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Feasibility Study of Superconducting Current Limiter Application in a Cogeneration Plant.

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***Abstract*—Fault current limiters (FCL) are being developed using high temperature superconductors. Possible applications of FCL are medium and high voltage energy supply systems. In this field conventional protection against high currents often cause high expenses. Using a superconducting FCL gives an economic advantage, if technical problems can be solved at lower costs or if the usage of a FCL makes savings in other equipment possible.**

This work deals with possible applications of a superconducting fault current limiter within a medium voltage auxiliary power network of a typical small cogeneration power plant. For possible installation locations in the existing energy supply system of Braunschweig, Germany, calculations of short circuit currents were made. Thereby is kept track of the question, whether the power plant can be expanded while staying or becoming short-circuit-proof. One result of the work is that the auxiliary power system of the power plant is an especially interesting installation location for a FCL. Advantages of a FCL compared to conventional strengthening of the installations are discussed.

***Index Terms*—Fault current limiter, grid integration, simulation.**

I. INTRODUCTION

The occurring currents in energy supply systems can exceed the nominal currents at a short-circuit many times. The grid has to be short-circuit-proof, otherwise major damages can occur. At first this means, that all equipment has to be able to bear the short-circuit currents which appear under error conditions, without damages until disconnection. Secondly, the circuit breaker which is designated for the cutoff has to be able to intercept the short-circuit current. To guarantee short-circuit strength the equipment in the grid has to be overdimensioned in comparison to the normal operating conditions. A fault current limiter can produce relief in these situations.

The use of a FCL has to provide an economic advantage compared to the classic approach to justify the additional charges and the higher complexity of a current limiter.

Additional information of possible applications for superconducting fault current limiters can be found in [1], [3] and [4]. Due to the intended expansion of the cogeneration power plant of the power authority in the city of Braunschweig, Germany, we examined a sub-grid of the local distribution network to discuss the possibility of an application and the economic efficiency of an FCL in a typical grid of a medium sized city.

At first it was thought about an adoption of a FCL in the 110 kV grid, but because of the high short-circuit strength of this part of the grid it turned out to be not essential after the first calculations. The focus lies rather on an application in the auxiliary power grid of the local cogeneration plant (HKW). This grid is characterized by high short-circuit currents and our calculations turned out, that the auxiliary power is already only restricted short-circuit proof in the actual situation. The intended expansion of the plant would be impossible without large and costly changes in the power plants auxiliary power grid. Therefore we discuss the question, if this situation can be improved by a FCL. Hence, an application in the medium voltage range is analyzed.

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II. INVESTIGATED GRID AND CALCULATIONS

A. *Calculation of the short-circuit current:*

A three-pole (symmetric) short-circuit is the primary constructions parameter for the short-circuit capability of installations and equipment, therefore only this error condition was considered in the calculations. Because of the same amplitude in all three conductors of the three-phase system, a uniphase equivalent circuit diagram is sufficient for the calculation of the symmetric short-circuit. The approach with an equivalent voltage source at the spot of the short-circuit according to [5] and [6] were used.

The calculations were made with the grid calculation program NEPLAN [12]. The FCL was simulated by a serial RLC-element with pure ohmic rate (L=0 H*;* C=0 F). The resistance was presumed to $R = 10\ \Omega$. This value conforms to the normal state resistance of the current limiter after the complete quench of the superconductor. This value is only an assumption, because the normal state resistance of a superconducting FCL is generally a result of the device construction.

B. *Investigated grid:*

1) *Actual grid:*

The investigated sub-grid (Fig. 1) is a cogeneration plant with its proper voltage transformation substation in the city of Braunschweig. It is divided into the 110 kV city-grid and the 6 kV station supply grid of the plant. The station supply feed-in can occur from the 110 kV grid over two parallel 110/6 kV transformers (00BBT01 and 00BBT02). The medium voltage grid of Braunschweig is connected by the 20 kV busbar (00ADA).

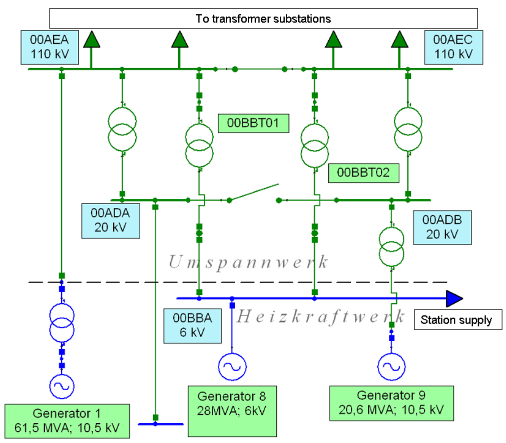

Fig. 1. Actual setup of the energy outgoing feeder and the station supply accommodation of the cogeneration plant in the city of Braunschweig.

According to information of the operator, only loads in the urban area are connected on this busbar. These loads were disregarded for the short-circuit calculation under the terms of [5], because the participation of asynchronous motors are sufficiently low and no power flow calculation has to be made. Generator 1 (Fig. 1, left) feeds over a main transformer directly into the 110 kV grid and is the biggest in the plant with 61.775 MVA. The feeding of generator 9 (right) with 20.6 MVA occurs over the 20 kV busbar and the power transformer 102. Generator 8 feeds directly into the 6 kV station supply grid of the plant.

The arrows at the top of Fig. 1 at the 110 kV busbar refer to the connection to the upstream 110 kV grid of Braunschweig with an additional generator (gas turbine "Generator Nord") and two feedings from upstream high voltage grids. This grid was also considered in the calculation. The arrow on the 6 kV station supply busbar refers to the connected station supply of the cogeneration plant.

2) *Station supply of the cogeneration plant:*

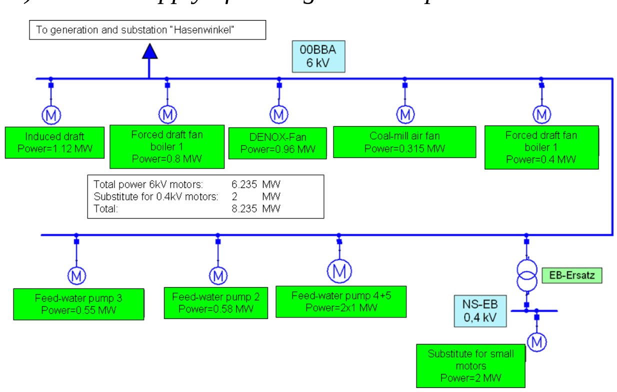

Fig. 2. Station supply busbar "Heizkraftwerk Mitte" without feeding. All motors are asynchronous motors. A 2 MW motor on 0.4 kV serves as substitution for the large number of small motors in the station supply.

The station supply of a plant cannot be disregarded, because it consists mostly of rotating loads, particularly synchronous and asynchronous motors. Fig. 2 illustrates the station supply of the cogeneration plant. Nine large 6 kV (Fig. 2) asynchronous motors are directly connected to the busbar. Additionally ther are a number of 6/0.4 kV transformers connected to the busbar. These transformers feed the 0.4 kV sub-grids in the plant, which supply mainly the numerous small traction units in the station supply. Because these drives cannot be neglected (ref. 4) Essential assumptions and [5]) we had to make some assumptions for these motors, since there is no information available about the loads connected to these sub-grids.

3) *Intended expansion:*

Fig. 3 shows the intended expansion. It contains an additional generator with a nominal power of 60 MVA and a nominal voltage of U_r = 10.5 kV. On the one hand this generator shall feed into the high voltage grid over a transformer and on the other hand it shall also ensure the station supply of the "Heizkraftwerk Mitte". Therefore the output-circuit of the generator is connected additionally over a 10/6 kV transformer to the 6 kV station supply busbar and one of the existent 110/6 kV transformers drops out. The station supply of the new block is estimated to 2.5 MW.

Additionally, the direct connection of another generator with approximately 12.5 MVA to the 6 kV station supply busbar is planed.

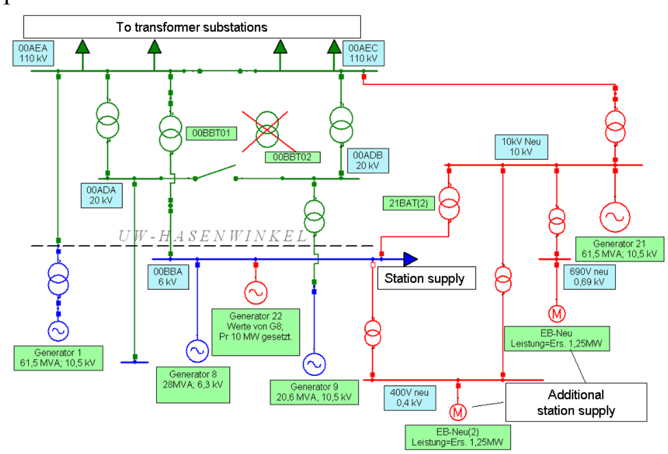

Fig. 3. Voltage transformation substation "Hasenwinkel" and cogeneration plant extended by the new installation.

4) *Essential assumptions:*

Assumptions had to be made, because for some equipment not all data were available.

a) *Assumption for motors in station supply:*

The equivalent impedance of asynchronous motors for the short-circuit calculation is calculated according to [5]:

$$Z_M = \frac{1}{I_a / I_n} \cdot \frac{U_n}{\sqrt{3} I_n} \qquad (1)$$

U_{rM} and I_{rM} are the rated voltage and the rated current. Z_M is the short-circuit impedance of asynchronous motor. I_a is the starting current and I_n the nominal current.

As described in [7] a ratio of I_a/I_n=7 was used if the correct value was unknown. The often used ratio of I_a/I_n=5 did not appear to be appropriate, because, the two known pull-in currents are even bigger than seven-times the nominal current. According to [5] and [6] the short-circuit currents calculated with this assumptions are most likely larger than the real ones. Therefore the error made is on the safe side. Beside the large 6 kV motors many small electrical drives are used in the power plant. These engines are connected to a 0.4 kV grid that is feeded by the 6 kV station supply grid via transformers.

There are no exact data about the exact number, type and operating conditions of these motors. As informed by the operating company (BS|ENERGY), the whole station supply of the cogeneration plant has a value of approximately 8.5 MW. Thereof are already 6.235 MW covered by the nominal active power of the 6 kV motors. For the rest is the active power of the reserve motor assumed to 2 MW. For these drives I_a/I_n=5 was used according to [5], [7] and [8].

b) Generators:

The reactances of the generators were known or assumed according to [8].

c) Grid feeding:

Two grid feedings to the 110 kV city grid are accounted for. They deliver an initial AC short-circuit current of $I_k''_{NORD}$ = 5.9 kA and $I_k''_{SÜD}$ = 5.8 kA. The ratio *R/X* of the feeding has a value of 0.1 according to [8].

d) Transformers:

The characteristics of the transformers of the existing installation are completely known and respected.

e) Conductors:

For the entire 110 kV grid all conductors and power lines are completely known and considered up to the voltage transformation stations in upstream highest voltage grid (400 kV) with all required characteristics for the whole 110 kV grid. The power cable-connections of the voltage transformation station and the cogeneration plant, as well as at the additional generator in the 110 kV grid were not available. Since the typical length of these cables is in the range of a few meters to a maximum of 300 meters, their influence on the calculations is very small. Therefore, no conductors were considered whose length and type are not known. At these points ideal connections are assumed.

III. Results

The aim of this work was to calculate the short-circuit currents in the presented grid to determine the advantages of the use of a FCL and to identify reasonable locations for an application. Therefore the 110 kV busbar of the voltage transformation substation and the 6 kV station supply bar were regarded as error nodes.

Different grid versions were considered in the calculation, whereas different switching states were considered. This way the initial short-circuit currents I_k'' were respectively determined for a circuit of all equipments on the grid and for the deactivation of one equipment at a time.

Due to the assumptions and the method of calculation, some inaccuracies greater than a few ampere are expected Therefore all numerical values of the results are approximated to full 10 A on the 110 kV section and to full 100 A on the 6 kV section. This way the order of magnitude can be identified in an adequate way and it is possible to derive cognitions from the results.

A. Results identical in all variants:

The contribution of the asynchronous motors to the initial short-circuit alternating current I_k'' on the station supply bar in the power plant stays always unchanged in all regarded grid versions with or without FCL. The motors contribute with $I_{k,M}''$ = 6.9 kA to the short-circuit current.

The participations of the four 110 kV feedings in I_k'' on the 110 kV busbar and the participation of the generators 1 and 9 are also unchanged. The sum of these participations is 12.79 kA.

B. Calculation of the 110 kV busbar:

The comparatively small new in-feed rating of the generators 21 and 22 from the expansion leads to an additional maximum $\Delta I_k''$ of 0.87 kA on the 110 kV busbar, resulting in an I_k'' of 13.66 kA in the voltage transformation substation. The busbar is constructed for initial short-circuit ratings of S_k''=5 GVA (corresponds to I_k''=26.24 kA) and is therefore not endangered. Therefore, this busbar is not regarded in the following sections anymore.

C. Calculation without FCL:

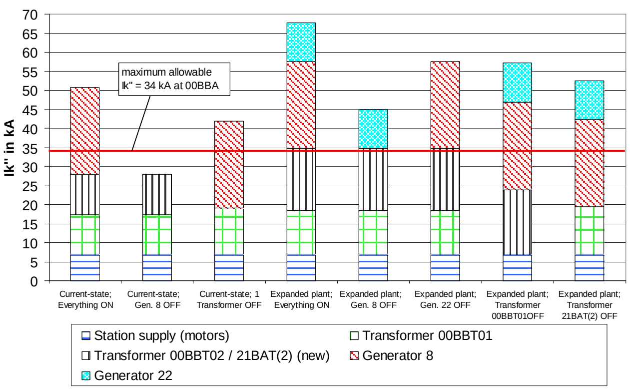

Fig. 4. Initial short-circuit current I_k'' on the 6 kV station supply busbar in different switching states. Actual grid status and with intended expansion.

The results of the calculation for the 6 kV station supply busbar are shown in Fig. 4 for the actual and the expanded grid. Based on the left column, it can be concluded, that the maximum I_k''=34 kA for which the busbar is designed, is exceeded in nearly all switching statuses. Since Generator 8 has its own share of approximately 22.9 kA in the high initial short-circuit currents, the only safe operating conditions would be with generator 8 turned off or only with generator 8 feeding the busbar (Transformers turned off). But a station supply accommodation only with generator 8 is not possible because of reliability reasons and a supply without generator 8 is not desirable because of economic reasons.

These results already negate the question about the expandability of the installation. An additional generator coupled direct on the station supply busbar (generator 22) and another in the new generating unit would further increase the short-circuit rating on the busbar. Nevertheless, the impact of an expansion was analyzed.

These results let the use of a FCL in the station supply busbar seem attractive.

There are two different possible locations for a FCL in the station supply: 1. the new section of the plant and 2. the old busbar. With the two generators 8 and 22 feeding directly the

6 kV busbar ($I_{k,G8}''$=22,9 kA and $I_{k,G22}''$=10,2 kA) the maximum allowable short-circuit current is already reached. Together with the large asynchronous motors the maximum value is always exceeded. Therefore it is not possible to achieve short-circuit proof operation if generator 22 is installed as planned, even if a FCL is used in the new section of the plant. Because of this a switching status without generator 22 was examined too.

D. FCL in the connection to the new generating unit:

Also the intermeshing has to be regarded as a cause for the high short-circuit currents in addition to the problem of oversized generator ratings in the grid. The intermeshing results from the redundant accommodation of the station supply. The station supply busbar is connected in parallel to the 110 kV grid over the transformers 00BBT01 and 21BAT(2). A FCL could be installed in the connection to the new plant installation to reduce this problem. For the calculation the FCL is switched in the current path on the overvoltage side of the station supply transformer 21BAT(2), because this part delivers the greatest contribution to the short-circuit current (ref. Fig. 4) compared to transformer 00BBT01.

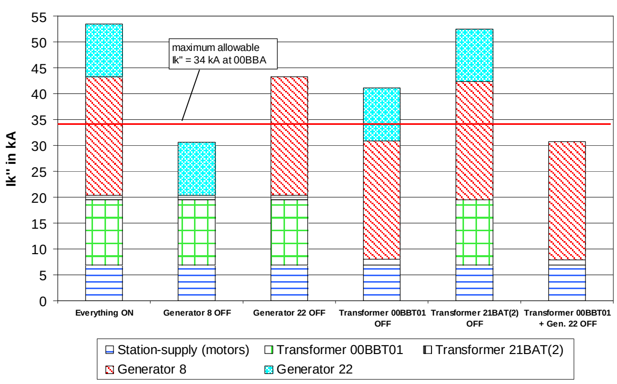

Fig. 5. Initial short-circuit current I_k'' on the 6 kV station supply busbar in the expanded grid. Different switching states are shown.

Fig. 5 shows the results of the calculation. Due to the FCL in the connection of the new installation, the limited part in this situation contributes only 1 kA to the initial short-circuit current on the station supply busbar. This way, an acceptable operating condition without generator 8 can be achieved. The operation with both generators on the station supply busbar at the same time is still not possible. But with a FCL in this configuration the use of generator 8 without exceeding the acceptable short-circuit current is possible for the first time. The expansion of the plant installation would be possible without generator 22. But the busbar is still not short-circuit proof if the transformer 00BBT01 and generator 8 are operating. This operating condition seems not to be required, because the transformer only has to be used as an emergency accommodation. But, in this case the busbar is not short-circuit proof, therefore this situation is not entirely satisfyingly.

E. FCL in the old busbar of the station supply

A possibility to assure the short-circuit strength of both, the established and the new installation, is the construction of the established 6 kV station supply busbar (00BBA) in the cogeneration plant, since it is constructed as redundant system. If the two identical busbars are connected permanently by a FCL, the equipment that contribute to the short-circuit current could be split to the two parts of the resulting busbar. During normal operation the superconducting FCL has no influence on the busbar. But in case of a short-circuit on one of the sides, it limits the short-circuit current the other side of the busbar respectively.

The segmentation of the connected equipment should be symmetrically in respect of it's short-circuit rating to minimize the short-circuit currents on both sides. One possible configuration (including the expanded grid), which is also the base for the calculations in this work is shown in Fig 6. All asynchronous motors and one transformer were connected to the right side and generator 8 was connected to the left side together with the second transformer because of the great participation of generator 8 to the short-circuit current. For the expanded grid was the new generator 22 also connected to the right side.

In Fig. 7 are the results of the calculation for both halves of the busbar shown separately. The first four of the columns in this figure apply to the switching status in the actual grid. It can be recognized that, in spite of the high short-circuit rating of generator 8 the assessment threshold is maintained on the left half. A short-circuit proof operating would be possible in all switching states.

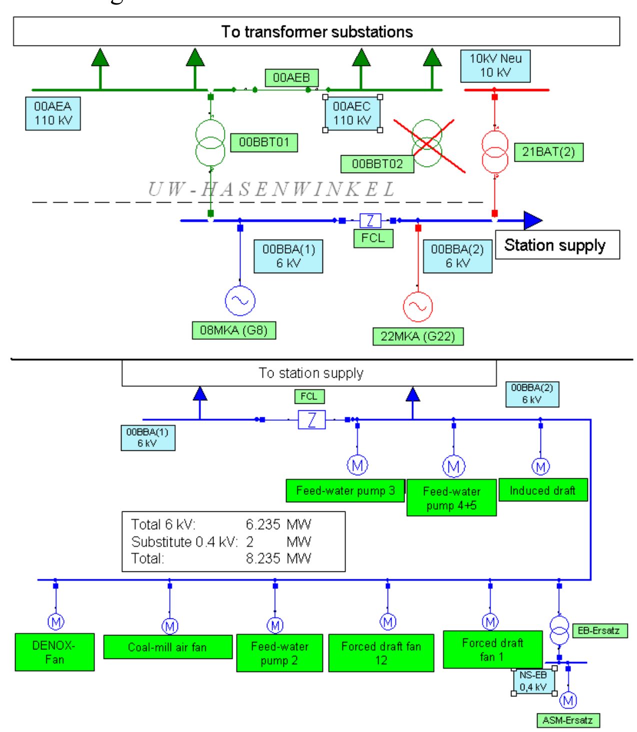

Fig. 6. Possible segmentation of the 6 kV station supply busbar. Connection of the feeding (up, just relevant parts are displayed) and the motors in the station supply (down).

Even with regard to the expanded grid it is nearly possible to obtain an acceptable short-circuit current by the segmentation of the busbar and thus the short-circuit power. I_k'' will not be exceeded about more than 2.5 kA on the left half and not about more than 0.6 kA on the right half. It has to be examined in the course of the detailed planning of a possible integration of a FCL, to what extent an exceeding of the maximum short-circuit current of the busbar is maintainable.

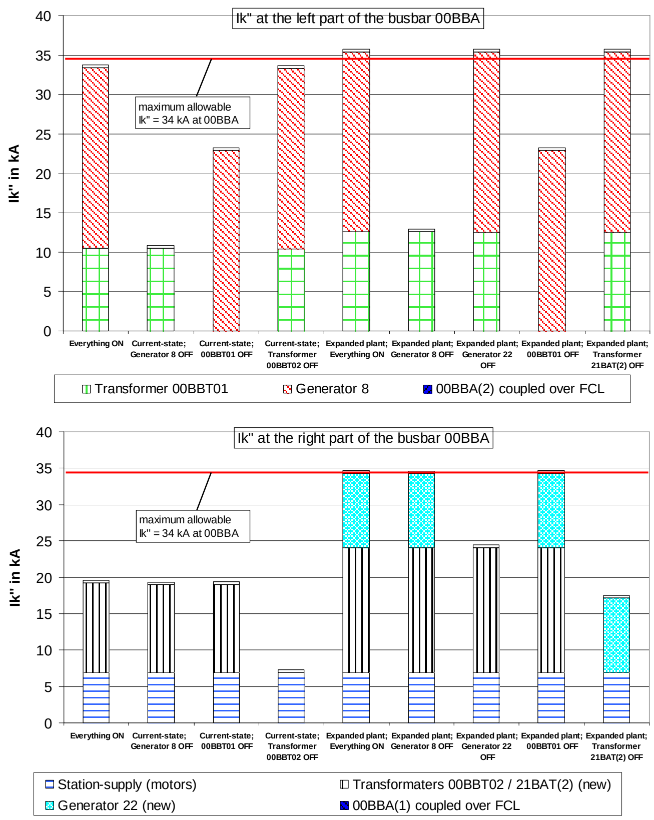

Fig. 7. Initial short-circuit current I_k'' on the two 6 kV station supply busbars (linked by a FCL) in the actual and expanded grid

Additionally, the short-circuit current could be reduced a bit by a slightly modified construction of the new generator 22, whose operating data for this work is based on assumptions.

IV. Conclusion

The calculations have shown that the use of a superconducting fault current limiter in the considered station supply grid of a cogeneration plant can restore the already endangered short-circuit reliability. Furthermore, even new installations with additional feed-in or short-circuit ratings can get connected to the established infrastructure without the need for additional investments. This is possible, because the regarded station supply busbar is constructed as a redundant system, thus a segmentation of the short-circuit rating with following coupling over a FCL is possible. None of the alternatively calculated variants without segmentation of the busbar would allow the connection of all equipment to the grid without exceeding the maximum short-circuit current.

A. *Framework of this work*

The reasonable use of a superconducting fault current limiter depends significantly on the technical and economical framework of every individual case. Some aspects are discussed, that interacts significantly.

For the planned expansion and even for the actual operating condition, a strengthening of the short-circuit strength oft station supply is essential. Especially the high short-circuit rating of generator 8 has a major impact on the high short-circuit currents on the station supply busbar. Because a high efficiency of the installed equipment to the energy production is aspired, the achievement of the short-circuit strength just under the condition that generator 8 is turned off, is no alternative. This restricts the possibilities to limit the short circuit current of the busbar by preventing possible equipment switching statuses. Additionally there have to be always at least two channels of supply conducted in parallel to the station supply, because of reliability reasons. Now the limitation of the short-circuit current by a FCL between the generator 8 and the busbar or in the connection to one of the transformers that feed the station supply could be regarded. This would stabilize the actual handling but would have no effect on the expanded grid. Therefore this possibility was not examined any further.

The alternative to the use of a current limiter is an reconstruction investment – a replacement of the busbar and all related circuit breakers. Besides the high costs for the necessary high-power equipment this would mean a large constructions works and a long downtime of the power plant, with the corresponding costs. Perhaps even other installations would have to be renewed in this process.

Therefore a segmentation of the station supply grid seems to be the best solution to limit the short-circuit current. This could also be done without a superconducting FCL by coupling the resulting grid groups on a higher voltage level by the two existing transformers (00BBT01 and 00BBT02). But there the redundancy would get lost for faults, because in the case of a breakdown of one of the transformers, the affected grid part could not be supplied anymore. Additionally the transformers would impair the energy balance via their losses and would generate additional costs thereby.

B. *Operating characteristics of the FCL*

The operational losses and characteristics of superconducting fault current limiters are already discussed in other works (e.g. [9], [10] and [11]).

C. *Prospects*

In the considered grid the superconducting fault current limiter is an interesting possibility, to solve the problem of the too high short-circuit currents on the station supply busbar. Beside the often mentioned fields of application, e.g. the grid coupling in the high voltage range, the expansion of established installations or the subsequent improvement of the short-circuit strength in existing grid structures are interesting fields of application for a superconducting current limiters, even in the medium voltage range. However, it is not possible to make a general statement of the economic efficiency of a FCL. The alternatives have to be analyzed in every individual case. Generally it can be concluded, if the alternatives to a FCL generate high costs or need long time spans to implement, a superconductive fault current limiter can be a technical and economical reasonable solution.

V. Acknowledgment

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VI. References

[1] M. Noe, M.Steurer, *High-temperature superconductor fault current limiters: concepts, applications and development status.* Supercond. Sci. Technol. 20 (2007) R15–R29

[2] P.Komarek, *Hochstromanwendung der Supraleitung.* Stuttgart: Teubner, 1995.

[3] M. Lindmayer; J. Grundmann, *Hochtemperatur-Supraleiter in Betriebsmitteln der elektrischen Energietechnik: Stand der Forschung.* ETG-Tagung Technische Innovationen in Verteilnetzen. Wuerzburg, 01.-02.03.2005

[4] P. Behrens, *Der supraleitende Strombegrenzer als Schutzgerät in Verteilungsnetzen.* Berlin, Offenbach: VDE-Verlag, 2004.

[5] EN 60909-0 (IEC60909-0): *Short-circuit current calculation in three-phase a. c. systems*; 2003.

[6] IEC Report 60909-1: *Short-circuit current calculation in three-phase a. c. systems – Part 1: Factors for the calculation of short-circuit currents in threephase a. c. systems according to IEC 60909-0,2003,* IEC 60909-0; 2003.

[7] H. Jordan, *Asynchronmaschinen: Funktion, Theorie und Technisches*, Vieweg Verlag Braunschweig. 1975.

[8] G. Funk, *Der Kurzschluß im Drehstromnetz,* München: R. Oldenburg Verlag, 1962.

[9] R. Kreutz; *et al. System Technology and Test of CURL 10, a 10 kV, 10 MVA Resestive High-Tc Superconducting Fault Current Limiter*, IEEE Transactions on Applied Superconductivity Jg. 15 (2005), Nr.2, S. 1961-1964.

[10] H. Frey; R. Haefer: *Tieftemperaturtechnologie,* Düsseldorf: VDI-Verlag, 1981.

[11] H-P. Kraemer *et al. Test of a 2 MVA medium voltage HTS fault current limiter module made of YBCO coated conductors,* Journal of Physics: Conference Series 97 (2008)

[12] BCP Busarello + Cott + Partner AG, *NEPLAN Electricity - Analysis tool for electrical networks*; Bahnhofstrasse 40, CH-8703 Erlenbach, Switzerland, www.neplan.ch