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IMPACT OF NEW GENERATOR CIRCUIT-BREAKER TECHNOLOGIES ON POWER PLANT AVAILABILITY AND PROFITABILITY

Mark Seelig
ABB High Voltage Technologies Ltd.
High Current System Division
Brown Boveri-Strasse 5, CH-8050 Zurich, Switzerland
+41 1 318 39 90 (Tel), +41 1 318 16 44 (Fax), Mark.Seelig@ch.abb.com

ABSTRACT

Today, the use of generator circuit-breakers for the switching of generators at their terminal voltage is widespread because they offer many advantages when compared to the unit connection such as lower first costs, simplified operational procedures and better fault protection.

With the recent successful certification of a 160 kA-generator circuit-breaker modern SF_6 generator circuit-breakers are now available for generating units up to 1400 MW. Another new development has been the integration of all the associated items of switchgear within the generator circuit-breaker enclosure as an option to their separate installation. Such items include a series disconnector, earthing switches, short-circuiting switches, current transformers, single-pole-insulated voltage transformers, protective capacitors and surge arresters. Depending on the type of power plant additional items like starting switches and braking switches can be mounted in the generator circuit-breaker enclosure, too. This greatly improved functionality of generator switchgear allows the realisation of simpler and more economic layouts of power plants. Beside a substantial reduction of the first costs this new solution, being fully factory assembled and tested, also makes possible considerable saving in time and expenditures for erection and commissioning.

Modern SF_6 generator circuit-breakers make it possible to interrupt all types of fault currents within four cycles. This rapid clearance of fault currents helps to avoid expensive secondary damage of power plant equipment and consequently long down times for repair. An example of a serious secondary damage being caused by the delayed clearance of the fault current is the bursting of the transformer tank following an internal fault in the transformer. Another incident is the thermal destruction of the generator damper winding due to a short-time unbalanced load condition when the resulting negative sequence current is not interrupted immediately. Although they have a low probability of occurrence such outages have a substantial effect on the availability of a generating unit and on the overall performance of an operating utility. It can be shown that a layout using a modern SF_6 generator circuit-breaker, due to the rapid clearance of fault currents thus rendered possible, positively affects the availability of the power plant and that the resulting economical benefit to the operator is considerable.

1. INTRODUCTION

Since the first delivery of a specific purpose generator circuit-breaker consisting of three metal-enclosed, phase-segregated units and using compressed air as operating and arc-extinguishing medium in 1970 there has been a continuous development of this piece of power plant equipment. In the 1980's the first generator circuit-breaker using SF_6 gas as arc-extinguishing medium was introduced into the market. Recently, a SF_6 generator circuit-breaker with a rated current of 24,000 A (naturally cooled, higher rated currents with forced air cooling) and a short-circuit breaking current of 160 kA at a maximum service voltage of 30 kV has become available. This breaking capacity corresponds to the highest short-circuit breaking current ever achieved with a single SF_6 interrupter unit. The development was rendered possible by using the most advanced SF_6 self-extinguishing technology. With this achievement modern specific purpose generator circuit-breakers using SF_6 gas as arc-extinguishing medium are now available for generating units with ratings up to 1400 MW.

2. FEATURES OF MODERN GENERATOR CIRCUIT-BREAKERS

In addition to the obvious requirements that a generator circuit-breaker when closed, must carry the full load current of the generator and ensure the required insulation level at all times it must also be capable of performing the following functions:

- Synchronise the generator with the main system
- Separated the generator from the main system (switching off the unloaded/lightly loaded generator)
- Interrupt load currents (up to the full load current of the generator)
- Interrupt system-fed short-circuit currents and generator-fed short-circuit currents
- Interrupt currents under out-of-phase conditions (up to an out-of-phase angle of 180°)
- Synchronise the generator-motor with the main system when the machine is started in the motor mode (in pumped storage power plants, with SFC or „back-to-back“ starting)
- Close on and interrupt the starting current of the generator-motor when the machine is started in the motor mode (in pumped storage power plants, with asynchronous starting)
- Interrupt generator-fed short-circuit currents at frequencies below 50/60 Hz (in gas-turbine, combined-cycle and pumped storage power plants, depending on the start-up supply)

The electrical and mechanical performance required of a generator circuit-breaker exceeds by a considerable degree that required of standard medium-voltage distribution switchgear. A comparison of typical performance requirements for generator circuit-breakers with those for medium-voltage circuit-breakers according to IEC Publication 60056 [1] clearly illustrates that this IEC Standard does not adequately cover the requirements applicable to generator circuit-breakers. The only standard available world-wide which covers specifically the requirements for generator circuit-breaker is IEEE Std. C37.013 [2]. This standard contains, in addition to rating information and other relevant characteristics, guidelines for the type-testing of generator circuit-breakers.

The positioning of the generator circuit-breaker between the generator and the main transformer, where its performance directly influences the plant output, places very high demands on its reliability. While a sound and mature design and careful selection of all components and individual parts are essential factors, the required equipment quality and reliability can only be achieved by exhaustive testing of all relevant aspects. A part of this testing programme are the type tests which have to be performed in accordance with [2] (Fig. 1).

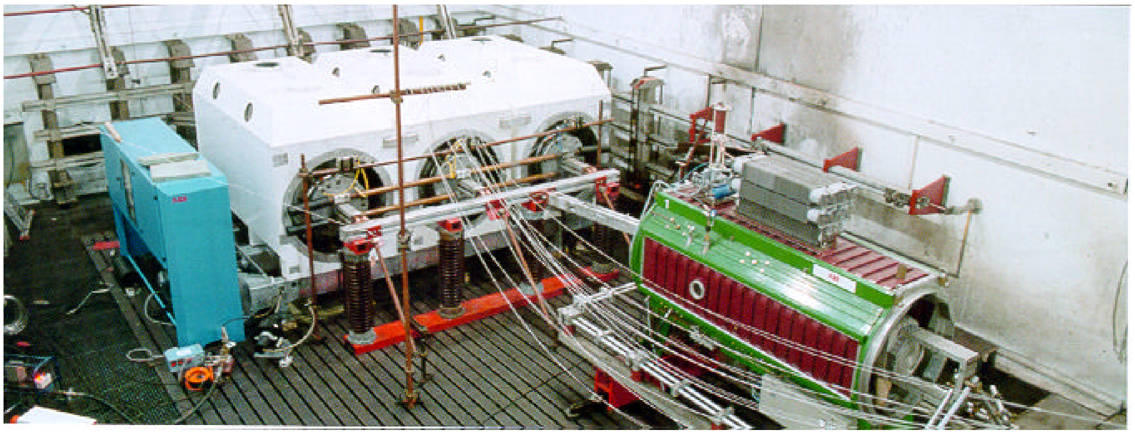

Figure 1: 160 kA-Generator Circuit-Breaker During Short-Circuit and Load Current Switching Tests at KEMA

SF_6 generator circuit-breakers that fully meet the above performance requirements are available with the technical data listed in Table I.

Modern generator switchgear does not only consist of an interrupter unit. All the associated items of switchgear can nowadays also be integrated into the generator circuit-breaker enclosure as an option to their separate installation. Such items comprise a series disconnector (Fig. 2, item 2), earthing switches (Fig. 2, items 3 and 4), short-circuiting switches (Fig. 2, item 7), current transformers (Fig. 2, items 13 and 14), single-pole-insulated voltage transformers (Fig. 2, items 9, 10, 11 and 12), protective capacitors (Fig. 2, item 16 and 17) and surge arresters (Fig. 2, item 15). Depending on the type of power plant additional items such as starting switches (for gas-turbine and hydro power plants) (Fig. 2, items 5, 6 and 8) and braking switches (for hydro power plants) (Fig. 2, item 7) can also be mounted in the generator circuit-breaker housing. An example of the arrangement of these items in a generator circuit-breaker enclosure is shown in Figure 3.

Type	HGC 3	HEC 3/4	HEC 5/6	HEC 7/8
Rated Maximum Voltage	21 kV	25.3 kV	25.3 kV	30 kV
Rated Frequency	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz
Rated Dielectric Strength: • Impulse Withstand Voltage • Power Frequency Withstand Voltage	 125 kV peak 60 kV	 125 kV peak 60 kV	 125 kV peak 60 kV	 150 kV peak 80 kV
Rated Continuous Current: • With Natural Cooling • With Forced Air Cooling	 Up to 7700 A	 Up to 13000 A	 Up to 13000 A	 Up to 24000 A

	N/A	Up to 24000 A	Up to 24000 A	Up to 38000 A
Rated Peak Withstand Current	190 kA_{peak}	300 kA_{peak}	360 kA_{peak}	600 kA_{peak}
Rated Short-Time Withstand Current	63 kA/3 s	100 kA/3 s	120 kA/3 s	200 kA/3 s
Rated Short-Circuit Making Current	190 kA_{peak}	300 kA_{peak}	360 kA_{peak}	440 kA_{peak}
Rated Short-Circuit Breaking Current	63 kA	100 kA	120 kA	160 kA
Standard	IEEE C37.013	IEEE C37.013	IEEE C37.013	IEEE C37.013

Table I: Technical Data of ABB's SF_6 Generator Circuit-Breakers

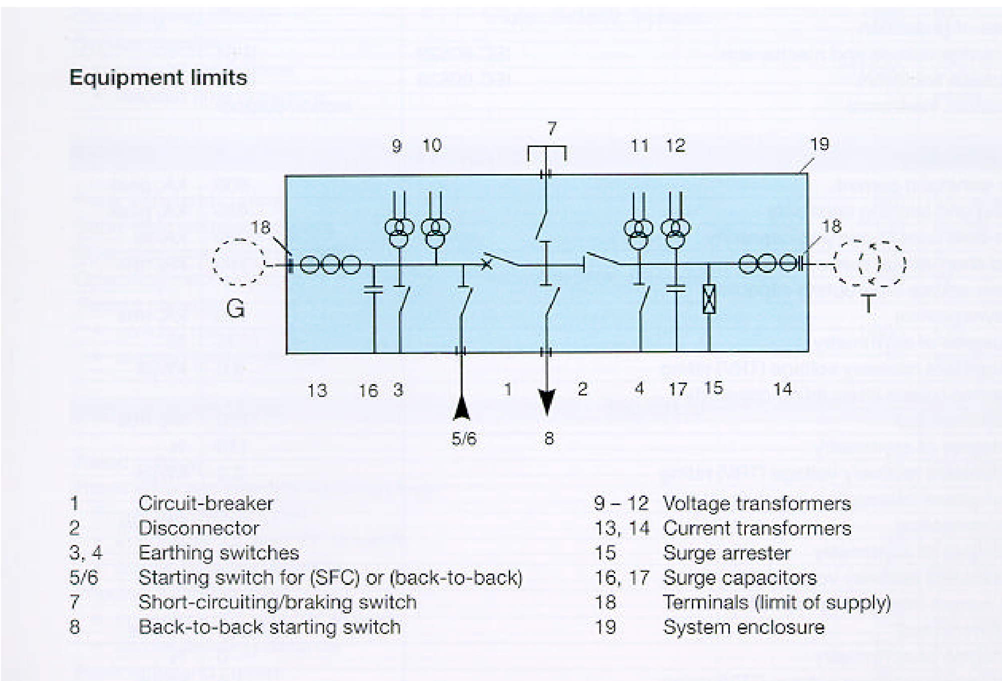

Figure 2: General Layout of ABB's Generator Switchgear

This greatly improved functionality of the generator switchgear allows the realisation of simpler and more economic power plants layouts. Beside a substantial reduction of the first costs this new solution, being fully factory assembled and tested, also makes possible considerable saving in time and expenditures for erection and commissioning.

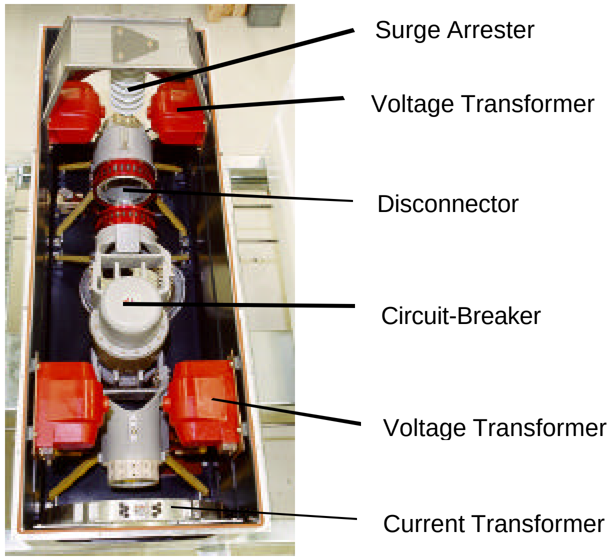

Figure 3: Top View of one Pole of a Generator Circuit-Breaker Type HGC 3

3. SPECIAL FEATURES FOR GAS-TURBINE AND COMBINED-CYCLE POWER PLANTS

When a gas-turbine generator is started-up, its rotor must be accelerated by external means to about 30 % of the rated speed before the start-up process becomes self-sustaining, i.e. before the turbine can generate sufficient power to continue process independently. The energy required for this purpose can be provided for instance by a pony motor or a static frequency converter (SFC). Starting-up with the help of a pony motor is suitable for smaller machines but has several disadvantages when applied to larger machines and especially to single shaft units in combined-cycle power plants. For this reason the use of SFC starting equipment is becoming more and more widespread.

Modern generator switchgear also contains the switching functions required for SFC starting within its enclosure. The output of the SFC (voltage of variable amplitude and frequency) is fed to the generator terminals via the starting switch (Fig. 2, item 5). The starting switch is required to carry the current supplied by the SFC for 3 to 5 minutes. Its rated voltage is chosen according to the rated voltage of the SFC which in general is considerably lower than the generator rated voltage. Starting switches for SFC starting of gas-turbine generators are available with the following technical data (Table II):

Type	HGC 3	HEC 3/4	HEC 5/6	HEC 7/8
Rated Voltage	7.2 kV	12 kV	12 kV	24 kV
Rated Frequency	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz
Rated Dielectric Strength in Position "O":				
• Impulse Withstand Voltage	125 kV_{peak} 60 kV	125 kV_{peak} 60 kV	125 kV_{peak} 60 kV	150 kV_{peak} 80 kV
• Power Frequency Withstand Voltage	40 kV_{peak}	60 kV_{peak}	60 kV_{peak}	125 kV_{peak}

Rated Dielectric Strength in Position "C": • Impulse Withstand Voltage • Power Frequency Withstand Voltage	20 kV	36 kV	36 kV	50 kV
Current Carrying Capability:	2500 A/10 min.	4000 A/10 min.	4000 A/10 min.	4800/10 min.
Rated Peak Withstand Current	150 kA_{peak}	240 kA_{peak}	288 kA_{peak}	360 kA_{peak}
Rated Short-Time Withstand Current	50 kA/1 s	80 kA/1 s	96 kA/1 s	130 kA/1 s
Standard	IEC 60129	IEC 60129	IEC 60129	IEC 60129

Table II: Technical Data of Starting Switches for Gas-Turbine Generators

4. SPECIAL FEATURES FOR HYDRO AND PUMPED STORAGE POWER PLANTS

In pumped storage power plants, when a machine is started-up in the motor mode (pumping mode) it has to be accelerated to its rated speed before it can be connected to the system (unless asynchronous starting is used). The two most common methods for starting-up generator-motors in the motor mode are the static frequency converter (SFC) and the „back-to-back“ starting arrangements.

Again, all switching functions required for SFC and „back-to-back“ starting can be supplied within the generator switchgear enclosure. In case of the SFC starting arrangement the output of the SFC (voltage of variable amplitude and frequency) is fed to the terminals of the machine in question via the starting switch (Fig. 2, item 6) and in case of the „back-to-back“ starting arrangement the output of the generator used for starting-up (voltage of variable amplitude and frequency) is fed via the „back-to-back“ starting switch of that unit (Fig.2, item 8) and the starting switch (Fig. 2, item 6) to the terminals of the machine to be started-up. During „back-to-back“ starting the generator circuit-breaker - because of its ability to interrupt fault current also at frequencies below 50/60 Hz - ensures an adequate protection of the equipment. In both cases the starting switches are required to carry the starting current for 5 to 10 minutes and their rated voltage needs to be equal to the generator rated voltage. Starting switches for SFC or „back-to-back“ starting of generator-motors in the motor mode are available with the following technical data (Table III):

Type Rated Voltage	HEC 3/4 24 kV	HEC 5/6 24 kV
Rated Frequency	50/60 Hz	50/60 Hz
Rated Dielectric Strength in Position "O": • Impulse Withstand Voltage • Power Frequency Withstand Voltage Rated Dielectric Strength in Position "C": • Impulse Withstand Voltage	125 kV_{peak} 60 kV 125 kV_{peak} 60 kV	125 kV_{peak} 60 kV 125 kV_{peak} 60 kV

• Power Frequency Withstand Voltage		
Current Carrying Capability:	4000 A/20 min.	4000 A/20 min.
Rated Peak Withstand Current	300 kA_{peak}	360 kA_{peak}
Rated Short-Time Withstand Current	100 kA/1 s	120 kA/1 s
Standard	IEC 60129	IEC 60129

Table III: Technical Data of Starting Switches for Generator-Motors in Pumped Storage Power Plants

Another important issue in all hydro power plants is the braking of the machine after it has been disconnected from the system. Electrical braking is attractive because it allows to substantially reduce the wear of the mechanical braking system and hence to increase the maintenance intervals and to decrease the associated costs. Electrical braking typically sets in at 50 to 60 % of the rated speed of the machine. Mechanical braking is then applied only at 10 % or less of the rated speed.

For the purpose of electrical braking of machines in hydro power plants modern generator switchgear can be equipped with a braking switch (Fig. 2, item 7). The arrangement according to Figure 2 has the advantage that the making and breaking of the braking circuit is carried out by means of the generator circuit-breaker and that the braking switch itself only needs to carry out mechanical operations. The current used for the electrical braking typically is in the range of 1.0...1.3-times the rated current of the machine and usual braking times lie in the order of 5 minutes. Figure 4 shows a generator circuit-breaker with integrated braking switch during the temperature rise test. Braking switches are available with the technical data listed in Table IV.

5. ADVANTAGES OF THE USE OF GENERATOR CIRCUIT-BREAKERS

A major objective of all operators of power plants is the achievement of the highest possible plant availability at the lowest possible cost. As already mentioned, the greatly improved functionality of modern generator switchgear allows the realisation of simpler and more economic power plant layouts. The use of modern SF_6 generator circuit-breakers further helps the operator of a power plant in reaching the aforementioned target in the following ways:

Simplification of operating procedures:

- During the starting-up or shutting-down of a generator only one circuit-breaker needs to be operated thus reducing the number of the switching operations necessary.
- In the normal case the automatic rapid changeover switching equipment required to transfer the unit auxiliary supplies from the station to the unit transformer (and vice versa) is not needed.
- The division of responsibility for the operation of the power plant and for the operation of the high-voltage system is clearly defined.

Type	HEC 3/4	HEC 5/6
Rated Voltage	24 kV	24 kV
Rated Frequency	50/60 Hz	50/60 Hz
Rated Dielectric Strength: • Impulse Withstand Voltage • Power Frequency Withstand Voltage	 125 kV$_{peak}$ 60 kV	 125 kV$_{peak}$ 60 kV
Current Carrying Capability:	17000 A/10 min.	17000 A/10 min.
Rated Peak Withstand Current	300 kA$_{peak}$	360 kA$_{peak}$
Rated Short-Time Withstand Current	100 kA/1 s	120 kA/1 s
Standard	IEC 60129	IEC 60129

Table IV: Technical Data of Braking Switches for Hydro Generators

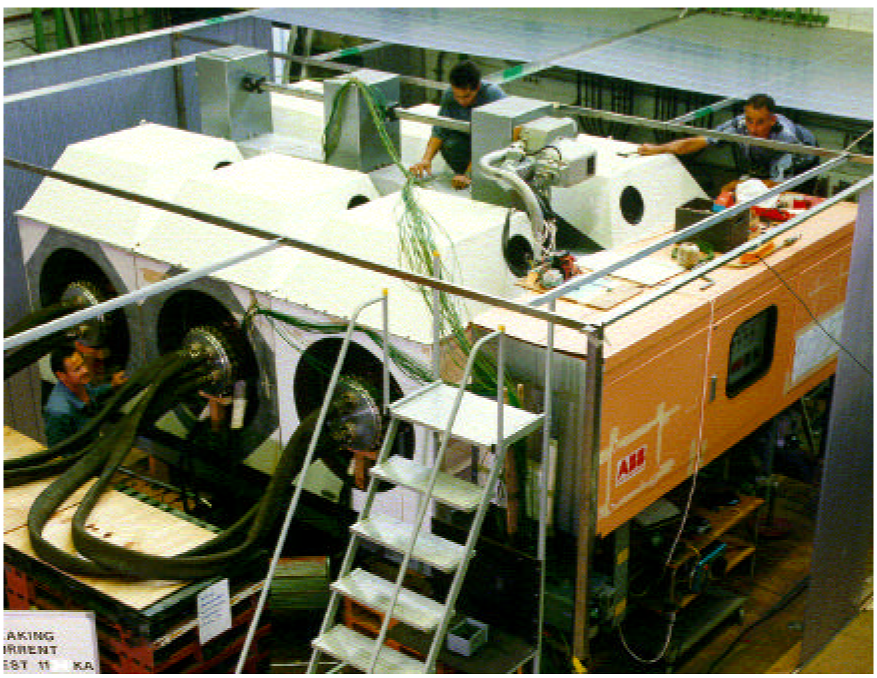

Figure 4: Braking Switch During Temperature Rise Test

Improved protection of the generator and the main and unit transformers:

- The differential protection zones of the generator, the main transformer and the unit transformer can be arranged to achieve maximum selectivity.
- Generator-fed short-circuit currents are interrupted within a maximum of four cycles whereas the reduction of the fault current by the rapid de-excitation equipment may require a number of seconds.

Increased security and higher power plant availability:

- Simplified operational procedures and clearly defined operational responsibilities reduce the likelihood of operational errors.
- The application of a generator circuit-breaker increases the general availability of the power plant auxiliary equipment.
- Synchronising at the generator voltage level with the help of a generator circuit-breaker is considerably more secure than synchronising with a high-voltage circuit-breaker [3].
- The rapid changeover of the auxiliary supplies during the starting-up and shutting-down of the unit with the associated high inrush currents and resulting stresses is eliminated and possible damage to the drive motors of pumps, fans, etc. is thus avoided.
- The rapid and selective clearance of all types of faults avoids expensive secondary damage and the consequently long down times for repair. A case of serious secondary damage being caused when the generator-fed fault is not immediately interrupted is the bursting of the transformer tank following an internal fault in the main or unit transformer. Another case is the thermal destruction of the generator damper winding due to short-time unbalanced load conditions. Such conditions can arise due to single or two phase faults within the main transformer or on its connections to the high-voltage circuit-breaker.

Transformer Failures:

Common causes of main transformer internal failures are the flashover of a bushing, winding interturn faults, failures of the tap-changer and carbonisation and/or excessive moisture content of the transformer oil. Even if the system-fed component of the fault current is interrupted by the high-voltage circuit-breaker within approximately 3 to 4 cycles, in a layout without a generator circuit-breaker the generator continues to supply a fault current throughout the de-excitation time interval which may last for several seconds. The internal pressure resulting from the vaporisation of the transformer oil is a function of the product of arc current and time. This pressure stresses the transformer tank, and, if it rises above a certain value, will cause the tank to rupture, with a resulting oil spillage and possibly an oil fire. Tank rupture may occur after 4.5 to 5 cycles. The presence of a generator circuit-breaker which allows a rapid clearance also of the generator-fed component of the fault current can therefore make up the difference between a repairable damage and a catastrophic event with severe environmental pollution and possible personnel jeopardy [4], [5].

Short-Time Unbalanced Load Conditions:

A three-phase short-circuit represents a symmetrical loading of a generator. Single- and two-phase faults on the other hand represent a short-time unbalanced load condition with critical mechanical and thermal stresses for a generator [6]. The thermal stresses result from the negative sequence component of the fault current which interacts with the generator damper windings. Unbalanced load conditions can give rise, within a very short time, to critically high temperatures in the damper windings. These temperatures are particularly critical for turbo generators and in the worst case may cause the rotor to jam in the stator. If a generator circuit-breaker is present it will separate the generator from the fault within four cycles and thus effectively prevent damage to the generator. If no generator circuit-breaker is fitted, the generator will continue to supply a negative sequence current until de-excitation is completed. The de-excitation may take several seconds, during which time the generator may suffer severe damage.

Specifically, the use of modern SF_6 generator circuit-breakers positively affects power plant availability in three ways:

- The use of generator circuit-breakers allows the plant auxiliary supplies to be drawn directly from the high-voltage transmission system at all times, i.e. also during the critical start-up and shut-down phases of the plant operation. Supply from this source is considerably more reliable than that from a local sub-transmission network and results in an improved plant auxiliary equipment availability.

- The rapid interruption of generator-fed short-circuit currents reduces the resulting fault damage and shortens repair times, thereby also contributing to an increased power plant availability. Although they have a low probability of occurrence such outages have a substantial effect on the availability of a generating unit and on the overall performance of an operating utility.
- Compared to high-voltage circuit-breakers modern SF_6 generator circuit-breakers exhibit higher maintenance intervals as they are especially designed for a high mechanical and electrical endurance. Depending on the application the down-time of an unit due to circuit-breaker maintenance can therefore be significantly reduced when a generator circuit-breaker is used.

A higher availability leads to an increased number of the operating hours and hence to a higher profit for the operator of the power plant. Substantial surplus of receipts can be achieved in this way and the payback time for the expenditures of a generator circuit-breaker is generally very low [7].

6. CONCLUSIONS

With the recent successful certification of a 160 kA-generator circuit-breaker modern SF_6 generator circuit-breakers are now available for generating units up to 1400 MW. Generator switchgear today not only comprises the generator circuit-breaker but also the associated items of switchgear like a series disconnector, earthing switches, short-circuiting switches, current transformers, single-pole-insulated voltage transformers, protective capacitors and surge arresters. Depending on the type of power plant additional items such as starting switches and braking switches can be mounted in the generator circuit-breaker enclosure, too. This greatly improved functionality of generator switchgear allows the realisation of simpler and more economic layouts of power plants.

Further it can be shown that the use of power plant layouts with generator circuit-breakers compared to power plant layouts without generator circuit-breakers allows the achievement of a higher plant availability. The increased number of operating hours thus rendered possible directly leads to a higher profit for the operator of the power plant. Substantial surplus of receipts can be realised in this way and the payback time for the expenditures of a generator circuit-breaker is generally very low.

7. REFERENCES

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NAME: SEELIG, Mark
DESIGNATION: Area Sales Manager
INSTITUTION: ABB
ADDRESS: Brown Boveri Str. 5, 8050 Zurich
COUNTRY: Switzerland
TEL. : 1-318-3990
FAX: 1-318-1644
E-MAIL: mark.seelig@ch.abb.com