Impact of New Generator Circuit-Breaker Technologies on Nuclear Power Station Protection, Availability and Profitability

M. Palazzo and G. Cavaliere

The present paper investigates how the use of a generator circuit-breaker can help improve the protection and increase the availability as well as the profitability of the largest nuclear power stations. A simulation of the behaviour of a nuclear power station has been carried out with the help of the Monte Carlo method. The analysis provides important insights in the optimization of power station layouts, evaluating the possibility of applying different power station topologies. A comparison between different generator circuit-breakers extinguishing technologies is also provided.

El presente artículo investiga cómo el uso de un interruptor de generador puede ayudar a mejorar la protección y aumentar la disponibilidad, así como la rentabilidad de las mayores centrales nucleares. Una simulación del comportamiento de una central nuclear se ha llevado a cabo con la ayuda del método de Monte Carlo. El análisis proporciona información importante en la optimización de los diseños de las centrales eléctricas y la posibilidad de su aplicación en distintos tipos de central. También se ofrece una comparación entre las diferentes tecnologías de extinción en los interruptores de generador.

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INTRODUCTION

The liberalization of electric power systems puts a strong pressure on the issues concerned with the availability of power stations. In a market scenario where power stations are held by different generating companies, outages may have significant economic consequences. Moreover long unavailability periods (e.g. in case of severe failures of the step-up transformer) may affect the rate of return of investments related to power stations. Therefore the problem of operating power stations with the highest possible availability at the lowest possible cost has become more and more important in recent years. Obviously, how a generator is connected to the high-voltage grid and how the power supply to the unit auxiliaries is secured has a decisive influence on the availability of a power station [1]–[5].

The present paper specifically investigates how the use of a generator circuit-breaker can help improve the protection and increase the availability as well as the profitability of the largest nuclear power stations.

A comprehensive survey of different fault conditions occurring in several power stations has been performed. In order to carry out a more thorough investigation on the application of generator circuit-breakers a simulation of the behaviour of a nuclear power station has been carried out with the help of the Monte Carlo method. The analysis provides important insights in the optimization of power station layouts, evaluating the possibility of applying different power station topologies. A comparison between different generator circuit-breakers extinguishing technologies is also provided.

HISTORY OF THE DEVELOPMENT OF GENERATOR CIRCUIT-BREAKERS

Initially in the larger power stations the individual generators were connected by means of their generator circuit-breakers (GenCBs) to a common busbar at their terminal voltage. The circuit-breakers used for switching the generators were distribution-type units.

The continuous growth in size of the generators meant that the generator ratings exceeded the current-carrying capability and the interrupting capability of the switchgear available at that time. As a consequence the larger generators could no longer satisfactorily be switched at their terminal voltage [6]. For this reason the unit connection was introduced in power stations [7]. One of the disadvantages of the unit connection is that the unit auxiliary supplies cannot be obtained from the unit auxiliary transformer if the generator is not operating. This means that during the start-up and shut-down periods the unit auxiliary supplies must be obtained from an alternative source which is normally a station transformer connected to the high-voltage grid.

The use of a GenCB installed between generator and the associated step-up transformer offers many advantages when compared to the unit connection such as simplified operational procedures, better protection of power station equipment, higher power station availability and higher economic benefit [5], [8]. These and other reasons represented the impulse which led to the development of GenCBs specifically designed for this purpose during the 1960s. The first GenCB designed to be installed in the run of generator busducts used compressed air as operating and arc-extinguishing medium.

In the 1980s SF_6 GenCBs were successfully introduced into the market. The design of these circuit-breakers was a three-phase system in single-phase enclosures, supplied fully assembled on a common frame with operating mechanism and control equipment. Mainly the economical aspect and reasons of reliability and maintainability convinced power station operators of this modern arc-extinguishing medium.

In some cases a generator circuit-breaker of lower rating is used as a load switch. This switch is normally capable of interrupting a current magnitude higher than the rated current of the generator. This capability allows this device to be used for normal switching operations but not under fault conditions. The load switch can perform synchronizing as well as normal shutdown tripping operations, hence allowing the unit auxiliaries to be fed through the step-up and unit auxiliary transformers. One of the disadvantages of the load switch compared to a GenCB is that it cannot interrupt fault currents, thus reducing the protection of generator and power transformers and the availability of the power station layout. When a fully rated GenCB is employed in place of a load switch, faults in the generator zone can be cleared without requiring a transfer of the supply power for the unit auxiliary system.

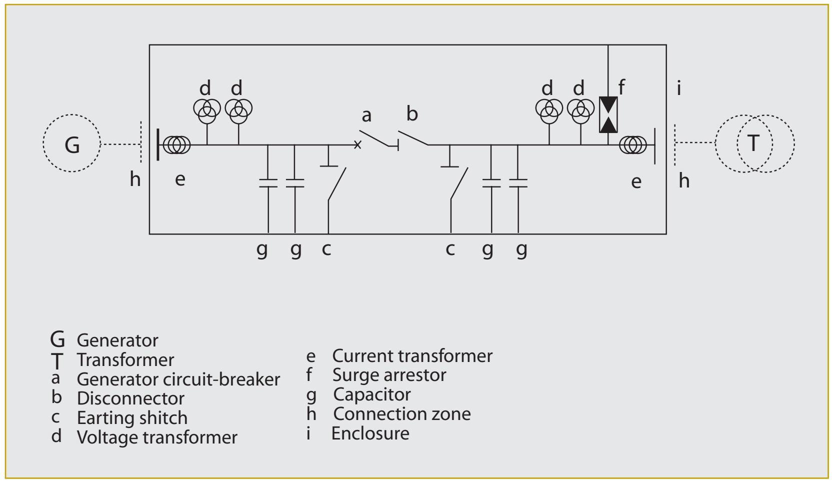

Figure 1. Single line diagram of the generator circuit-breaker system HEC 9.

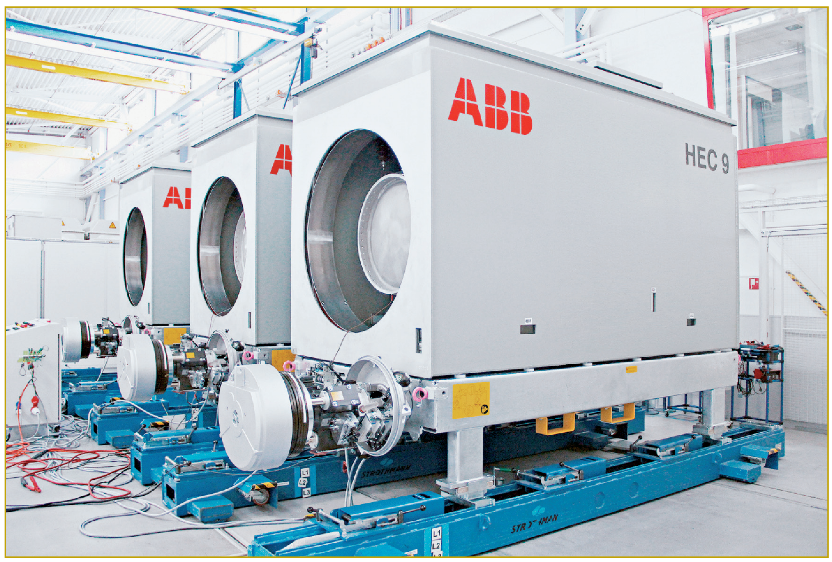

Figure 2. View of the three poles of the generator circuit-breaker system HEC 9.

Today the state-of-the-art technology SF_6 GenCB type HEC 9 with short-circuit breaking currents up to 250 kA is available (see Fig. 1 and Fig. 2). This breaking capacity corresponds to the highest short-circuit breaking current ever achieved with a single SF_6 interrupting unit. The development was made possible by using the most advanced SF_6 self-blast principle. With this achievement modern SF_6 GenCBs can now be delivered for the largest nuclear generating units.

REQUIREMENTS FOR THE APPLICATION OF GenCBs IN THE LARGEST NUCLEAR POWER STATIONS

The requirements imposed on GenCBs greatly differ from the requirements imposed on general purpose transmission and distribution circuit-breakers. Due to the location of installation between the generator and the step-up transformer a GenCB must meet high technical requirements with respect to rated normal current and fault currents. Furthermore the currents of very high magnitude which GenCBs have to deal with are associated with very steep transient recovery voltages. The test quantities given for general purpose transmission and distribution circuit-breakers for the short-circuit and out-of-phase current switching tests do not adequately cover the above requirements. The only standard which covers the requirements for GenCBs is IEEE Std C37.013-1997 (R2008) with its amendment IEEE Std C37.013a-2007 [9], [10]. The question whether the requirements laid down in [9] and in [10] are adequate for the application of GenCBs in modern power stations and especially in the largest nuclear ones is considered in the present work.

A comprehensive survey of short-circuit currents occurring in 139 power stations has been performed. Generators ranging from 16 MVA to

2,002 MVA have been surveyed. The fault transients simulations have been performed by means of the Electromagnetic Transients Program (EMTP) [11]. The system-source and generator-source short-circuit currents have been specifically analysed.

The system-source short-circuit current is the short-circuit current to be interrupted by the GenCB in case of a three-phase fault occurring between the generator and the GenCB. In all the simulations fault initiation takes place in the moment when the voltage in one phase passes through zero, thus leading to the highest degree of asymmetry in that phase. The calculations have been based on the maximum service voltage of the HV-System. In the simulations it has been assumed that the contacts of the GenCB part 40 ms after fault initiation (i.e. a typical contact parting time for GenCBs). The magnitude of the a.c. component of the short-circuit current and its degree of asymmetry are evaluated at this instant.

The results depicted in Fig. 3 show that the a.c. component of the system-source short-circuit breaking current (I_{SCsys}) tends to increase with generator rated power. The maximum observed value of I_{SCsys} for nuclear power stations is 248 kA. The degree of asymmetry of the system-source short-circuit current at contact separation (DOA_{sys}) seems to be less dependent upon generator rated power and shows an average value of 72.2% (see Fig. 4). No currents exhibiting delayed current zeros (DCZ) are observed (i.e. DOA_{sys} is never higher than 100%). It is remarkable that for large nuclear power stations DOA_{sys} is somewhat lower. A time constant of 133 ms seems to be adequate to cover the requirements for most applications irrespectively of generator rated power.

The generator-source short-circuit current is the short-circuit current to be interrupted by the GenCB in case of a three-phase fault occurring between the step-up transformer and the GenCB. The source of this current is the generator through no power transformer. In the simulations fault initiation takes place in the moment when the voltage in one phase passes through zero, so that the highest degree of asymmetry is obtained in that phase. The calculations have been based on the maximum operating voltage of the generator. It has been assumed that the contacts of the GenCB part 40 ms after fault initiation. The magnitude of the a.c. component of the short-circuit current and its degree of asymmetry are evaluated at this instant.

The results depicted in Fig. 5 show that the magnitude of the generator-source short-circuit breaking current (I_{SCgen}) is usually lower than I_{SCsys} and the ratio I_{SCgen}/I_{SCsys} does not seem to be dependent upon generator rated power. A value of I_{SCgen} equal to 80% of I_{SCsys} would cover the requirements for the majority of applications. The degree of asymmetry at contact separation (DOA_{gen}) is generally higher than 100% thus confirming that generator-source short-circuit currents typically exhibit DCZ (see Fig. 6). For nuclear power generators rated above 1,600 MVA values of DOA_{gen} up to 120% have been observed. Further investigations have shown that DOA_{gen} is somewhat constant within a practical range of contact parting times.

The results of the survey show that the requirements laid down in IEEE Std C37.013-1997 (R2008) and in IEEE

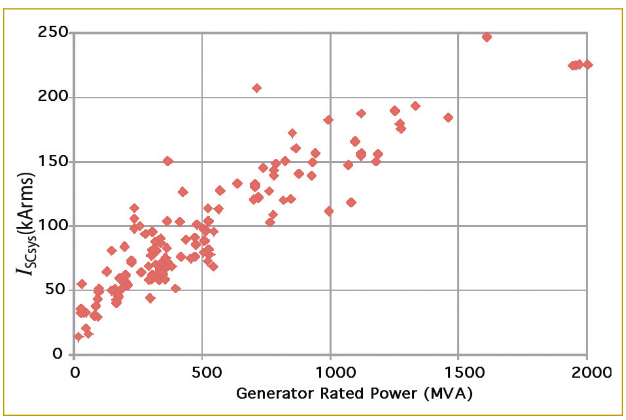

Figure 3. A.C. component of the system-source short-circuit breaking current as a function of generator rated power.

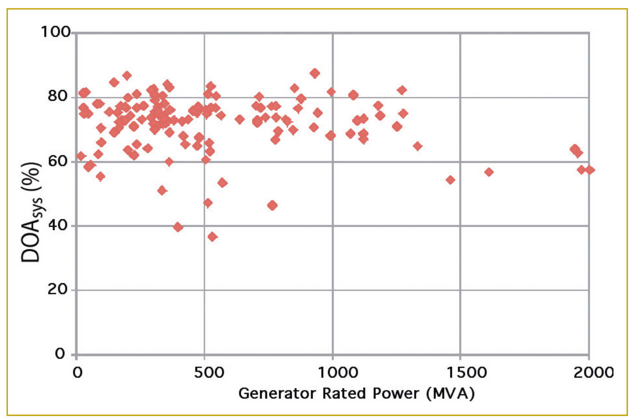

Figure 4. Degree of asymmetry of the system-source short-circuit breaking current as a function of generator rated power.

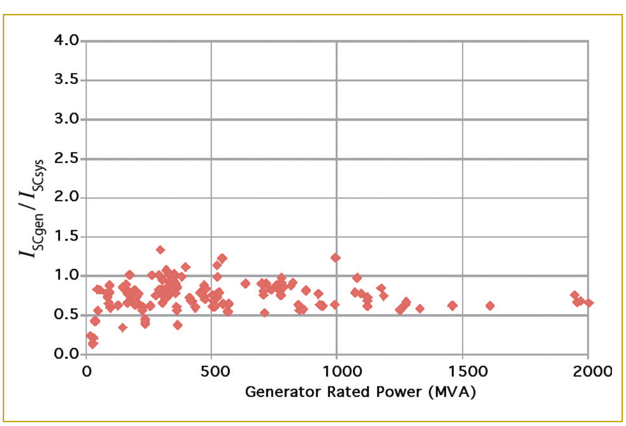

Figure 5. Ratio of the a.c. component of the generator-source short-circuit breaking current to the a.c. component of the system-source short-circuit breaking current as a function of generator rated power.

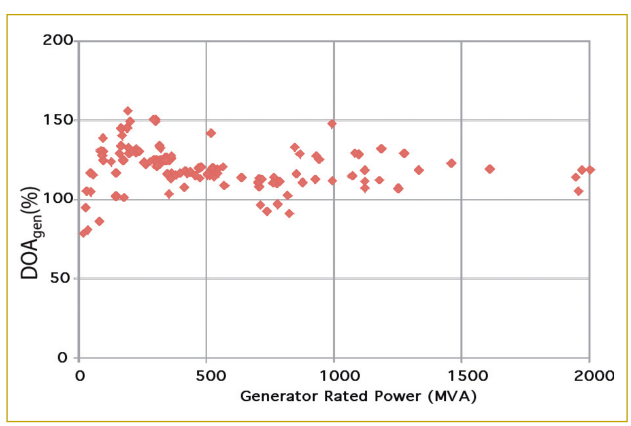

Figure 6. Degree of asymmetry of the generator-source short-circuit breaking current as a function of generator rated power.

Std C37.013a-2007 with respect to the system-source short-circuit currents are still adequate whereas the requirements concerning the generator-source short-circuit currents do not properly represent the stress imposed on GenCBs. The successfully tested interrupting capability of the SF_6 GenCB type HEC 9 makes this GenCB suitable for safe and reliable application even in the largest nuclear power stations.

RELIABILITY OF GenCBs

The installation of a GenCB between the generator and the associated step-up transformer, where its performance directly influences the output of the unit, places high demands on its reliability. In order to assess the reliability of GenCBs a comprehensive survey has been carried out on major failures occurred to air-blast and SF_6 GenCBs. According to [12] a major failure is defined as a failure of a switchgear or controlgear which causes the cessation of one or more of its fundamental functions. Failure data obtained from the operating history of GenCBs operating in 108 countries from January 1970 have been analysed.

A population of 52,696 GenCB-years installed in different types of power stations has been surveyed. The sample size per different GenCB technology is depicted in Table I.

The average failure frequency has been computed by dividing the total number of major failures occurred to the observed population of GenCBs by the cumulative service time of equipment.

The results summarised in Table II show that the average failure frequency of air-blast GenCBs is 5.6 times higher compared to SF_6 GenCBs with hydro-mechanical spring operating mechanism.

The difference between the reliability parameters of air-blast and SF_6 GenCBs can be mainly attributed to the higher complexity of the former technology and to the aging of its components.

In comparison with SF_6 circuit-breakers much higher pressures are used in air-blast circuit-breakers. Since pressurized air has a relatively long time constant to recover to its non-conducting state, special means need to be applied to reduce the rate-of-rise of transient recovery voltage to values the circuit-breaker can cope with. A resistor is generally mounted in parallel to the interrupting chamber of air-blast GenCBs. The disadvantage of this solution is that additional interrupting units are necessary to interrupt the resistor current. These additional interrupting units increase the complexity of the system, lead to additional sources of failures and in turn reduce the overall reliability of the GenCB.

Also the mechanical endurance of an air-blast GenCB is much shorter than that of a SF_6 GenCBs which leads to a lower maintenance frequency and therefore to a higher availability of SF_6 GenCBs.

Furthermore air-blast is an obsolete technology which features several disadvantages compared to SF_6 GenCB (e.g. higher noise levels, longer opening times, longer-lasting down time due to maintenance operations and lower availability of spare parts).

A comparison with the results shown in [13] and in [14] confirms that hydro-mechanical spring operating mechanisms installed on GenCBs have a lower average failure frequency compared to spring, hydraulic or pneumatic operating mechanisms installed on HVCBs.

GenCB technology	Sample size (GenCB-years)
Air-blast	14,261
SF_6 with hydro-mechanical spring operating mechanism	24,091

Table I. Sample size per GenCB technology.

GenCB technology	Major failures per 100 GenCB-years
Air-blast	0.666
SF_6 with hydro-mechanical spring operating mechanism	0.120

Table II. Average failure frequency per GenCB technology.

Equipment used to connect the generator to the step-up transformer	Unavailable throughput power (MW)
SF_6 GenCB	218.5
Air-blast GenCB	219.2
Load switch	231.4

Table III. Results of availability simulations.

AVAILABILITY ANALYSIS OF NUCLEAR POWER STATION LAYOUTS

For the present work the nuclear power station layout depicted in Fig. 7 has been analysed. The 1,800 MW generator is connected to the step-up transformer by means of a SF_6 GenCB. The difference in the power station layout availability brought about by the use of an air-blast GenCB or a load switch has been investigated as well. The analysis has been carried out with the help of a computer program based on the sequential Monte Carlo simulation. This is a very powerful technique to quantitatively estimate the reliability of complex systems like nuclear power stations; furthermore it allows to quantify the impact of the connection scheme of a generator to the extra high-voltage grid on the availability of the power station [15].

During a simulation run, when a failure occurs it is treated by tripping the circuit-breakers forming the protection group of the failed component immediately after the occurrence of the failure. After the time necessary to isolate the failed component (i. e. the switching time) the circuit-breakers are closed again. When the repair of the component is completed (or a spare part has become available), the above procedure is repeated. Also the transfer of the auxiliaries between different sources during the starting-up and the shutting-down of the unit (or when a failure occurs) is modelled. One of the results obtained from the simulations is the throughput power of the power station, i. e. the power delivered to the grid. Reliability parameters for power station equipment has been obtained from published literature [1], [2], [16]-[20]. Circuit-breakers probabilities fail-to-open and fail-to-close have been taken into account as well.

The simulations have been carried out assuming that the power station supplies base load. The availability of the unit has been set to 88%. The results of the simulations are summarized in Table III.

The difference in the throughput power directly reflects the contribution of the different technologies used to connect the generators to the step-up transformer on the availability of the power station. The results show that the use of a layout with a SF_6 GenCB positively affects the availability of the nuclear power station.

In order to make a more thorough comparison between the different options, an economic analysis has also been carried out. For the economic evaluation the following issues have been considered: income, acquisition costs, installation and commissioning costs, preventive maintenance costs and corrective maintenance costs. The power delivered to the grid is calculated by subtracting the power consumed by the auxiliaries from the throughput power. The throughput power takes into account the unavailable power calculated by means of Monte Carlo method for each power station layout variant as shown in Table III. A figure of merit has been calculated for each layout according to the following formula:

$$FM = \sum_{t=1}^{N} \left\{ \left[\frac{1}{(1+r)} \right]^{t} \times (IN_t - MC_t) \right\} - AC - IC \tag{1}$$

where:

- FM is the Figure of Merit of the nuclear power station layout which is equal to the present value of the cash flows of the below monetary items;
- IN_t is the income in year t (based on power delivered to the grid and energy selling price);
- MC_t are the maintenance costs of selectable equipment in year t;
- AC are the acquisition costs of selectable equipment;
- IC are the installation and commissioning costs of selectable equipment;
- r is the discount rate;
- N is the service life expressed as number of years which is set to 30.

The results of the economic analysis show that the layouts with SF_6 or air-blast GenCBs have a higher figure of merit compared to the layout with load switch. The economic advantage of the layout with SF_6 GenCB is 7% higher than that of the layout with air-blast GenCB. This figure is mainly related to the higher protection and reliability provided by the SF_6 GenCB and to lower maintenance frequency, duration and costs compared to air-blast GenCBs.

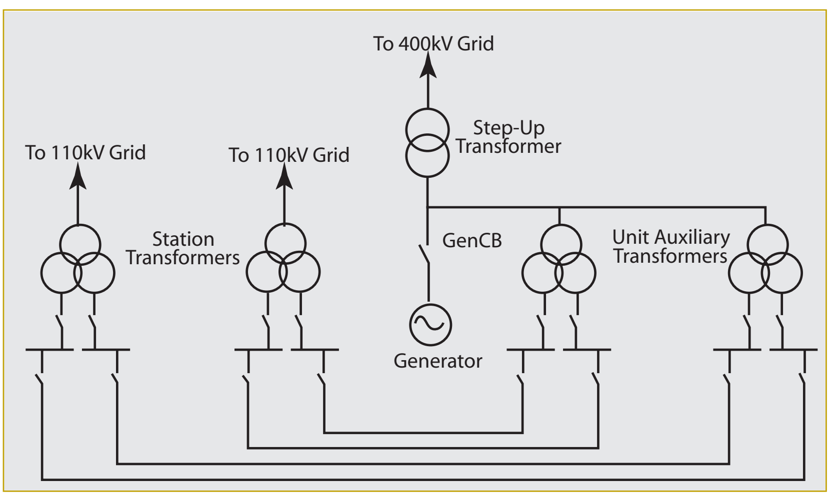

Figure 7. Single line diagram of a 1,800 MW nuclear power station.

CONCLUSION

This research work shows that the use of SF_6 GenCBs results in a higher power station availability for the largest nuclear power stations. Furthermore SF_6 GenCBs provide a distinctive economic advantage over air-blast GenCBs and load switches.

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