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## LIFE MANAGEMENT FOR GENERATOR CIRCUIT-BREAKERS

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### Introduction

Today, the use of generator circuit-breakers for the switching of generators at their terminal voltage is wide spread. The paper considers the technical requirements which a generator circuit-breaker must satisfy, the performance of tests which adequately cover the stresses occurring in service being a principle prerequisite for satisfactory operational service. Further service experience gained with generator circuit-breakers is reported. The paper then describes a method of determining the life cycle cost of generator circuit-breakers. The discussion covers all cost factors arising during the operational life of the switchgear. Particular reference is made to the case of the replacement of older type switchgear by a modern, reduced-maintenance design of circuit-breaker. A case history relating to the experience of a Swiss power supply company is reported.

### Key Words

Generator circuit-breaker - Service requirement - Service experience - Life cycle cost - Replacement

### 1. General

#### 1.1 Life management

Life management of equipment covers all those measures and activities necessary to ensure satisfactory operation at minimum cost over the entire life-time of an apparatus. These include, amongst other factors, a comprehensive maintenance concept, the provision of supervisory and maintenance staff, the provision of spare parts and the necessary storage facilities and all measures taken to allow for a possible fault or failure.

Life management starts with the initial evaluation phase of a piece of equipment. Equipment is only capable of providing satisfactory service when it is capable of meeting fully the requirements placed upon it, under both normal and abnormal service conditions. Specifications must therefore fully reflect the operational requirements and equipment, ostensibly conforming to such a specification, must be designed and tested in full accordance with recognized and relevant standards. Parallel to technical performance, the cost incurred in relation to a piece of equipment is a major factor in its evaluation. This equipment cost

includes not only the initial capital outlay, but also all those expenses arising from its installation, operation, maintenance and, at the end of its service life, its disposal. These total cost of ownership and use are collectively termed "life cycle cost". The calculation and comparison of life cycle cost as an integral part of the evaluation process allows a well-founded decision to be made.

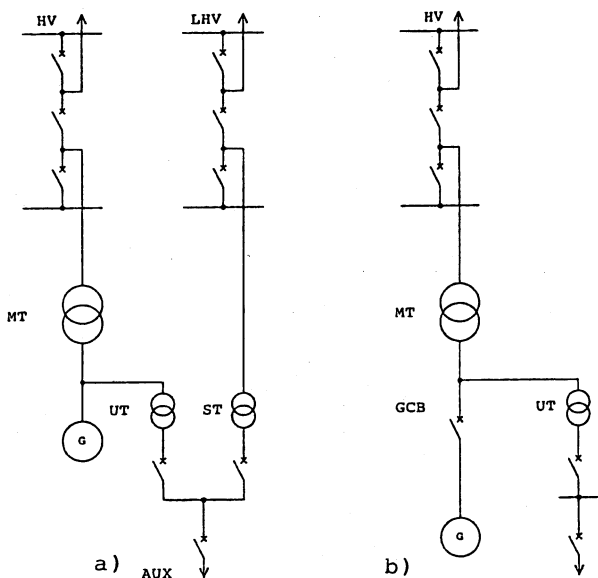
#### 1.2 Review of generator circuit-breaker development

The development of the generator circuit-breaker has been decisively influenced by trends in generator design and power plant layout. Initially, in the larger power plants the individual generators were connected via generator circuit-breakers to a common busbar at their terminal voltage. The circuit-breakers used for switching the generators were distribution type units. The continuous growth in the size of the individual generator meant that the generator ratings began to outweigh the switchgear ratings so that in the early 1940's the larger generators could no longer be satisfactorily switched at terminal voltage. In addition, the increasing current ratings led to the development of a new type of generator main connection, the "isolated phase busbar" design. For these and other reasons the busbar type power plant layout was replaced by the "unit connection", each generator being connected via a main step-up transformer and a high voltage circuit-breaker to the high voltage transmission system. Under the prevailing conditions the unit arrangement of generator and transformer became the standard system of connection for generators. It is however a characteristic of this type of connection that the unit auxiliary supplies cannot be obtained from the unit transformer unless the generator high voltage circuit-breaker is closed i.e. the machine is synchronized. This means that during the start-up and shut-down periods the unit auxiliaries must be transferred to an alternative source. This is normally a station transformer connected directly, either to the high voltage system or a local sub-transmission network (Figure 1a)).

In the mid 1960's a number of far-sighted engineers from power supply authorities recognized that switching large generators at terminal voltage would more readily fulfil trends in operational procedures and better meet requirements for plant security and economy. They provided the impulse that led to the development of switchgear expressly designed for this purpose. The first

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generator circuit-breaker was delivered to a power plant in Germany in 1972. The circuit-breaker comprised three cylindrical, metal enclosed, phase-segregated units, the operating and arc-extinguishing medium being compressed air. The concentric cylindrical layout allowed the circuit-breaker to be readily installed in the run of the generator isolated phase busbars. The use of this circuit-breaker, located between the generator and its unit and main transformers, meant that the plant auxiliary supplies could be obtained at all times from the unit transformer i.e. also during the starting and shut-down periods. Therefore the station transformer could either be completely omitted or used as an emergency shut-down transformer only (Figure 1b)).



MT	Main transformer
UT	Unit transformer
ST	Station transformer
CO	Rapid changeover switching equipment
GCB	Generator circuit-breaker
HV	Transmission system
LHV	Sub-transmission system
AUX	Generator unit auxiliaries

Figure 1: Power plant layouts:

- a) Layout without a generator circuit-breaker  
b) Layout using a generator circuit-breaker

During the intervening years, the development of the generator circuit-breaker and associated switchgear has continued. In the 1970's, when generator unit sizes increased to a level of 1200 MW, generator circuit-breaker current ratings rose to 50,000 A with a corresponding breaking capacity of 275 kA at service voltages of up to 30 kV. The following decade saw the introduction of the first generator circuit-breaker using SF<sub>6</sub> gas as its arc-extinguishing medium. Circuit-breakers using this technology are now available with current ratings up to 20,000 A and breaking capacities of 120 kA at rated voltages up to 25.8 kV. The most recent development has been the integration of all the associated items of switchgear within the circuit-breaker housing as an option to their separate installation. Such items include series disconnectors, grounding switches, current transformers, single pole insulated voltage transformers, protective capacitors and surge arrestors. When required the grounding switch can be arranged to provide an external connection for a start-up supply as used for example in gas turbine plant. This development accommodates the trend towards the use of integrated system solutions and away from individual components in power plant construction.

### 1.3 Aspects of generator circuit-breaker application

A major objective of all power plant operating companies is the achievement of the highest possible plant availability at the lowest possible cost. The use of generator circuit-breakers can help in reaching this target in the following ways:

- ◆ simplification of operating procedures:
  - the installation of the generator circuit-breaker directly in the generator connections provides a clear and logical plant arrangement
  - during the starting up or shutting down of the generator only one circuit-breaker must be operated reducing the number of 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 no longer required
  - the division of responsibility for the operation of the power plant and the switching of the high voltage system is clearly defined
- ◆ improved protection of the generator and its main and unit transformers:
  - the differential protection zones of the generator, main transformer and 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 requires 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
  - the rapid and selective clearance of all types of faults avoids expensive secondary damage and the consequently long down times for repair. An example of serious secondary damage being caused by the delayed clearance of a fault is the bursting of the transformer tank following an internal fault in the main or unit transformer. Another incident 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. The generator rapid de-excitation equipment is in most cases too slow to avoid such secondary damage

### 2. Technical requirements for generator circuit-breakers

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

- synchronize the generator with the main system
- separate the generator from the main system (switching off the unloaded generator)
- interrupt load currents (up to full load current of the generator)
- make and break currents under out-of-phase conditions
- interrupt generator-fed short-circuit currents
- interrupt system-fed short-circuit currents

When used in pumped-storage power plants the generator circuit-breaker must also:

- synchronize and switch the generator/motor when the machine is operating in the motor mode

Depending on the arrangement of the start-up supply, the generator circuit-breaker when used in gas-turbine, combined-cycle and pumped-storage power plants may be required to:

- interrupt generator-fed short-circuit currents at frequencies below 50 Hz

### 2.1 Performance requirements

The electrical and mechanical performance required of generator circuit-breakers, exceeds by a considerable degree that required of standard medium voltage distribution switchgear:

- normally a generator circuit-breaker must carry a continuous load current approaching its full rated current, therefore all the active parts operate continuously at a higher temperature
- the switching duty varies widely. In the case of thermal power plant a circuit-breaker may only be required to carry out a mechanical CLOSE-OPEN-operation (CO-operation) once or twice per year or even less frequently. On the other hand in a pumped-storage power plant 5 CO-operations per day at currents up to approximately 60% of the generator/motor rating are usual and in extreme cases up to 10 CO-operations per day may be attained
- independent of the load phase angle, the interruption of load currents gives rise to transient recovery voltages with comparatively high RRRV-values and short time delays
- a generator circuit-breaker must be able to make and break currents under out-of-phase conditions
- the short-circuit currents which must be interrupted by a generator circuit-breaker are characterized by high DC components. Generator-fed short-circuit currents normally exhibit the phenomenon of missing current zeros
- the transient recovery voltages following the interruption of currents under out-of-phase and fault conditions are characterized by high RRRV-values and extremely short time delays

A comparison of typical performance requirements for generator circuit-breakers with those for medium voltage circuit-breakers according to [1] is given in Table I. It clearly illustrates that the IEC-Standards for circuit-breakers (and also the corresponding ANSI-Standards) do not adequately cover the requirements applicable to generator circuit-breakers. It is merely mentioned that where circuit-breakers are installed in the vicinity of generators or large transformers, higher DC components and RRRV-values must be expected. No values for these quantities are specified however.

### 2.2 Standards and tests

Particularly in the United States of America, the non-existence of a standard fully applicable for generator circuit-breakers has, in the past, created problems associated with their application in nuclear power plants. On the one hand the responsible authorities recognized the safety and security arguments in favour of the use of generator circuit-breakers; on the other, they were only able to accept equipment which had been fully type tested in accordance with a relevant and recognized standard. This situation gave rise to the creation of an IEEE Working Group with the task of developing a standard for generator circuit-breakers. This working group comprised representatives of power supply authorities, testing laboratories and from the major manufacturers of generator circuit-breakers. The working group was able to call on previous work done in this field, in particular the results of investigations made by a CIGRE task force into the characteristics of the transient recovery voltages associated with generators circuit-breakers [2], [3]. The work of the IEEE group was completed in 1989 with the issue of the world-wide first valid standard specifically relating to generator circuit-breakers.

This standard contains, in addition to rating information and other relevant characteristics, guidelines for the type-testing of generator circuit-breakers. A revised version together with an application guide was published in 1993 [4].

Table I: Comparison of the service requirements for generator circuit-breakers with the corresponding values according to [1]

Parameter	Requirements for generator circuit-breakers	Requirements according to IEC 56 111
<b>Switching of system-fed short-circuit currents:</b>		
- Breaking current	IsC	IsC
- DC-component [%]	70.....80 1)	25 1)
- Recovery voltage [kV]	0.87 U	0.87 U
- Rate-of-rise of recovery voltage [kV/us]	3.5.....6.0	0.47 3)
- Time delay [us]	< 1	13 3)
- Peak value [kVpeak]	1.84 U	1.72 U
<b>Switching of generator-fed short-circuit currents:</b>		
- Breaking current	0.4.....0.8 IsC	0.6 IsC
- DC-component [%]	100.....130 1)	not specified
- Recovery voltage [kV]	0.87 U	0.87 U
- Rate-of-rise of recovery voltage [kV/us]	1.6.....2.2	1.16 4)
- Time delay [us]	< 0.5	8 4)
- Peak value [kVpeak]	1.84 U	1.84 U
<b>Switching under out-of-phase conditions:</b>		
- Breaking current	0.4.....0.6 IsC	0.25 IsC
- DC-component [%]	80.....100 1)	not specified
- Recovery voltage [kV]	1.23 U 2)	1.44 U
- Rate-of-rise of recovery voltage [kV/us]	3.3.....5.2	0.35 5)
- Time delay [us]	< 1	not specified
- Peak value [kVpeak]	2.60 U	2.55 U
<b>Switching of load currents:</b>		
- Breaking current	I <sub>r</sub>	not specified
- Recovery voltage [kV]	0.43 U	not specified
- Rate-of-rise of recovery voltage [kV/us]	1.0.....1.6	not specified
- Time delay [us]	< 1	not specified
- Peak value [kVpeak]	0.92 U	not specified

U: Rated voltage  
I<sub>r</sub>: Rated current  
IsC: Rated short-circuit breaking current

- 1) Contact parting time 60 ms
- 2) Out-of-phase angle 90 degrees
- 3) Test duty 4 for rated voltage 24 kV
- 4) Test duty 3 for rated voltage 24 kV
- 5) Test values for rated voltage 24 kV

The positioning of the generator circuit-breaker between the generator and its main transformer, where its performance directly influences the plant output, places very high demands on its reliability. While a sound and mature design and a 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 type tests which have to be performed in accordance with [4].

### 3. Service experience with generator circuit-breakers

Circuit-breakers designed specifically for the switching of generators have been in service since the early 1970's, so that a considerable amount of operational experience under varying service conditions is now available. In particular, sufficient data is available to allow a soundly based reliability analysis of generator circuit-breaker performance. Table II gives the reliability data for generator circuit-breakers and for comparison purposes, available information for other power plant components.

The service experience gained over such a long time span has been an essential input into the continuing development of generator switchgear and has also provided a basis for the determination of maintenance procedures. This practical experience supported by knowledge gained from extensive development testing and accelerated life tests has provided an important basis for sound maintenance recommendations.

Table II: Characteristic reliability data

Component	Failure rate [1/a]			Source
	MV	110 kV	380 kV	
Unit transformer	0.095			[5]
Station transformer		0.098		[5]
High voltage circuit-breaker		0.024	0.087	[5]
Type DR air-blast generator circuit-breaker	0.005			*)
Type HE SF6 generator circuit-breaker	0.003			*)

\*) Failure statistic of manufacturer

#### 4. Life cycle cost of generator circuit-breakers

##### 4.1 Life cycle cost concept

There are a large number of different models, which have been developed for the determination of the life cycle cost of a piece of equipment [6]. In this report the following model will be used:

$$LCC = LCA + LCS + LCU + LCD \quad (1)$$

LCC: life cycle cost  
LCA: acquisition cost  
LCS: life support cost  
LCU: life unavailability cost  
LCD: disposal cost

The cost of acquisition includes the initial cost of the equipment and the cost of putting into service. The life support cost covers all costs arising from the operating and maintenance of the equipment during its life time. The term life unavailability cost covers costs which the plant operator incurs when the equipment is unserviceable, it includes the loss of income and/or profit which arises due to the inability of the operator to supply power from the plant. The cost of disposal consists of the costs involved in disposing of the equipment at the end of its working life. If the equipment has a residual value (LVD), this is included as a negative term.

Monetary values are time dependent, and can only be compared, summed or subtracted when they are referred to the same point in time. For this reason a cash value corresponding to each cost term must be calculated to allow for interest and inflation rates:

$$PV-C = [1/(1+r)]^i C \quad (2)$$

PV-C: present value of cost C  
C: expense payable in i years in "zero-year" currency value  
r: effective discount rate (interest rate - inflation rate)  
i: number of years

An appropriate time reference point is the date of the commissioning of the equipment. The life cycle cost of a generator circuit-breaker can therefore be determined by the following formula:

$$PV-LCC = LCA + \sum_{i=1}^N \{ [1/(1+r)]^i (CS_i + CU_i) \} - [1/(1+r)]^N LVD \quad (3)$$

PV-LCC: present value of life cycle cost  
LCA: acquisition cost  
CS<sub>i</sub>: operating and maintenance cost in the i<sup>th</sup> year after commissioning  
CU<sub>i</sub>: outage cost in the i<sup>th</sup> year after commissioning  
LVD: residual value of equipment after N years of service  
r: effective discount rate (interest rate - inflation rate)  
N: number of years of service (service life)

When various alternatives are compared during the evaluation of a generator circuit-breaker it will be obvious that the alternative giving the lowest cash value is the most economical. The same method can also be used to evaluate the economical aspects of a proposed replacement or retrofit project. This may be a question, relating to an existing power plant, as to whether it is economical or not, to replace an older type circuit-breaker with comparatively high operating and maintenance costs by a modern low maintenance unit. The answer is positive in those cases where the following condition is fulfilled (Alternative 1: continued operation with the existing circuit-breaker; Alternative 2: replacement of the circuit-breaker with a reduced maintenance design):

$$LCA_2 < \sum_{i=1}^L \{ [1/(1+r)]^i (\Delta CS_i + \Delta CU_i) \} - [1/(1+r)]^L \Delta LVD \quad (4)$$

with  $\Delta CS_i = CS_{1i} - CS_{2i} \quad (4a)$   
 $\Delta CU_i = CU_{1i} - CU_{2i} \quad (4b)$   
 $\Delta LVD = LVD_1 - LVD_2 \quad (4c)$

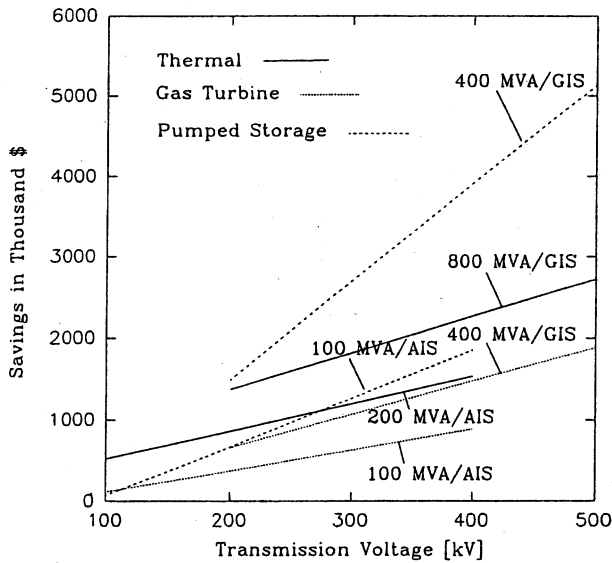
LCA<sub>2</sub>: acquisition cost of Alternative 2  
CS<sub>1,2i</sub>: operating and maintenance cost in i<sup>th</sup> after the commissioning of Alternatives 1 and 2  
CU<sub>1,2i</sub>: outage cost in the i<sup>th</sup> year after commissioning of Alternatives 1 and 2  
ΔLVD<sub>1,2</sub>: residual value of Alternatives 1 and 2 at the end of the period under consideration  
r: effective discount rate (interest rate - inflation rate)  
L: period under consideration in years

##### 4.2 Acquisition cost

The acquisition cost of generator switchgear comprise the initial cost of the equipment plus the installation and commissioning costs.

The initial equipment cost of a particular type of generator switchgear is dependent on the required technical data and also on other considerations such as open or single-pole enclosed design, indoor or outdoor installation, and the limits of supply for the associated ancillary equipment such as disconnectors, grounding switches, instrument transformers, surge arrestors, protective capacitors, etc..

Where the layout of the power plant has already been decided, the evaluation of the initial equipment cost of the generator switchgear presents no problems. However when alternative layouts are still under discussion, for example where a unit connection is to be compared with a generator circuit-breaker layout, the situation is more complex. In such a case the initial costs of all items of equipment which are not identical in both layouts must be determined and compared. Typical examples of such items besides the generator circuit-breaker are the station transformer with its associated high and low voltage switchgear, the unit transformers of varying capacity, the rapid changeover switching equipment for the unit auxiliaries, etc.. The initial equipment costs for typical layouts of various types of power plant (see Appendix) have been analysed in this way (Figure 2). These comparisons take into account the voltage level of the transmission system and the power plant rating. World market prices for each item of equipment were used to provide the cost basis for the comparisons. The results indicate that in most cases, the use of a generator circuit-breaker provides an economical alternative to the unit type generator connection.



GIS Gas-insulated h.v. switchgear  
 AIS Air-insulated h.v. switchgear

Figure 2: Possible savings in initial equipment cost resulting from the use of generator circuit-breakers in power plants of different ratings (for layouts refer to Appendix)

During the continuing development of the generator circuit-breakers special attention has been paid to the reduction of the installation and commissioning costs. While the initial air-blast generator circuit-breaker comprising three single pole units and separate control panel required considerable site work, development has now proceeded so far that the SF<sub>6</sub> circuit-breaker is supplied as fully operational unit. The single mounting frame houses the three circuit-breaker poles, its operating mechanism and the control and supervisory equipment. By these means the circuit-breaker installation and commissioning costs have been reduced to approximately 10 to 20 % of the corresponding value for the air-blast circuit-breaker. The transition from generator circuit-breaker to the generator switchgear system concept will further reduce these costs, integrating as it does the ancillary components within the framework of the circuit-breaker housing. These items are fitted, wired and tested in the factory and supplied with the circuit-breaker as an operational unit requiring the minimum of site installation and commissioning.

4.3 Life support cost

The life support cost of a generator circuit-breaker consists of the costs resulting from the operating and the maintenance of the switchgear. These include such factors as the personnel costs of the staff required for the supervision of the equipment, the energy requirements of the switchgear auxiliaries, a share of the plant infrastructure (e.g. spare parts store, etc.), support of a service organization including training of maintenance staff and the direct costs for maintenance personnel and replacement parts. It is obvious, that by far the larger part of the operating and maintenance cost is attributable to the maintenance of the equipment.

For some time, development in all sectors of switchgear technology has shown a strong trend towards designs requiring minimum maintenance. This trend is also evident in generator circuit-breaker development. In comparison with the air-blast

circuit-breaker the maintenance requirements of a modern SF<sub>6</sub> generator circuit-breaker design have been greatly reduced. The reduction in circuit-breaker maintenance requirements is illustrated in Table III, which compares the intervals between maintenance for air-blast and SF<sub>6</sub> circuit-breakers, and also the time expenditure required for carrying out a maintenance.

Table III: Intervals between maintenance for generator circuit-breakers

Type of circuit-breaker:			
- Arc-extinguishing medium	SF <sub>6</sub>	SF <sub>6</sub>	Air-blast
- Rated current [kA]	6.3	12	20
- Rated short-circuit breaking current [kA]	63	120	200
Intervals between maintenance:			
- Based on time in service [a]	10	10	6 - 8
- Based on mechanical CO-operations	10,000	5,000	2200
- Based on current breaking operations:			
- 60 % of rated current	5,000	1,800	2200
- 100 % of rated current	3,000	700	2200
- 100 % of rated short-circuit breaking current	5	5	5
Time expenditure:			
- Time expenditure [man-days]	3	3	15

In most power plants and under normal conditions the number of operations a generator circuit-breaker has to perform are low so that maintenance requirements are determined by the time criterion. In power plants whose operation requires a high number of switching operations, as for example in pumped-storage power plant, the need for maintenance is determined by the number of mechanical operations or by the accumulated breaking current limit. In this case the number of operations which can be performed before maintenance is required is given by the following relationship:

$$n = 100 / \left\{ \sum_i \left[ p_i / N(I_i) \right] \right\} \quad (5)$$

- n: permissible number of operations before maintenance is required
- p<sub>i</sub>: percentage of operations at a current I<sub>i</sub>
- N(I<sub>i</sub>): number of operations at I<sub>i</sub> allowable in accordance with accumulated breaking current curve

Especially in applications with a high number of switching operations the use of a condition monitoring device is a good policy. A condition monitoring device allows the maintenance intervals to be optimized and unnecessary maintenance to be avoided. Micro-processor based condition monitoring devices are available for use with SF<sub>6</sub> generator circuit-breakers, these register the contact erosion for each operation using current and arcing time measurements. Prior to the circuit-breaker reaching the limiting value the device provides an appropriate warning signal.

4.4 Life unavailability cost

The life unavailability cost for a generator circuit-breaker besides the cost for the repair of the circuit-breaker includes all the costs which a plant operator incurs by an inability to supply power from the plant due to a failure of the generator circuit-breaker. The annual outage cost may be represented by the following expression [6]:

$$CU = \sum_j \lambda_j T_{op} / 8760 [CF_j + CL_j T_{dj} + CR_j MTTR_j] \quad (6)$$

CU: annual outage cost

- $\lambda_j$ : average failure rate for a mode  $j$  failure [1/a]  
 MTTR $_j$ : mean time to repair of a mode  $j$  failure [h]  
 $T_{op}$ : operating hours per year [h]  
 $T_{dj}$ : average down time due to a mode  $j$  failure [h]  
 $CF_j$ : duration independent costs arising from each mode  $j$  failure  
 $CL_j$ : loss and compensation expenses per hour of down time due to a mode  $j$  failure  
 $CR_j$ : repair labour cost per hour for a mode  $j$  failure

An evaluation of the costs of unavailability can be readily performed if the power plant layout is already firm at the time of the evaluation of the generator circuit-breaker. In this case the relevant costs for the circuit-breaker types under consideration can be directly compared. The problem is more complicated when various power plant layouts are to be compared with each other. At this point only some hints are given how the application of generator circuit-breakers can influence power plant availability in a positive sense.

The use of generator switchgear allows the plant auxiliary supplies to be drawn direct from the high voltage transmission system at all times, i.e. also during the critical start-up and shutdown 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 improvement plant auxiliary equipment availability. Very large fossil fired thermal power plants and nuclear power plants are built with a station transformer and generator circuit-breakers, this arrangement provides additional redundancy in respect of the auxiliary supplies. Further 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.

In [7] the influence of the use of a generator circuit-breaker on the availability of a particular type of nuclear power plant has been qualitatively examined. The gain resulting from the higher availability of the generator was compared with the capitalized losses due to the unavailability of the generator circuit-breaker. The net capital gain calculated amounted to \$ 800,000 resulting from the use of a generator circuit-breaker.

#### 4.5 Disposal cost

The disposal cost of generator switchgear comprise the costs involved in disposing the equipment as required by regulations at the end of its working life. The generator switchgear can also have a residual value which is defined as the costs which can be recovered when the equipment is resold or scrapped.

### 5. Evaluation of a generator circuit-breaker for use in a pumped-storage power plant

A practical example of the application of the method of cost calculation described is given in the following and relates to the evaluation of a generator circuit-breaker for use in a pumped-storage power plant in Switzerland.

The pumped-storage power plant Mapragg is owned by the Kraftwerke Sarganserland AG, this company is itself a subsidiary of the Nordostschweizerischen Kraftwerke AG. The power plant was commissioned in 1977 and is equipped with three 115 MVA generators which supply their output to the 380 kV transmission system via a four winding transformer (Figure 3). Power consumption in the pumping mode is 53 MW at a maximum water volume of 12 m<sup>3</sup>/s. The switching of the generator/motors is performed at the 11 kV level by individual circuit-breakers.

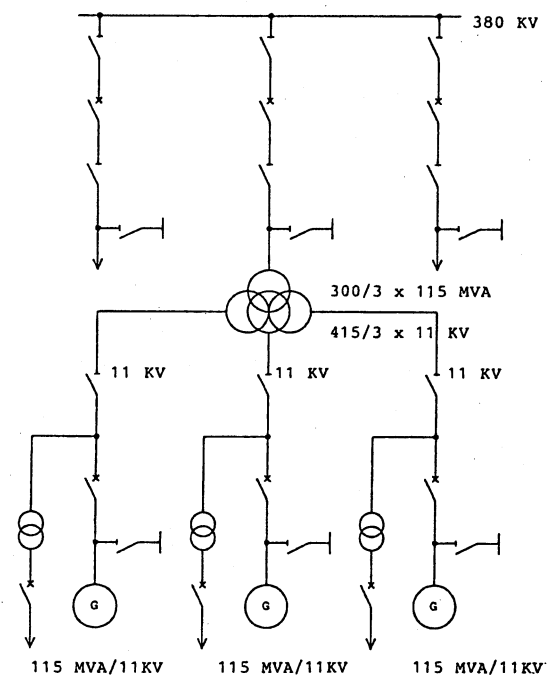


Figure 3: Single line diagram of the Mapragg Pumped-storage Power Plant

These generator circuit-breakers have a current rating of 6700 A and a short-circuit breaking current of 90 kA. The plant is used to provide high value peak load energy and runs in the motor/pumping mode at periods of low load, i.e. overnight and at weekends. Each generator circuit-breaker makes an average of 625 CO-operations per year under various conditions as listed:

- 56 % at < 100 A: generator operation, regulator closed
- 1 % at 5000 A: generator operation, full load
- 43 % at 2000 A: motor operation

The relative high number of operations resulted in the past in frequent outages due to circuit-breaker mechanical failures. The original circuit-breakers were of the air-blast type and of a rather old design. An intensified maintenance programme resulted in a slight improvement in availability, but caused an disproportionate increase of the operating and maintenance costs. The company therefore decided to examine the economics of replacing the existing circuit-breakers with modern SF<sub>6</sub> circuit-breakers as an alternative to continuing to use the air-blast units. In order to make a meaningful comparison of the relative economics, the life-cycle-costs of both alternatives were calculated. Based on the expected remaining service life of the air-blast circuit-breakers the calculations were made for a 15 year period ending in the year 2007. The operating and maintenance costs and the outage costs for the air-blast circuit-breakers were based on the plant operator's experience since commissioning. Nine circuit-breaker failures were experienced in this period, with an average outage time of one to three days for each occurrence. A failure effectively meant the loss of a third of the plant's output at a cost of up to \$ 40,000 per day depending on the time of the outage. As the air-blast circuit-breaker is no longer in production, it was assumed that the costs of spare parts would rise more steeply than general prices and this was allowed for by a surcharge of 5 % per annum. The corresponding information for the SF<sub>6</sub> generator circuit-breaker were derived from service experience data provided by the manufacturer. Figure 4 shows the cumulative operating and maintenance costs and the unavailability costs as forecast for both types of circuit-breakers over the 15 year period.

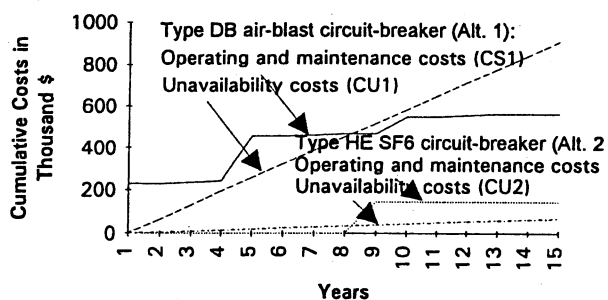


Figure 4: Forecast of the operating and maintenance costs and unavailability costs for the Mapragg Pumped-storage Power Plant:

- Alternative 1: existing air-blast circuit-breakers
- Alternative 2: new SF<sub>6</sub> circuit-breakers

The life cycle costs for the two alternatives using an effective discount rate of 3 % per annum were calculated to be:

Continued operation with existing circuit-breakers: \$ 1,247,000

Replacement of the circuit-breakers with SF<sub>6</sub> units: \$ 1,043,000

The replacement alternative was shown to offer considerable economic advantages and it was decided to proceed on this basis and equip the Mapragg power plant with modern circuit-breakers. The SF<sub>6</sub> circuit-breakers were commissioned during the winter of 1993/94. The installation of these circuit-breakers allows the intervals between maintenance to be increased from 4 to 8 years. Further, it is expected that the considerably higher reliability of the SF<sub>6</sub> generator circuit-breaker will virtually eliminate unplanned plant outages due to generator switchgear failures.

The user has decided to monitor the condition of the contacts of the SF<sub>6</sub> generator circuit-breakers installed at the Mapragg power plant by means of the method of dynamic resistance measurement [8]. The performance of this measurement requires the circuit-breaker to be taken out of service. The simultaneous recording of the contact resistance and the contact stroke allows the point of transfer from the main to the arcing contacts and the position of the tip of the arcing contacts to be determined. This information defines precisely the position of the arcing contact in relation to the contact movement and hence allows the degree of contact wear to be determined. For this purpose it is necessary to record the finger print reference of the circuit-breaker by carrying out this measurement with the circuit-breaker in new condition. The corresponding measurements have been carried out on the circuit-breakers in question during the routine testing.

## 6. Conclusions

Life management for generator circuit-breakers covers all measures and activities necessary to ensure a satisfactory operation at minimum cost over the entire life-time of the circuit-breaker. Life management starts already in the initial evaluation phase with the choice of the circuit-breaker optimally suited for a given application. The calculation of the life cycle cost allows a well-founded decision to be made in this respect.

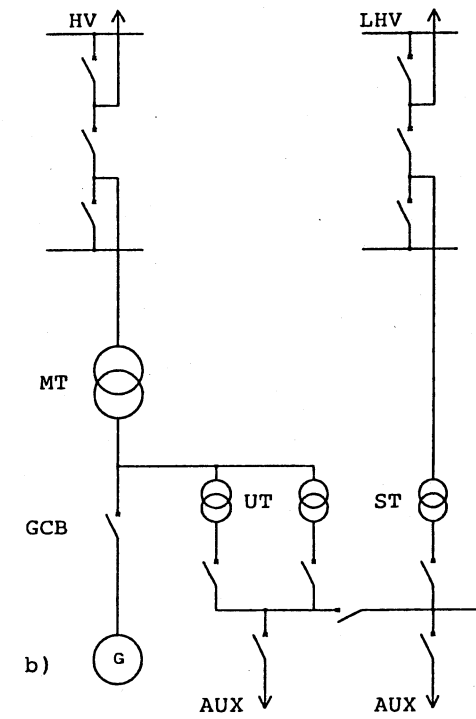
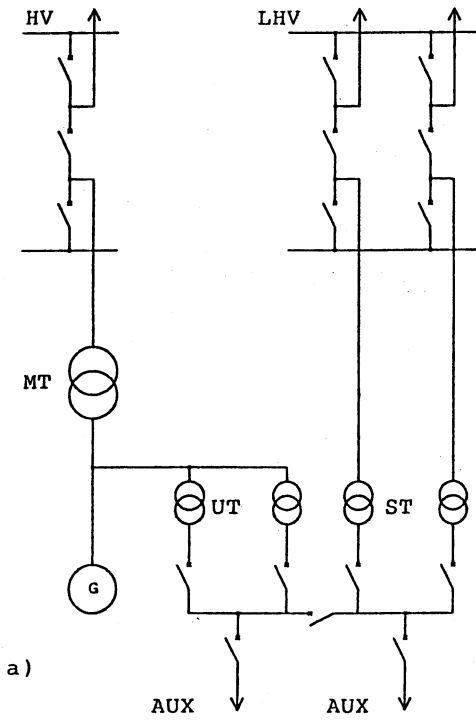
The procedures described in this paper permit the evaluation of the life cycle cost of generator circuit-breakers. In those cases where the power plant layout is already firm, the life cycle costs of the circuit-breaker alternatives may be evaluated and directly compared. Also where the replacement of existing circuit-breakers due to excessive maintenance costs, or retrofitting of a power plant is under consideration the methods described allow a ready analysis of the relative economics and provide a valid basis for comparison. When alternative plant layouts are to be compared, e.g. generator circuit-breaker scheme with a unit connection, the life cycle costs for all non-identical equipment must be calculated and included in the comparison. Experience shows that, in addition to the technical and operational advantages, the use of generator switchgear generally provides the most economical solution to power plant design. In order that these advantages, both technical and economical, be fully realized, generator switchgear must meet the highest standards of quality and reliability. Essential factors are a mature, well conceived design, careful material and component selection, rigorous quality control procedures and exhaustive testing under practice related conditions.

## References

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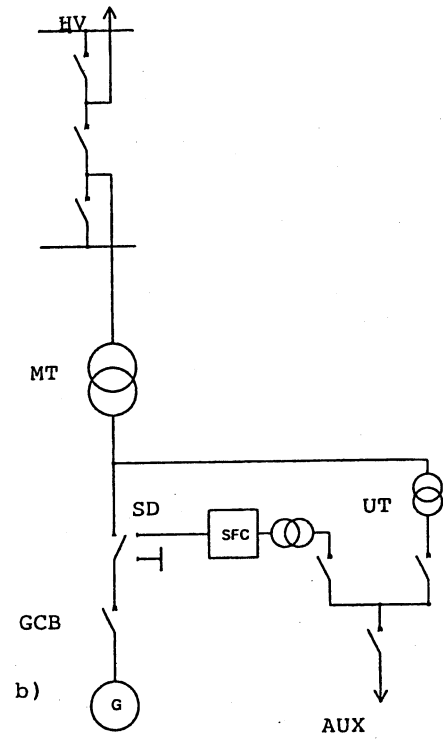
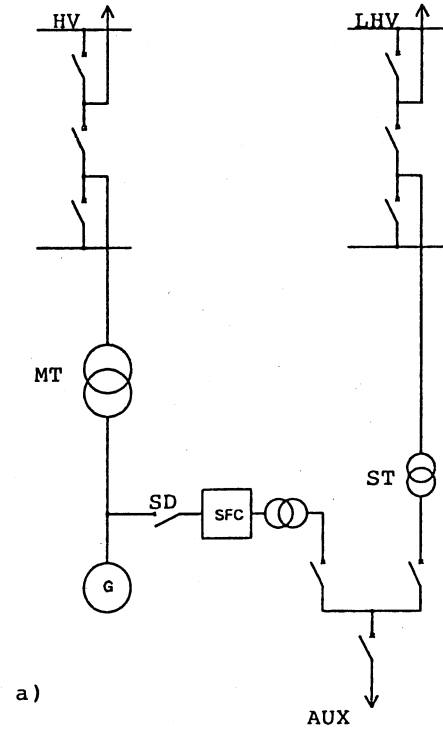
## Appendix: Typical power plant layouts for thermal, gas turbine or combined-cycle and pumped-storage power plants

Figures A1, A2 and A3 show typical power plant layouts for thermal power plants, gas turbine or combined-cycle power plants and pumped-storage power plants. The comparisons of the initial equipment cost incurred by power plant design variants given in Figure 2 are based on these layouts.



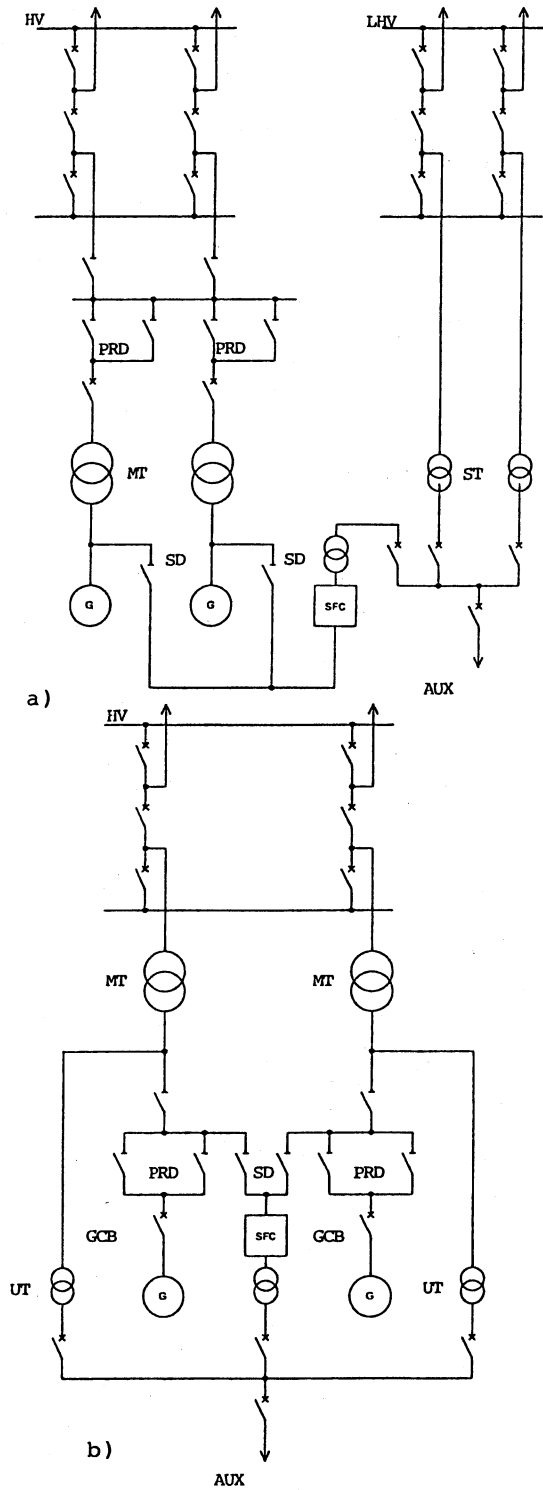
MT Main transformer  
 UT Unit transformer  
 ST Station transformer  
 GCB Generator circuit-breaker  
 HV Transmission system  
 LHV Sub-transmission system  
 AUX Generator unit auxiliaries

Figure A1: Typical layouts for thermal power plants:  
 a) Layout without a generator circuit-breaker  
 b) Layout using a generator circuit-breaker



MT Main transformer  
 UT Unit transformer  
 ST Station transformer  
 GCB Generator circuit-breaker  
 SD Starting disconnector  
 SFC Static frequency converter  
 HV Transmission system  
 LHV Sub-transmission system  
 AUX Generator unit auxiliaries

Figure A2: Typical layouts for gas turbine or combined-cycle power plants:  
 a) Layout without a generator circuit-breaker  
 b) Layout using a generator circuit-breaker



- MT Main transformer
- UT Unit transformer
- ST Station transformer
- GCB Generator circuit-breaker
- SD Starting disconnector
- PRD Phase-reversal disconnector
- SFC Static frequency converter
- HV Transmission system
- LHV Sub-transmission system
- AUX Generator unit auxiliaries

Figure A3: Typical layouts for pumped-storage power plants:  
 a) Layout without a generator circuit-breaker  
 b) Layout using a generator circuit-breaker

