NETWORK PLANNING APPROACH WITH RESPECT TO AN EFFECTIVE INTEGRATION OF SUPER CONDUCTING CABLE LINES IN DISTRIBUTION GRIDS

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ABSTRACT

Recent projects show the practical capability of super conducting cables (SCC) in real distributions grids. In terms of grid modifications, refurbishment of substations or the supply of large industrial consumers SCC can be taken into account and play possibly an important role. The problem is to find out a proper grid structure with SCC to achieve real technical and economic benefits. In this paper new planning criteria and methods with respect to an optimal utilization of SCC in distribution grids were found and applied to real example networks. The key issue was the holistic planning approach. This comprised several planning steps as grid analysis, load estimation, state determination of existing grid devices and strategic planning methods. The results showed cases of a beneficial and less beneficial SCC applications which could be found out by the presented method depending on the prevailing circumstances of the grid.

INTRODUCTION

Current projects like "AmpaCity" in Germany [1, 2] and ongoing research activities on the field of super conducting cables (SCC) encourage considerations to find out possibilities of optimization of large city networks by super conducting technology [3]. The application of SCC in city networks promise the partial or fully resignation of 110-kV-substations, 110/10-kV-transformers as well as 110-kV-cables. During necessary structural adjustments, refurbishments of old substations or the supply of large customers, the application of SCC should be taken into account and possibly it can play an important role in the future. Nevertheless, to achieve real technical and economic benefits a comprehensive network planning approach has to be applied as described in the following.

The main goal is to work out the necessary planning criteria and methods as well as network structures with respect to an optimized SCC application. In addition special guidelines and recommendations are proposed.
Firstly the present paper identifies the network functions which can be taken over by SCC prospectively. Based on that, an advanced network planning approach which leads to real technical and economic benefits is introduced. Different network planning concepts of large cities applying SCC are presented and discussed. In particular different geo- and topographic conditions of large cities will be considered in this network planning process. Beyond that findings of long-term planning are the basis of short- or medium-term measures of SCC application.
Additionally the presented planning concept can be a motivation for further work on this field focused on the issues of power utilities.
In the following, the 110-kV voltage level represents exemplary the subtransmission system in Germany. The results can be transferred to other subtransmission voltage levels worldwide as well.

FRAMEWORK OF CITY NETWORK UTILITIES

The development of the large city electrification went along with the fast dispersion and steady increase of the installed loads. The securing of the supply of all customers required high scientific and technical pioneering spirit from the beginning.
At an early stage the utilization of high voltage substations and cables became necessary to ensure reliable supply of large cities. The utilization of new equipment was associated with high costs and numerous lessons learned (e.g. SF6-equipment). Nevertheless the experience shows that technical innovations induced beneficial progress in many aspects.

Also nowadays further technical advancements in large and upcoming megacities are indispensable. Different problems can be addressed as the followings:

- strong load increase in megacities
- supply of large industrial consumer loads of around 40 MVA
- infeed of renewables
- e-mobility
- refurbishment strategies of existing installations

The answers on these problems lead to the need of further installation areas, high voltage cables (e.g. 110-kV-cables), long installation periods and high installation costs. For example a forced slight movement of substations out of the optimized location implicates numerous and expensive relocations of medium voltage cables. Also the pure replacement of existing installations, to ensure the supply reliability, is affiliated with significant problems. The slogan "never change a

running system" is not valid anymore in this case.
This results to following requests on new technologies to be applied:

- downsizing of equipment and installations (miniaturization)
- increase of the load capacity and flexibility of power system devices
- minimization of losses and environmental impacts (e.g. EMC)
- advanced operating behavior

SCC-applications open important possibilities to cover the stated requests beneficial.

NETWORK PLANNING APPROACH

The key questions to be answered during the planning process are: Does the general 1:1-replacement of all 110-kV-equipment by 10-kV-SC-equipment make sense and which planning methods are necessary for a SCC application?

The results of investigation have shown that a selective network consideration - even in very simple cases - will not lead to a proper solution for SCC applications. The achievement of technical and economic benefits requires an overall view on the network structure and possibly to find out a new network architecture.

City Network Architecture

The common architecture of large city networks is characterized as follows. The electrical power will be mainly supplied by HV- or EHV-lines form outside the city which should be retained as well as the coupling HV- or EHV-substations. The power transfer inside large cities is provided by 110- and 380-kV-equipment. During increasing loads new 110- or 380-kV-cables will be installed. The power distribution is arranged by 110/MV-kV-substations. The load of one substation refers to 30 to 50 MVA. The limitation is caused by the limited transmission capacity of the outgoing MV-cables.
The motivation for 10-kV SCC installation can be the supply of new consumers up to 40 MVA instead of new installation of a 110/MV-substation and 110-kV-cables. Further the refurbishment of an existing 110-kV-substation or cable can be avoided by a 10-kV-SCC installation as well as new necessary installations of 380-kV-cables by 110-kV-SCC systems.

Reliability Criteria and SCC Technology Issues

The SCC application requires considerations regarding the reliability of supply. The (n-1)-criterion will be kept in any case of planning approach. This implies the technically capability of SCC to maintain a parallel cable operation as well as sudden changes from 50%-loading to 100% nominal load in case of cable failures. Super conducting cables imply a short-circuit current limitation facility. Consequently the infeed of SCC will not increase the short-circuit current level at the consumer network. Thus there can be expected rather problems in terms of protection relay pick-up issues as the exceeding of the permissible short-circuit capacity.
The investigations have assumed that the state of the art of SCC technology in terms of reliability and economy corresponds already to the existing conventional equipment [1, 2]. SCC installations with a rated loading of 40 MVA are already in practical test operation [1]. The maximum 10-kV-SCC length, assumed in this paper, was between 4 and 5 km. The rated loading of 110-kV-SCC can be expected as 400 MVA [3]. It is assumed that SCC will be available for real practical application during the next years.
If a higher permissible loading of SCC is available in the future, the network planning concepts would get further structural degrees of freedom.
Up to now the SCC equipment is not standardized. This leads to different possible solutions. These have to be worked out and contrasted with each other. Nevertheless a standardization of SCC equipment is absolutely necessary for a wide and efficient application in power utilities in the future.

Workflow

The workflow of the proposed network planning approach contains several working steps:

- determination of the aging state of existing equipment
- analysis of 110-kV-network structure
- estimation of load development for the 110-kV-network (steps of future loadings)
- execution of a long-term structural network planning including alternative 1 (consideration of conventional equipment) and alternative 2 (consideration of SCC) as well as the comparison of alternative 1 and 2
- proposal of a new conception of 110-kV-network

The elaboration of alternative 1 represents a conventional planning approach and is already well known [4, 5]. The elaboration of alternative 2 considers the application of SC-equipment and will be discussed comprehensively based on example cases in the following section. The results of alternative 2 includes additionally the question which 110-kV-substation should be replaced by SCC or which should be retained.

SC-PLANNING EXAMPLES

The SC-equipment can be relevant for the network development in cities and megacities in the future. These distribution networks are characterised with a high load density and high increase as well as a limited amount of space.
In this field SC-equipment is able to play a significant role to reduce effort and consequently costs, especially in case of the replacement of existing HV-equipment.

Operational Planning

The planning approach with SCC enables the possibility to improve the network development by reducing the voltage level for a definite transmission capacity. In most cases an extension of a distribution grid is possible without a HV-level like 110 kV conventional technique. The following Fig. 1 shows the conventional planning approach regarding a network extension with a 40-MVA-station. A 110-kV-network is introduced which means additional 110-kV-cables and two transformers 110/10-kV to fulfil the (n-1)-criterion.
Under consideration of SCC the 110-kV-cables and 110/10-kV-transformers can be avoided. The approach is depicted in Fig. 2.
The supply of the extension load (40 MVA) is taken over by two SC-cables on 10-kV-level. Only one additional 40 MVA transformer is needed to maintain (n-1)-reliability of the downstream network. Two 110-kV-cables and one 110/10-kV-transformer can be saved consequently and for the whole network only one system voltage of 10 kV exists.

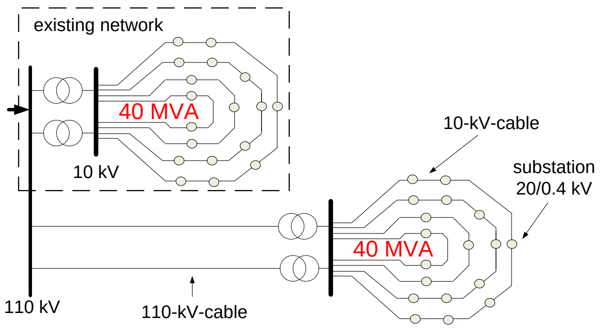

Figure 1: 40 MVA network extension (conventional)

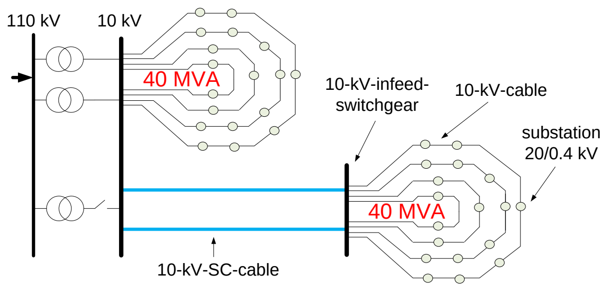

Figure 2: 40 MVA network extension with SCC

By realising the same reliability with less equipment, the use of SCC has also an economical benefit besides the technical ones (e.g. lower losses). “AmpaCity” shows that an approach with SCC is approximately in the same range of costs as a solution with conventional HV-equipment [1]. With a broad acceptance the costs will decline and SCC is more profitable [3] especially in case of ongoing standardisation. An early consideration of SC-equipment in long-term planning can reduce costs in the future because the planning horizon is about 20 to 50 years.
The enormous benefits of SCC in terms of network simplification will bring additional savings, e.g. the replacement of high voltage networks through medium voltage networks.
This approach is also applicable for the replacement or refurbishment of existing 110-kV-equipment in distribution systems, in particular if the existing MV-level fits to that one of the available SCC. The partial conversion of an existing 110-kV-distribution network can be done step by step but always under consideration of the planning targets of a strategic planning approach which is describe in the following with respect to megacities.
Furthermore, a SCC is also a preferable option to connect large industrial consumers (> 20 MVA load) to the existing grid. The monetary efforts can be considerably lower if the SCC is installed instead of 110-kV-overhead lines.

Long-term Strategic Planning for Megacities

Megacities have more than 1000 MVA load and different geo- and topographical conditions and structures. The following example cases describe mid- and long-term SC-network planning approaches to provide high reliability besides lower required space and monetary efforts.

Megacity up to 1200 MVA

The following example describes a city with a circular border and a diameter of about 10 km. The maximum load of this city is approximately 1200 MVA and is evenly distributed. Due to the above mentioned technical issues of SCC the load is divided into stations of 40 MVA which contains six to eight 10-kV ring cables in conventional technology to supply the customers. This means 30 of these stations exist. These are fed from two stations outside the city which are connected to the EHV-transmission system.
The range of 40 MVA per station is caused by the limited loading capability of the conventional 10-kV-medium voltage cables.
A conventional approach to plan such supply networks is to use subtransmission networks (e.g. 110 kV) to transport the power closer to the loads with lower losses. The conventional approach requires numerous and expensive 110-kV-equipment. In the following three variants of planning approaches will be shown. Fig. 3

illustrates a network planning concept with partly 10-kV-SCC application and 110-kV-SC-equipment.
The (n-1)-criterion in Fig. 3 is realised via parallel cables for each station and double busbars for the 380/110-kV-stations as well as the 110/10-kV-SC-stations which are not drawn because of graphical clarity. In our opinion, this is a preferable approach to ensure reliability. A possible disadvantage of this alternative is that substations for transformation of the voltage are necessary inside the city and considerable space for these stations is required.
Under consideration of the transport capacity of SCC a different planning approach is conceivable. Each of the 40 MVA stations will be supplied via SCC on MV-level. Therefore no additional substations for voltage transformation are needed inside the city. The result of this alternative is shown in Fig. 4. The (n-1)-criterion is realised with parallel cables and double busbars, also not drawn because of graphical clarity in Fig. 4.
Another alternative, which is ensuring the (n-1)-security, is to supply the stations with two SC-cables each from a different 380/10-kV-stations.
The infeed of the whole city can be extended with an additional 380/10-kV-station to reduce the amount of SC-cables connected to the 380/10-kV-station as shown in Fig. 5.

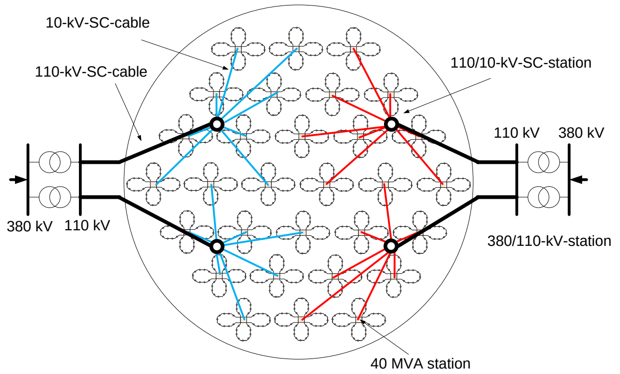

Figure 3: 1200 MVA planning concept with two voltage levels

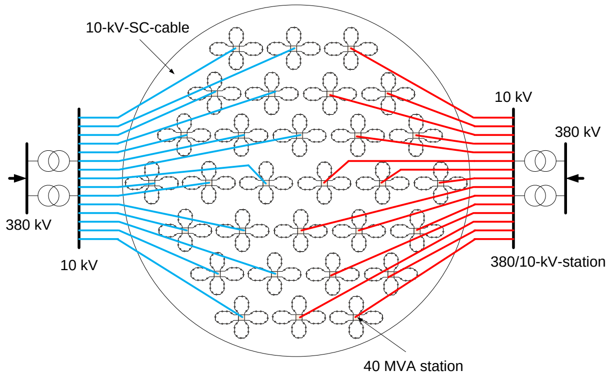

Figure 4: 1200 MVA planning concept with one voltage level

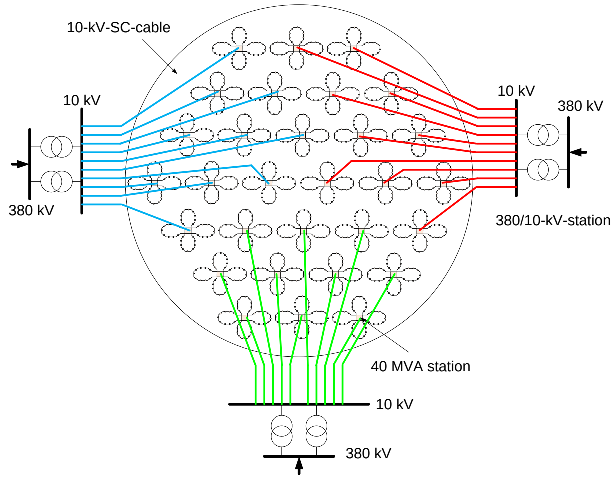

Figure 5: 1200 MVA planning concept with an additional 380/10-kV-station

Megacity up to 4800 MVA

In particular for large cities up to 4800 MVA a high transport capacity of the used equipment is needed. In conventional technique only EHV-equipment is possible which means high monetary efforts and space. In this context, the SCC can play a significant role because HV-SC-equipment is able to transport the same power with a lower voltage level. This enables the use of cable systems with lower efforts as EHV-cables or gas insulated line (GIL) systems.
The distribution grid for a bulky megacity with a maximum load of 4800 MVA is planned based on the assumptions that MV-SCC is able to transport 40 MVA and HV-SCC has a transport capacity of 400 MVA.
The supply area is clustered into load centres with 40 MVA based on the geo- and topographic condition as well as load distribution. The single load centers are aggregated to areas with a load of 400 MVA which are supplied via 110/10-kV-SC-substations. The EHV-stations are located outside the city and supply the 110/10-kV-SC-substations. The Fig. 6 illustrates the planned network structure.
For graphical clarity in Fig. 6 the parallel cables and double busbars, which provide the reliability, are not drawn. This is a possible planning approach for a circular city border.
In particular seaside cities have a typical longitudinal structure, as shown in Fig. 7. The limited width of the city area allows a supply with 10-kV-SCC exclusively. 110/10-kV-SC-subsations are not necessary in this case. A further characteristic of this geo- and topographic condition is that no load centres above a capacity of 40 MVA need to be considered and the SCC-application becomes preferably. This example shows the decisive impact of the geo- and topographic condition of the city areas on the network planning concept.

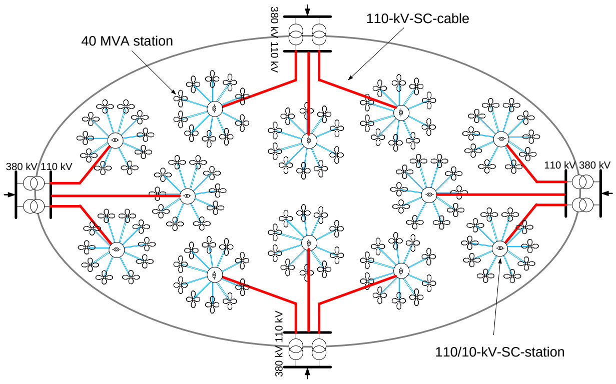

Figure 6: 4800 MVA planning concept with HV- and MV-SCC

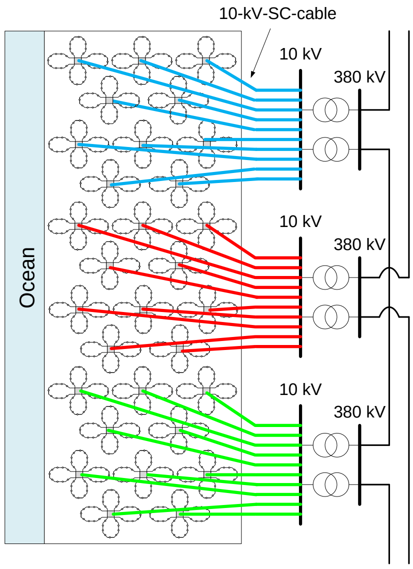

Figure 7: Megacity with longitudinal structure

CONCLUSIONS

The above mentioned planning approach is a first step to integrate SCC in the extension or refurbishment process of distribution networks. Around the world different installations of SC-equipment exist and are tested. The next step will be the standardization of this equipment. If this goes hand in hand with the requirements to SC-equipment in the network planning, the acceptance for SCC will rise at power utilities.

In most cases, the integration of SCC into existing networks has several technical and economic benefits. But this operational procedure should always be performed under consideration of a long-term planning scenario.

The presented examples describe the possible integration of SCC and a vision of a long-term implementation and operation of SCC-networks for megacities with high requirements to space and load density. In this cases SCC-application has its most important technical benefits. Generally the achievement of optimal planning concepts for SCC application requires high expert experience and creativity.

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