APPLICATIONS OF HTS FAULT CURRENT LIMITERS IN THE DANISH UTILITY NETWORK

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SUMMARY

The electric power utilities are continuously working on improvements of the network system, such that numerous different technological, environmental and economical requirements from authorities and customers can be satisfied. For this purpose the electric network system is redesigned and reinforced although the increase in demand for electrical power is moderate. In particular, an increasing focus on aesthetic and environmental requirements have implied that overhead lines are replaced by cables, and old high polluting power plants are renewed with more environmentally feasible production units, and production from new renewable energy sources. The challenge of the future network design will be to meet these requirements by application of new high effective technologies in the network system. The new high temperature superconducting power components represent a new generation of system components for application in the electric utility networks because these devices have an inherent capability of operating at higher power ratings while exhibiting lower losses than conventional components.

The superconducting fault current limiter (SFCL) is such a new system component with a peculiar limitation characteristic that is unknown in the conventional fault current protection scheme. It is therefore expected that an introduction of SFCL in the electric power supply system can result in considerable improvements with concern to power supply quality, voltage quality and network flexibility.

This paper discusses the results of a questionnaire survey within the Danish electric utilities. The survey describes the expectations within the Danish electric utilities regarding the application of SFCL in the Danish transmission and distribution network with concern to needs, characteristic ratings and criterions of operation.

LIMITATION CHARACTERISTICS OF THE SFCL

The fundamental property of any superconducting fault current limiter is its peculiar capability to change from one state with extremely low impedance to another state defined by substantial larger impedance. In this utility survey the current limitation characteristics of the SFCL are restricted to the activation level of the SFCL, and the limitation of the short circuit current in the first few periods after the short-circuit fault has occurred.

The limitation characteristic of the superconducting fault current limiter is expected to met the following principal specifications:

- Activation current: \( I_{\text{activation}} > 2.5 \cdot I_{\text{rated}} \)
- Limitation of the peak current value: \( I_{\text{peak}} < 10 \cdot I_{\text{rated}} \)
- Limitation value of the current in the first half period: \( I_{\text{1st half period}} < 7 \cdot I_{\text{rated}} \)
- Limitation value of the current in the succeeding periods: \( I_{\text{limitation}} < 3 \cdot I_{\text{rated}} \)

UTILITY SURVEY OF NEED AND EXPECTATIONS TO A SFCL

Based on the above mentioned SFCL specifications, the Danish electric utilities were asked for their potential need of a SFCL in the transmission (400 and 132/150 kV), medium voltage (30/50/60 kV) and distribution (10/20 kV) network with concern to:

i) Increase the interconnection of the network system
ii) Avoid subdivision of the networks in future reinforcement
iii) Reduce the present short-circuit capacity if the networks are reinforced
iv) Other applications (e.g. bus-tie applications, connection of independent power production units etc.)

Finally, the utilities were asked for:

- Their knowledge about design, functioning and applications of the SFCL
- Their future expectations to use SFCL for special purpose applications in the network

RESULTS AND CONCLUSION

The questionnaire survey within the Danish electric utilities has indicated that the most obvious areas for application of SFCL technology are identified as a 10 kV bus-tie location of a 60/10 kV transformer substation and the feeder outlet location of 132 kV and 30 kV cables. The greatest prospective application of SFCL is anticipated to occur in the 132/150 kV transmission networks in the wake of system redesign and reinforcement. The survey has also shown that the utilities have a need for more information concerning the technical performance and economy of the SFCL, before they can take specific decisions on a possible introduction of SFCL into the network system.
Introduction

The electric power utilities are continuously working on improvements of the network system, such that numerous different technological, environmental and economical requirements from authorities and customers can be satisfied. For this purpose the electric network system is redesigned and reinforced although the increase in demand for electrical power is moderate. In particular, an increasing focus on aesthetic and environmental requirements have implied that overhead lines are replaced by cables, and old high polluting power plants are renewed with more environmentally feasible production units, and production from new renewable energy sources. The challenge of the future network design will be to meet these requirements by application of new high effective technologies in the network system. The new high temperature superconducting power components represent a new generation of system components for application in the electric utility networks because these devices have an inherent capability of operating at higher power ratings while exhibiting lower losses than conventional components.

The superconducting fault current limiter (SFCL) is such a new system component with a peculiar limitation characteristic that is unknown in the conventional fault current protection scheme. It is therefore expected that an introduction of SFCL in the electric power supply system can result in considerable improvements with concern to power supply quality, voltage quality and network flexibility Noe and Oswald (1).

The application of superconducting fault current limiter in the electric utility sector will clearly be dependent on to what extend the ongoing development of SFCL technology is able to fulfil the needs and requirements of the electric utilities. Although, the SFCL represents a new system component with a very fast and effective limitation characteristic, its introduction in the utility network will be constrained by a number of utility requirements with regard to investment costs, operation costs, performance, lifetime, maintenance, second source contractors etc. In addition to these device related specifications, the SFCL must satisfy a number of basic network related requirements with concern to voltage level, load current, operating sequence, influence on the existing overload and short circuit protection scheme etc.

This paper discusses the results of a questionnaire survey within the Danish electric utilities. The survey describes the expectations within the Danish electric utility sector.

Fig. 1. Principal design and simplified electric diagram of (a) a resistive fault current limiter and (b) a screened iron core fault current limiter.
utilities regarding the application of SFCL in the Danish transmission and distribution network with concern to needs, characteristic ratings and criterions of operation.

**Limitation characteristics of the SFCL**

The fundamental property of any superconducting fault current limiter is its peculiar capability to change from one state with extremely low impedance to another state defined by substantial larger impedance. This property is in most designs (the resistive and screened-core design) of fault current limiters associated with the transition from the superconducting state to a resistive limitation state. The transition sequence is initiated when the short circuit current is exceeding a certain transition value in the \( HJ \)-plane of the superconductors \( HJT \)-space diagram (H: magnetic field strength, J: current density, T: temperature). In the resistive state, power will be dissipated in the superconductor, and dependent on heat capacity and cooling conditions, the superconductor will be heated to a certain temperature Gromoll et al (2), Paul and Chen (3). From an application point of view, it is the temperature of the superconductor that is decisive for whether the SFCL can be kept in operation after the fault has been cleared, or it has to be disconnected until the superconductor has cooled down and regained its superconducting state. Two designs known as the Lockheed Martin HTS inductive/electronic current controller and the saturated iron-core FCL provide a limitation impedance, even though the superconductor remains superconducting during the fault Leung (4). Therefore, these devices do not have recovery time.

At present it is not clear which one of the designs the first commercial available SFCL will be based on. Therefore, only some few principal parameters can be used to evaluate its application potential. In this utility survey the current limitation characteristics of the SFCL are restricted to the activation level of the SFCL, and the limitation of the short circuit current in the first few periods after the short-circuit fault has occurred.

The limitation characteristic of the superconducting fault current limiter is expected to meet the following principal specifications:

- Activation current: \( I_{activation} > 2.5 \cdot I_{rated} \)
- Limitation of the peak current value: \( I_{peak} < 10 \cdot I_{rated} \)
- Limitation value of the current in the first half period: \( I_{1 \text{st half period}} < 7 \cdot I_{rated} \)
- Limitation value of the current in the succeeding periods: \( I_{limitation} < 3 \cdot I_{rated} \)

**Utility survey of need and expectations to a SFCL**

Based on the above mentioned SFCL specifications, the Danish electric utilities were asked for their potential need of a SFCL in the transmission (400 and 132/150 kV), medium voltage (30/50/60 kV) and distribution (10/20 kV) network with concern to:

i) Increase the interconnection of the network system
ii) Avoid subdivision of the networks in future reinforcement
iii) Reduce the present short-circuit capacity if the networks are reinforced
iv) Other applications (e.g. bus-tie applications, connection of independent power production units etc.)

Further, the utilities were asked which investment cost they will find acceptable for a SFCL indicated in relation to the price for conventional relay and breaking equipment.

Finally, the utilities were asked for:

- Their knowledge about design, functioning and applications of the SFCL
- Their future expectations to use SFCL for special purpose applications in the network

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![SFCL limitation characteristic](image)

**Fig. 2. Illustrative limitation curve of the superconducting fault current limiter.**
Results of the questionnaire survey

The questionnaire was forwarded to the entire Danish electric utility sector. The response from the 5 utilities operating the 400 and 150/132 kV transmissions network was 100 %. The number of response from the operators of the medium voltage network and distribution utilities were 8 (62 %) and 29 (33 %), respectively. Although, the response from the distribution utilities was limited to 33 %, the respondents represent more than 50 % of the Danish electric power consumption. In addition, it should be mentioned that the replies from some of the distribution utilities are rather insufficiently completed.

The operators of the transmission grid indicated that the dimensional short circuit current value (transient and breaking value) for new 400/150/132 kV equipment is 100/40 kA. At 400 kV, none of the utilities have problems with the present level of short circuit current, and they do not expect application of SFCL in the 400 kV network system. Consequently, only the responses of the survey related to the 150/132 kV, 60/50/30 kV and 20/10 kV networks are of relevance for an estimation of the prospective application of SFCL.

The responses from the utility survey with concern to the possible applications of SFCL in the 150/132 kV, 60/50/30 kV and 20/10 kV networks are shown in Table1.

From the table, it is seen that 40 % of the respondents indicated that a SFCL is an applicable solution for larger interconnection of the 150/132 kV network and 80 % find SFCL is applicable for avoiding subdivision in case of reinforcement of the network. All the respondents find that SFCL can be a usable solution for reducing the present short circuit power of the 150/132 kV network in case of reinforcement. About 40 % find that SFCL is an alternative to the conventional use of air core reactors, enlarged impedance of the transformers and in the protection scheme of independent power production units etc. Only one utility has responded on the question which price is acceptable for a SFCL (132 kV unit), and gives an estimate at twice the price of conventional breaking equipment.

The majority (more than 80 %) of all respondents find that they need more information about the design, functioning and applications of SFCL.

The utilities were finally asked about their future expectations to the use of SFCL when it becomes commercial available. In the 150/132 kV system, all the utilities indicated that they expect a prospective application of SFCL for special purposes in the future.

<table>
<thead>
<tr>
<th>Possible applications of SFCL for:</th>
<th>150/132 kV transmission network</th>
<th>60/50/30 kV medium voltage network</th>
<th>20/10 kV distribution network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of utilities</td>
<td>5</td>
<td>13</td>
<td>87</td>
</tr>
<tr>
<td>Usable respondents</td>
<td>5</td>
<td>8</td>
<td>29</td>
</tr>
<tr>
<td>Dimensional short-circuit current value</td>
<td>100/40 kA</td>
<td>100/40 - 63/25 kA</td>
<td>100/40 - 40/16 kA</td>
</tr>
<tr>
<td>Increase the interconnection</td>
<td>40 %</td>
<td>50 %</td>
<td>25 %</td>
</tr>
<tr>
<td>Avoiding subdivision</td>
<td>80 %</td>
<td>35 %</td>
<td>15 %</td>
</tr>
<tr>
<td>Reduce the present short-circuit power</td>
<td>100 %</td>
<td>25 %</td>
<td>30 %</td>
</tr>
<tr>
<td>Other applications</td>
<td>40 %</td>
<td>60 %</td>
<td>35 %</td>
</tr>
<tr>
<td>Acceptable initial cost of SFCL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of respondents</td>
<td>1</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Estimated price factor</td>
<td>2</td>
<td>1 - 3</td>
<td>1 - 3</td>
</tr>
<tr>
<td>Knowledge of the SFCL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>More information needed</td>
<td>80 %</td>
<td>90 %</td>
<td>95 %</td>
</tr>
<tr>
<td>Knowledge of the application of SFCL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>More information needed</td>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
</tr>
<tr>
<td>Prospective application of SFCL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SFCL is usable</td>
<td>100 %</td>
<td>60 %</td>
<td>55 %</td>
</tr>
</tbody>
</table>

Table 1. Applications, estimated acceptable price and expectations to the SFCL.
network. At the medium and distribution voltage level, the responses were 60 and 55% to that question.

Although, the utility survey has shown that the most obviously need for a SFCL is in the 150/132 kV transmission network, the application potential in the present network is presumably rather limited. As already mentioned, the short circuit level is kept at the dimensional value by a suitable subdivision of the network or by increasing the short circuit impedance of the network. The increased impedance is obtained either by use of transformers with enlarged impedance or by use of air-core reactors, installed as series reactance in the transmission cables. The disadvantages of these solutions are the voltage drop and the power losses in normal operation. Therefore, if SFCL is to be used instead of air core reactors, it is the current ratings of the transmission cables, which will set the normal and overload current ratings of the SFCL. Consequently, the specifications for a 150/132 kV SFCL will be a normal operation current between 200 and 500 A and a maximum load value ranging from 400 to 1000 A.

The corresponding specifications for a 30 kV SFCL which can substitute the air core series reactors in the 30 kV cables will be a normal load current at around 200 A with a variation of the maximum ratings between 400 to 1000 A.

However, the operation specifications for the SFCL are influenced by the voltage level and location in question, it is seen that the typical ratings of the normal and overload currents of the SFCL for the considered applications are 200 to 500 A and 400 to 1000 A, respectively.

In the case, where the device is installed in series with a cable the requirement to multi-operations is less restrictive than the corresponding application in an overhead transmission line. In contrast, an application where the SFCL is installed between the power generator and the generator transformer, the multi-operation demand is nearly indispensable. Nevertheless, and despite the application and location it will always be an advantage that the SFCL is multi-operationnal.

**Conclusion**

The needs and expectations of the Danish electric utilities with concern to the prospective application potential of superconducting fault current limiter in the existing Danish electric utility system have been investigated by a questionnaire survey. In the present power supply network, the most obvious areas for application of SFCL technology are identified as a 10 kV bus-tie location of a 60/10 kV transformer substation and the feeder outlet location of 132 kV and 30 kV cables. The greatest prospective application of SFCL is anticipated to occur in the 132/150 kV transmission networks in the wake of system redesign and reinforcement. The survey has also shown that the utilities have a need for more information concerning the technical performance and economy of the SFCL, before they can take specific decisions on a possible introduction of SFCL into the network system.

**References**


