Application of resistive high temperature superconducting fault current limiters in power-station service plant

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Abstract: - In this work the application of resistive HTS fault current limiters is examined in the voltage levels 10 kV, 0,69 kV and 0,40 kV of power-station service plant for power station units with generators of high rated power. Within this task the following goal-positions were pursued: On the one hand, the clearly reduced thermal and dynamic stresses as well as arcing fault stresses should lead to cost savings in the rating of switchgears and electrical equipment and to improvement of operator protection and switchgear protection. On the other hand, the use of previous conventional protection technique generally still should be possible.

The work illustrates that the fault current limitation must be treated as complex task of a coordinated system configuration. The technical evidence, that the application of HTS fault current limiters with bulk material is possible in power-station service plants was provided.

Key-Words: HTS fault current limiter, fault current limitation, superconductivity, power station service plant, arcing fault stress, current limitation factor, cost saving potential

1 Introduction

The discovery of high-temperature superconductors in the eighties has been leaded to worldwide intensive research about the further development of materials and their application in the field of electrical power engineering. The development of high-temperature superconducting (HTS) fault current limiters has a significant relevance. The heavy dynamic, thermal and arcing fault stresses, which will increase in the future by applying transformers of higher capacity, require the consideration of fault current limitation. HTS current limiters are therefore nearly perfect appliances, because they meet the requirements regarding very low impedance under normal operation and a high impedance under fault. Their mode of operation is based on the sudden changeover from superconductivity to normal conducting state. Thus a fast limitation of short-circuit currents before the first peak occurs. The cost pressure, which will last further on, requires simplifications in planning service plants of new power stations to be built, preserving the reliability and availability as far as possible. This subject matter becomes important due to the fact, that in the near future a certain number of new power plants has to be built. Hence it is a promising matter to examine the application of resistive HTS fault current limiters in service plants of power stations with high capacity, which is shown in this paper.

2 Short-circuit currents and arcing fault stresses

2.1 Short-circuit currents in the medium-voltage level

If there is to decide about the application of fault current limiters, it is to determine, which short-circuit currents occur in the grid. In connection with that it is important to know, of which motor-short-circuit currents (s.c. currents feeded from induction machines) and transformer-short-circuit currents (s.c. currents feeded from the grid by transformers) the total short-circuit current consists.

Figure 1 depicts a section of the grid of a service plant of a power station with two 800-MW-generators. In this example the main busbars A1 and B2 are switchgears, which supply induction machines of high rated power. The power of the equivalent induction machine (EM) consists of the power of the feed pump, the induced-draught fan and the forced-draught fan. The power of the equivalent induction machines connected to the low-voltage level is 50% of the infeeding transformer rated power. The coupling of two main busbars is to be taken into consideration.

In Figure 1 the maximum three-phase short-circuit currents are shown for a fault at main busbar A1:

initial short-circuit currents I_k''

peak short-circuit currents i_p

They were calculated according to the German VDE-standard [1] with short-circuit begin at voltage zero.

The total short-circuit currents in Figure 1 require the application of switchgears with the following parameters:

rated peak short-circuit current
I_{pk} = 125 kA

rated short-time withstand current
$I_{cw(1s)}$ = 50 kA

rated short-circuit breaking capacity
I_{ar} = 50 kA

The following conclusions can be drawn from the example:

- The short-circuit currents feeded by the transformers are significantly determined by the transformer parameters.

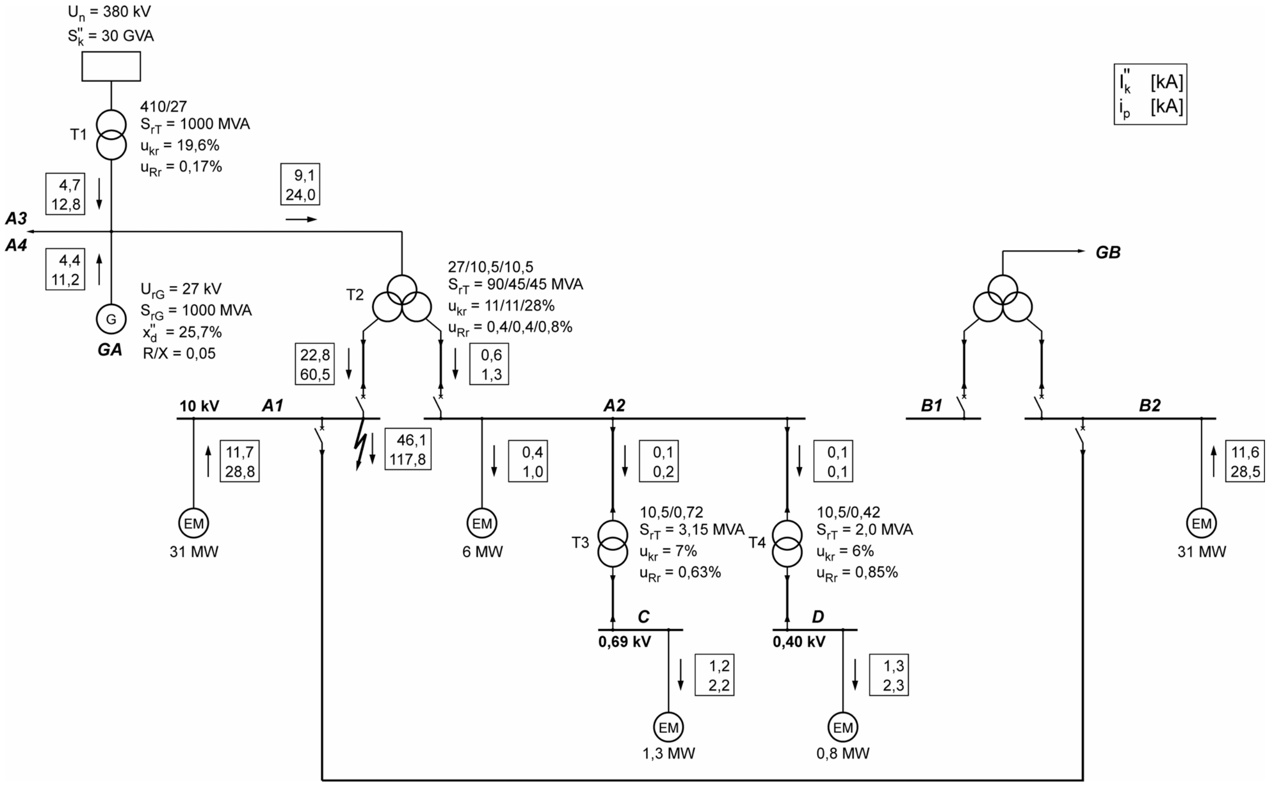

Figure 1: Grid of a power station service plant
Short-circuit at main busbar A1

The partial short-circuit currents are summed up at short-circuit location:

$$I_k'' = I_{kN}'' + I_{kM}'' \tag{1}$$

$$i_p = i_{pN} + i_{pM} \tag{2}$$

The short-circuit currents I_{kN}'' and i_{pN} contain the motor-short-circuit currents from main busbar A2 (including the low-voltage motors).

- The short-circuit currents from induction machines conducted over a transformer can be neglected.
- With an increasing number of low-voltage induction machines they make a contribution to the total short-circuit current, which is not negligible.
- In dependency of the grid topology the total motor short-circuit currents can reach or even exceed the transformer short-circuit currents.

2.2 Short-circuit currents in the low-voltage level

The influence of the 10-kV-induction machines on the short-circuit currents in the low-voltage level is very weak. Therefore only the induction machines connected to the low-voltage bar with the fault contribute to the total short-circuit current (Figure 2).

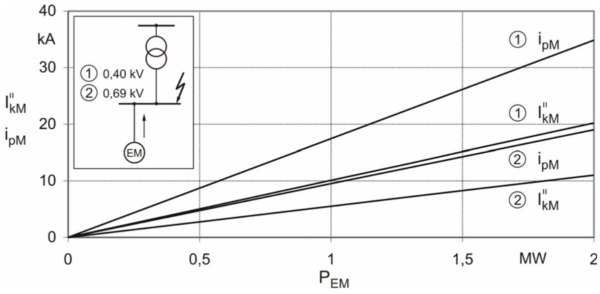

Figure 2: Motor-short-circuit current vs. power of the equivalent motor

The transformer short-circuit currents are primarily determined by the rated power of the infeeding transformers (Figure 3).

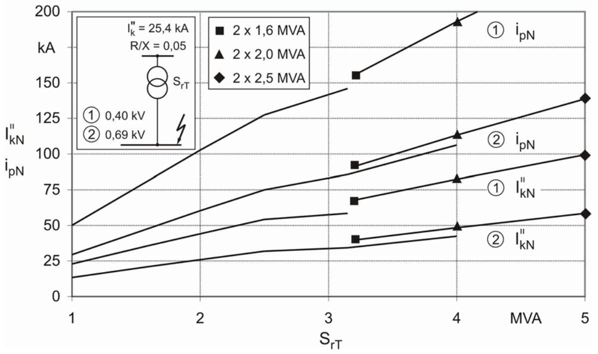

Figure 3: Short-circuit currents vs. transformer rated power

2.3 Arcing fault stresses

The arcing fault stresses are decisive for the design and structuring of the switchgears. With the short-circuit currents from Figure 3 the range of possible arc powers in low-voltage switchgears can be calculated in dependency of the transformer rated power (Figure 4).

The arc power in medium-voltage switchgears is mostly higher than in low-voltage switchgears. For a fault at main busbar A1 in Figure 1 an arc power in the range of $P_B = (40 \ldots 64)$ MW occurs. Therein the motor-short-circuit currents are not considered.

For the switchgear stress the arc energy

$$W_B = P_B \cdot t_{ag} \tag{3}$$

is decisive. For their determination only the transformer-short-circuit currents have to be considered. The fast decaying motor-short-circuit currents make only a negligible contribution.

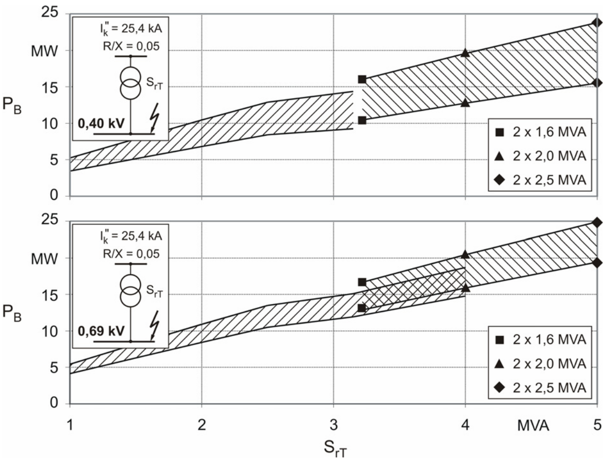

Figure 4: Arc power vs. transformer rated power

Permissible arc energies are [2]:

operator protection $W_B \leq 250$ kWs

switchgear protection $W_B \leq 100$ kWs

To obtain those arc energies, the total fault duration (total arc duration) should be in the range of milliseconds which is impossible with conventional switching and protective devices (Figure 5). For that reason the switchgears are completely encapsulated. This outer enclosure has to resist the very high pressures due to the arc and to avoid, that no flames and toxic gases come out.

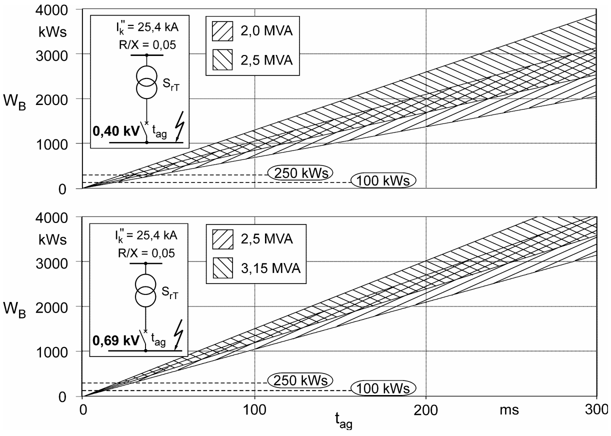

Figure 5: Arc energy vs. total fault duration

3 Goal of the current limitation

The application of HTS current limiters strives for the following goals:

- The limited short-circuit currents permit further on the application of conventional protective devices.
- The arc energy will be lessened to innocuous values for operators and switchgears.
- The reduced stresses under-run the lowest commercially available short-circuit withstand capability of appliances and switchgears.
- The total costs for appliances and switchgears in the power-station service plant with short-circuit limitation will be reduced to approximately 90% of these costs without current limitation.

It is not the goal to decrease the thermal and dynamic stresses as much as possible, because the selective protection then would not be applicable.

4 Installation locations

The lowest quantity of HTS current limiters will be required, when the limiters are applied in the infeed of the switchgears. A current limiter (CL) at location E1 (Figure 6) has to cover all fault locations in the whole 10-kV-grid, including the substations. The effective range should also include inner faults in the transformers T3 and T4 and in motors. The current limiter in E1 should not response to fault currents in the low-voltage level.

For the limitation of short-circuit currents in the low-voltage level the installation locations E2 and E3 can be taken into consideration. For installation location E2 lower rated currents are advantageous, but the transformer inrush currents must not trip the limitation process. Besides the transformation of the limiter resistance with the vector group Dy5 of the transformer at asymmetric faults has to be particularly considered. The effective range in the low-voltage level strongly depends on the length of the cable connections and there on their impedances.

A limitation of motor-short-circuit currents is inapplicable because this requires a current limiter in every motor branch. The dynamic and thermal stresses due to these currents have to be accepted. According to Figure 6 motor-short-circuit currents will be inevitably limited when using installation location E2 and faults in the transformer branch occur.

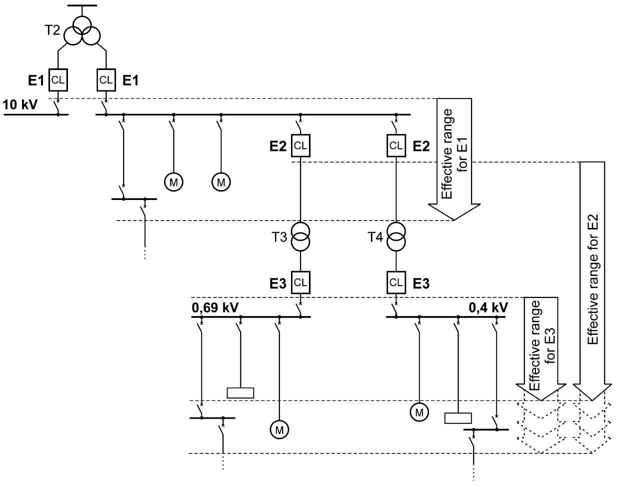

Figure 6: Installation locations for HTS current limiters

5 Demands on the limitation for protection technique purposes

For the determination of the limited short-circuit currents the maximum operating currents are the basis:

- The subtransient motor starting currents i_{AM} must not exceed the critical current of the HTS current limiter in principle. A slight, short-time exceeding will be tolerated by HTS current limiters made of bulk material.
- The quasi-stationary motor starting currents I_{AM} must not exceed the threshold of the short-circuit protection device.

$$I_{bmax} \le i_c \tag{4}$$

$$I_{bmax} \le \frac{1}{s_n} \cdot I_{EK} \tag{5}$$

i_{bmax}	peak value of the maximum operating current inclusive subtransient motor starting current
i_c	critical current of the HTS current limiter
I_{bmax}	maximum operating current (RMS value) inclusive quasi-stationary motor starting current
I_{EK}	threshold of the short-time delayed protection device
s_n	safety factor for non-tripping

The determination of i_{bmax} and I_{bmax} is shown in Figure 7 and equations (6) and (7).

$$i_{bmax} = \sqrt{2}\cdot\left(\sum_{n=1}^{n=m-1} I_{rM}^{(n)} + \sum_{n=1}^{n=t} I_{rT}^{(n)}\right) + i_{AM}^{(m)} \tag{6}$$

$$I_{bmax} = \sum_{n=1}^{n=m-1} I_{rM}^{(n)} + \sum_{n=1}^{n=t} I_{rT}^{(n)} + I_{AM}^{(m)} \tag{7}$$

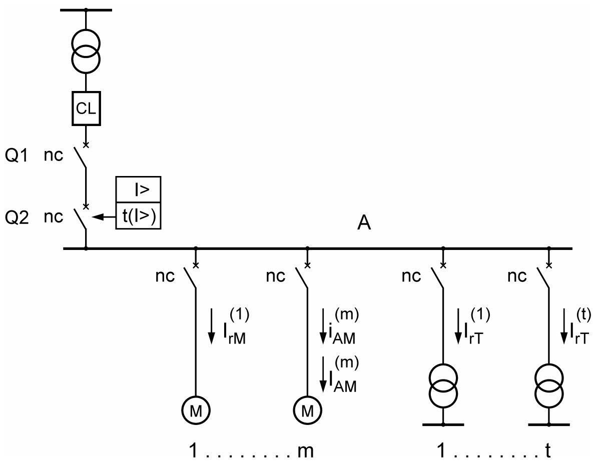

Figure 7: Determination of the maximum operating current

It is to be assumed, that all outgoing feeders except the motor m, which is starting-up, are in operation. Motor m has the highest subtransient and quasi-stationary starting current. The minimum limited short-circuit current has, under consideration of a safety factor, to be higher than the threshold of the selective protection function at circuit breaker Q2 (Figure 7).

$$I_{kNCLmin} \geq s \cdot I_{EK} \tag{8}$$

s safety factor for tripping

As the maximum limited short-circuit current is decisive for the decrease of stresses, the ratio

$$f = \frac{I_{kNCLmax}}{I_{kNCLmin}} \tag{9}$$

is to determine. The limited short-circuit currents are subscripted as follows:

CL	current limiter
N	short-circuit feeded by the transformer conducted via the current limiter

The factor f depends on the place of installation of the HTS current limiter (Table 1).

With the above mentioned equations the maximum short-circuit current, which is required for protection purposes, is calculated to

$$I_{kNCLmax} = f \cdot s_n \cdot s \cdot I_{bmax} \tag{10}$$

Place of installation	**max. s.c. current**	**min. s.c. current**	**f**
E1 , E3	three-phase s.c. ($R_{ME} \rightarrow \infty$)	line-to-line fault	1,28
E2	two-line-to-ground s.c.	line-to-line fault	2,2

Table 1: Ratio of maximum to minimum short-circuit current

With equation (10) the following values for $I_{kNCLmax}$ can be calculated (Table 2).

U_n [kV]	10	0,69	0,40
$I_{kNCLmax}$ [kA]	7,0	7,9	7,7

Table 2: Maximum limited short-circuit currents

6 Demands on the limitation for reduced stresses purposes

As mentioned above, it is the goal to reduce the thermal and dynamic stresses below the lowest commercially available short-circuit withstand capability of appliances and switchgears. For this purpose

- the thermal arc stresses of switchgears and
- the thermal and dynamic stresses of cables, switchgear units, transformers, medium-voltage circuit breakers, low-voltage circuit breakers (air circuit breakers and moulded-case circuit breakers)

were examined. In the following the procedure of determination the current limitation factors for the reduction of arc energy is shown. In Figure 8 and 9 the calculated limited short-circuit currents are diagramed versus the total fault duration with the parameter arc energy.

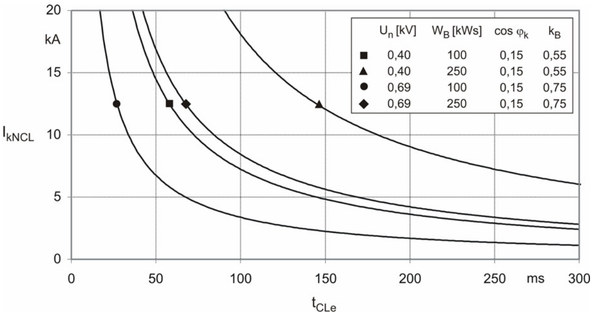

Figure 8: Limited short-circuit currents vs. total fault duration
nominal voltage 0,40 kV and 0,69 kV

The calculations were carried out by means of the linear arc model. Thereby unfavourable assumptions, e.g. maximum arc current limitation factors and a constant limited short-circuit current were taken into consideration.

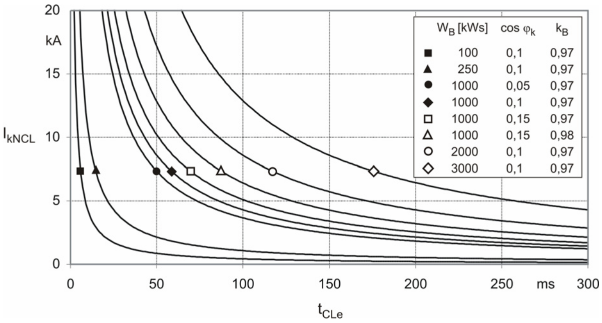

Figure 9: Limited short-circuit currents vs.
total fault duration
nominal voltage 10 kV

If the total fault duration, which is dependent on the protection concept, is specified to $t_{CLe} = 100$ ms and with respect to the limited short-circuit currents in Table 2, the following conclusions regarding the

- operator protection
  (permissible arc energy $W_B = 250$ kWs)
- switchgear protection
  (permissible arc energy $W_B = 100$ kWs)

are obvious from Figure 8 and 9:

- The requirements can be meet for 0,69-kV- and 0,40-kV-switchgears. The required short-circuit current limitation is realistic.
- For the 10-kV-switchgears the short-circuit currents have to be limited to such low values, which do not permit the application of conventional protective devices. Hence an arc energy of $W_B = 1000$ kWs is realistic.

7 Cost saving potentials

The cost saving potential will be shown for switchgears. The remarkable decrease of the dynamic and thermal stresses as well as the arc stresses provide perfect new possibilities for the switchgear unit design. It is the crucial point, that the arc stresses, which determined the dimensioning of switchgears so far, will become negligible. For the avoidance of arcs and the limitation of their effects a lot of additional measures had been put into practice.

There already exist suitable solutions, which meet the strong stresses and requirements. To adapt these switchgears to the clearly lower stresses seems to be not applicable, if economic effects (cost savings) are expected. Therefore the development of a completely new generation of switchgears is recommended. At the moment only a comparison with commercially available switchgears remains (Table 3).

	without CL			with CL		
U_n [kV]	10	0,69	0,40	10	0,69	0,40
I_{pk} [kA]	125	110	176	80	85	85
$I_{cw(1s)}$ [kA]	50	50	80	31,5	40	40
I_u [A]	3150	3200	4000	3150	3200	4000
I_{ar} , I_{cs} [kA]	50	50	75	20	50	75

Table 3: Parameters of commercially available
switchgears and infeeding circuit breakers

The parameters in the column “with CL” are considerably higher than required, because

- for the required rated busbar currents the natural thermal short-circuit strength and the natural peak short-circuit current withstand capability is already very high,
- high rated continuous currents I_u require only high rated service short-circuit breaking capacities I_{cs} so far.

The cost savings ΔK were calculated by means of equation (11)

$$\Delta K = \left(1 - \frac{K_{CL}}{K}\right) \cdot 100\% \qquad (11)$$

K_{CL}	costs with current limitation
K	costs without current limitation

The cost savings primarily result

- by application of circuit breakers with a rated short-circuit breaking capacity $I_{ar} = 20$ kA (medium-voltage switchgears),
- by application of circuit breakers with the lowest available rated service short-circuit breaking capacity for the respective rated continuous currents (low-voltage switchgears).

From Table 4 it is to be seen, that the cost savings for medium-voltage switchgears are higher. Taking into consideration the frequency of occurrence of switchgear units with different rated continuous currents, the enormous cost saving potential for medium-voltage switchgears becomes obvious.

U_n [kV]	10	0,69	0,40
Switchgear unit with incoming feeder			
I_u [A]	3150	3200	4000
Quantity	6	31	9
ΔK [%]	16	0	0
Basis I_{ar} [kA]	50	50	75
Switchgear unit with outgoing feeder			
I_u [A]	2000		
Quantity	8	23	22
ΔK [%]	24	5	5
I_u [A]	1250		
Quantity	10	2	5
ΔK [%]	30	4	4
I_u [A]	630		
Quantity	73	30	5
ΔK [%]	34	11	11
Basis I_{ar} [kA]	50	50	65

Table 4: Approximate values for cost savings for switchgears; 10-kV-switchgear units without protective devices

Quantity: average of switchgears in a new built power station unit

8 Conclusions

In this paper some aspects of the examination of application of resistive HTS current limiters in power-station service plants are given.

Resistive HTS current limiters have crucial technical advantages in comparison with other limiting appliances:

- HTS current limiters are inherently safe. Tripping devices with special algorithms or control units are not needed.
- By appropriate dimensioning of the HTS current limiter the desired limited short-circuit currents can be obtained. Hence conventional protective devices can be used further on.
- Only marginal overvoltages do occur during the limitation process.

The requested limitation parameters can be met by application of resistive HTS fault current limiters based on bulk material.

An essential result is, that the currently actual topic “arc withstand capability of switchgears” becomes insignificant. Besides remarkable cost savings in the field of switchgears as well as cables and their installation can be obtained for new power-station service plants, which have to be erected in the future. Taking into consideration, that until the year 2020 new power plants with a total power of approximately 40 GW have to be built, the enormous cost saving potential becomes obvious.

Impacts on the protection concept, like the detection of faults in outgoing branches or the maximum permissible fault duration of approximately $t_{CLe} = 100$ ms are not considered in this paper. They will be discussed in a future publication.

The work illustrates that the fault current limitation must be treated as complex task of a coordinated system configuration.

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