time and the associated increased thermal and mechanical stresses during the extended interruption time.

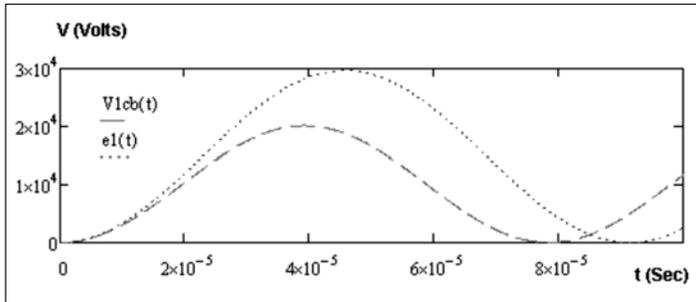
The maximum generator fed fault (**Figure 2**, fault location b) available at the site was calculated to be 11.73 kA rms symmetrical, 18.74 kA rms asymmetrical, and 31.1 kA peak. These ratings are also well within the published ratings of the 150VCP-WRG75 vacuum circuit breaker, which achieved generator source ratings of 50 kA rms symmetrical and 92 kA rms asymmetrical. The demonstrated breaker percent DC component is 110%, and the close and latch rating is 206 kA peak.

**Transient recovery voltage**

The resistance and stray capacitance of generator circuits is typically much less than normal distribution circuits. These characteristics combine to produce very high natural frequencies and in turn can result in extreme transient recovery voltages (TRV) with high rates of rise (RRRV).

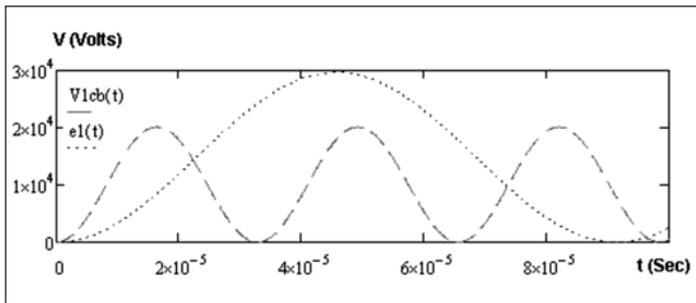
Two generator fault cases and three transformer source fault cases were studied to determine if the breaker capability was sufficient to meet the TRV requirements specific for this application. For all generator fault cases, the breaker capability was sufficient without the need for any additional capacitance to the system. However, the transformer source fault cases were more severe, and indicated additional capacitance was required.

Case 1 considered both generators connected in parallel to the GSU low-side bus with no additional capacitors. The Case 1 study showed no additional capacitance was needed because the system response was below the breaker capability curve. The system TRV (dashed line) and the breaker TRV capability (dotted line) are shown in **Figure 5**.



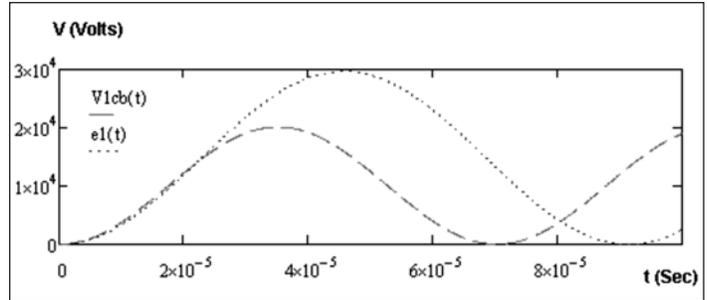
**Figure 5. Case 1—TRV Response—Two Parallel Generators Without Capacitors**

Case 2 considered only one generator connected to the GSU low-side bus with no additional capacitors. The Case 2 study indicated that additional capacitance was needed because the expected system response exceeded the breaker capability curve. The system TRV (dashed line) and the breaker TRV capability (dotted line) are shown in **Figure 6**.



**Figure 6. Case Study 2—TRV Response—Single Generator Without Capacitors**

Case 3 considered only one generator connected to the GSU low-side bus with 0.25 µF capacitors added. Case 2 indicated that adding the additional capacitance to the common bus would reduce the slope of the voltage wavefront to acceptable levels for this application. The system TRV (dashed line) and the breaker TRV capability (dotted line) are shown in **Figure 7**.



**Figure 7. Case Study 3—TRV Response—Single Generator with 0.25 µF Capacitors**

As a result of the analysis, the recommendation was to add one single-phase 0.25 µF capacitor to each phase of the overhead common generator bus on the line side of the generator circuit breakers.

**Surge protection**

The common generator bus connecting the two generators to the GSU has existing 15 kV station class surge arresters connected to the bus. No additional surge protection was required.

**Out-of-phase current switching**

Generator circuit breakers can experience unique out-of-phase current switching conditions. Prior to generator startup, with the breaker contacts open, the voltage across the contacts is the system voltage. As the generator starts, its voltage is out-of-phase until synchronization and the voltage across the contacts can reach 2.5 per unit, which may exceed the breaker’s rated voltage. IEEE C37.013 requires testing to this condition to verify that the breaker can perform switching operations under specified out-of-phase conditions in the event of accidental closing, followed by opening when the voltages are not in phase.

The example calculation in IEEE C37.013, Annex A, provides a 90-degree out-of-phase current condition, resulting in an out-of-phase asymmetrical peak short-circuit current that is lower than the generator terminal fault peak. Southern Company plant protection schemes prohibit the out-of-phase synchronization far below the 90-degree case given in the example. This condition is less severe than the three-phase symmetrical system source fault previously discussed; therefore, no further consideration was given to this condition.

**Outdoor NEMA® 3R enclosure design and testing**

The replacement breaker enclosure solution, shown in **Figure 8**, required physical packaging to facilitate the effective change-out of the existing oil circuit breakers during a scheduled outage with minimal peripheral disruption. In order to minimize changes to the existing station infrastructure, reduce construction costs, and limit installation downtime, a very compact footprint was required. The available height and width was limited by the existing overhead structures. The available depth was limited by an access road space with a buried rail, designated for removal of the GSU transformers.

The vacuum circuit breaker element had previously achieved a 5250A continuous current rating when tested as a component in a minimum-volume enclosure. However, now the breaker had to be packaged with proper thermal management in the outdoor NEMA 3R enclosure with roof bushings and secondary conduit connections. Design consideration was also given to provide front access by site personnel to enable future inspection and maintenance of the internal bus connections and the fixed breaker.

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The enclosure was designed and tested to the requirements of IEEE C37.20.3 [6] at the KEMA-Powertest LLC High Power Laboratory in Chalfont, Pa., achieving a continuous current rating of 5000A (convection ambient air cooling) and 5300A (with fans). The enclosure/breaker configuration was also successfully tested for momentary and short-time withstand currents and dielectric tests, including power frequency withstand, BIL, and partial discharge.

The internal connections to the roof bushings provided a challenge, but the allowable 65 degree C maximum temperature rise limits at rated current were ultimately met. Higher continuous current ratings are possible for future designs with physically larger roof bushings with higher voltage ratings or with iso-phase, segregated phase, or non-segregated phase bus configurations.



**Figure 8. Outdoor NEMA 3R Metal-Enclosed Vacuum Generator Circuit Breaker (Photo Courtesy of Eaton Corporation)**

Subsequent component breaker and enclosure test results encourage the high probability of future vacuum generator circuit breaker designs with continuous current capabilities of 6000A (convection ambient air cooled) and 7000A (with fans).

## Site installation

In general, the installation went very well due to the cooperation between Eaton and Southern Company designers and pre-planning by Alabama Power Company Transmission personnel who performed the installation. Key installation challenges were staying within the required spatial footprint, connecting the breaker's 5000A bushings to overhead conductors, and accommodating locations for secondary control conduits.

One issue encountered during the placement of the enclosure required an innovative solution. The forks of the forklift used were shorter than the depth of the breaker. Tubular channel of a length sufficient to pass all the way through the base support slots was placed over the forks of the forklift to move the breaker to its final installed location underneath the existing steel structures.

The primary current connections to the circuit breaker bushings are shown in **Figure 9**. The main generator bus consists of fabricated square tubular copper conductor that terminates at roof bushings on top of the conductor chase located behind the breaker. The primary connections to the generator-side breaker roof bushings are accomplished by custom-fabricated aluminum conductors.



**Figure 9. Circuit Breaker Bus Connections (Photo Courtesy of Southern Company)**

These conductors are approximately 6 feet long, 3–2500 kcmil per phase and segregated by phase in free air. The primary connections between the transformer-side circuit breaker bushings and the transformer are accomplished via similar open air conductors supported by overhead structures, approximately 2 feet in length. The circuit breakers receive 125 Vdc control power via conduits emerging from the concrete floor, connected to side-mounted terminal boxes.

## Conclusion

The installed vacuum generator circuit breakers have been placed into service as shown in **Figure 10**. The enclosure footprint and design flexibility allowed for an efficient installation that minimized construction time. Coupled with reduced future maintenance costs, the vacuum circuit breakers are expected to provide a reliable and cost-effective solution for this application.



**Figure 10. Installed Vacuum Circuit Breaker (Photo Courtesy of Southern Company)**

The successful implementation of vacuum generator circuit breakers for this hydro-plant project confirms the practical application and performance of vacuum circuit breakers in the 5000A range. In the near future, the environmentally friendly benefits of vacuum generator circuit breakers with continuous current ratings of 6000A (convection ambient air cooled) and 7000A with forced air fans will be extended to even larger generator unit applications.

## Acknowledgements

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- Larry G. Day—Alabama Power Company
- Ron D. Hartzel—Eaton Corporation, Manager MV Distribution Engineering
- R. William Long—Eaton Corporation, Consultant and Test Engineer

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- [2] IEEE Standard IEEE C37.013a-2007, (Amendment to IEEE Std C37.013-1997): Amendment 1: Supplement for Use with Generators Rated 10–100 MVA.
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