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HTS Power Technology for Future DC Power Grid

Liye Xiao, Shaotao Dai, Liangzhen Lin, Zhifeng Zhang and Jingye Zhang

***Abstract*—The increasing depletion of fos sil fuels and growing environmental pressures are leading mankind transiting from the use of traditional energy sources to that of renewable energy-based clean energy. As the renewable energy has the feature of instability, which thus brings significant challenges on the r eal-time power balance and power dispatching. Therefore, in order to secure the power supply, it is need to u pgrade the grid by selection of reasonable grid structure and operation mode. In this paper, a multiple-level direct current (DC) loop grid which would be the suitable mode for th e future power grid is suggested, and then the HTS DC power technology such as the HTS DC p ower cable and DC fault current limiter for the future power grid are discussed. Besides, we will report for the te st and operation of a 360m/10kA HTS DC cable which is being built and w ould be used for an electrolytic aluminum plant of Zhongfu Group in Henan Province, China.**

***Index Terms*—Renewable Energy, DC P ower Grid, HTS DC Power Transmission Cable, HTS Fault Current Limiter**

I. Introduction

WITH the depletion of fossil fuels and the growing pressure for the environment, it has been recognized that it's necessary to revolutionize the use of energy from the fossil energy to the renewable energy. In recent years, the renewable energy has been developing very rapidly in the world. For examples, in Europe, the United States and China, the average annual growth rate of installed capacity has surpassed more than 20%. In 2009, the renewable energy generation capacity has accounted for more than 62% of the newly installed power capacity in EU countries [1], which exceeded the newly installed capacity of traditional energy generation. Recently, the European Renewable Energy Council (EREC) has published a report entitled "RE-thinking 2050" [2], which estimated that according to the current development pace of renewable energy in Europe, by 2020, new generation capacity in Europe will all come from the renewable energy; the report also envisioned a 100% renewable energy supply system by 2050. In January 2011, German Advisory Council on the Environment presented a report "Pathways Towards a 100% Renewable Electricity System", which stated that 100% renewable electricity generation is possible in Germany by 2050 [3]. It was reported that the renewable energy could represent 40-45%of total energy consumption by 2050 in China [1]. It can be expected that in the near future, the primary energy will be dominated by the renewable energy and the terminal energy will be based on the electric power.

As it is well-known, the renewable energy is unstable, intermittent, uncontrollable, dispersed and diverse, and plus the renewable energy resources and the load resources are inconsistent in spatial and temporal distribution [4]. These significant changes in the energy resources will bring a series of great challenges for the future power grid, such as the real-time power balance and the power dispatching, the stability and safety of the AC power grid, the long-distance large-capacity power transmission, and the connections of the distributed systems to the large power grid [5].

However, all the renewable energies show spatial and temporal complementarities, if we "package" these multiple power resources together, the complementarities of resources can make the "power package" a relatively stable and controllable resource. For examples, the solar power can only be used during the daytime, while wind and waves energy can be even more robust at night; the hydro power resources are more abundant in the summer, and solar and wind resources are more abundant in the winter, and the bio-mass energy can be used to level the change of renewable energies (i.e., it can be regarded as energy storage). The energy resources at different places are also complementary at the same time [6-12]. Besides, the power batteries of electric vehicles (EVs) can play a role in smoothing the power output. Therefore, we can make the power supply more smooth, stable and controllable so as to meet the consumers' demands on electricity if we make full use of the complementarities of solar and wind power resources and the regulatory roles of the hydro power, biomass power and charging system of the electric vehicles by selection of a reasonable structure and operation mode of power grid [13].

In this paper, at first, we present a preliminary investigation the architecture of the multiple-level DC power grid for the renewable energy system. Then, the HTS DC power transmission cable and DC fault current limiter for the DC power grid are discussed. Besides, we also report the progress of the test of a 360m/10kA HTS DC cable and the design of a HTS resistive fault current limiter.

II. An Architecture for Future DC Power Grid: Multiple-Level DC Loop Grid [13]

A. Basic Structure for DC Power Grid

For the renewable energy system, it is competitive to operate the grid in DC mode because the DC grid can be easily to deal with the challenges from the renewable energy as described above. Actually, the Europe and US has already made plans to build DC power grid for the development of

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offshore wind power. In Europe, a super grid with DC mode has been proposed [14], which covers a wide area including the North Africa, Arab countries and all of the EU countries [15].

The DC grid should meet the following basic requirements: It can be accessed to by all renewable energies; It can take advantages of the spatial and temporal complementarities of different energy resources in order to improve the overall benefits of the grid; It can realize the two-way flow and control of power flexibly in order to achieve supply and demand interaction of the whole grid; It can accept in place a variety of power resources (including distributed powers) to improve the usage efficiency of the energy resources; It can secure the safety and reliability of electricity supply, and can provide satisfactory energy service to the user. For above reasons, we think that the basic structural mode of future power grid should be as follow: A DC loop busbar covering a certain area is the basic structural unit; Each loop busbar interconnects into a network structure via transmission and distribution lines; A variety of power supply and load can be easily accessed to each DC loop busbar; different loop busbars can achieve power transmission or two-way power exchange and control. This basic structural mode is shown in Fig. 1.

The basic structural mode is the most effective mode to make various renewable energy power stations and distributed power grid be connected, fully use of the complementarities in time and space of all kinds resources, and achieve interaction of the electricity power supply and load demand in the whole grid. The geographical distribution of the renewable energy power plants can not be determined by the electricity demands as the renewable energy is decentralized, which can only be in line with the natural distribution of the resources. The structural mode of the future grid has to adapt to the distribution characteristics of the resources. Meanwhile, the renewable energy has the characteristics of complementarities in time and space that should be fully utilized to decrease the randomness and fluctuations of the electricity power in the grid. Using the basic structural mode shown in the Fig. 1 can get a variety of decentralized renewable energy power plants or distributed power grid and electricity consumers accessed more easily, and realize a variety of complementary uses of the renewable energy and interaction of the power plant supply and users' demand on the busbars. Simultaneously, the interconnection of multiple loop grids is able to make the resources in a wide range complement better. The bi-directional power flow between loop grids can also be achieved. Once the partial fails, the network can be reconfigured by disconnect switches without causing a significant impact. In fact, the U.S. Electric Power Research Institute (EPRI) proposed the concept of Macro-Grid [16], which basic idea is also to use the DC loop grid to connect the power from the remote and the power within the loop grid.

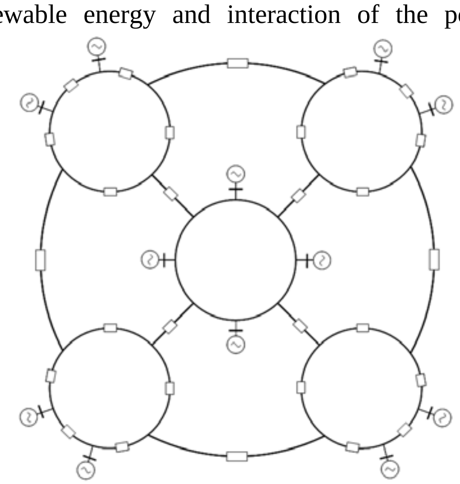

Fig.1. The basic structural mode of future power grid

B. *Multiple-Level DC Loop Grid*

As the basic pattern of uneven geographical distribution of the renewable energy resources and the load resources will continue to exist, cross-regional power transmission is inevitable. Also, a large number of distributed powers will be accessed to because the decentralized and diverse nature of the renewable energy. Therefore, the future power grid will be a complex large-scale grid with a feature of high transmission power, wide coverage, various accessed power and big difference in power class. To this end, it's necessary to take this basic structural mode as the basis, to construct a multi-level DC loop grid in line with the local conditions so as to achieve the optimal use of various power resources in a wide range and interaction of power supply and load demand.

The realization of the multi-level DC loop grid described in this article is as follows: at first, it is need to configure its basic grid structure with DC loop busbar in terms of the six levels of the grid including wide area large power grid, area power grid, regional power grid, local area grid, local distribution grid and terminal distribution grid. They are also called separately grid of level I-VI, the process from the level I to level VI, which is a transition process from the power supply side to the consumer side, also a transition process of the voltage from the high to the low class. The rated voltage from level I-VI can be fixed as ±800kV, ±800kV, ±500kV, ±100kV, ±20kV and ±100V respectively. Secondly, it is need to connect those DC loop busbars of the same level within the grid through the two-way power exchange control devices. Thirdly, it is need to connect each adjacent loop grid of level I-VI through transmission lines (or distribution lines) to achieve the electricity transmission from the power source side to the consumer side. Fourthly, it is need to connect each power source of different power rating to each level of DC loop busbars based on the time-space distribution characteristics of the power source and its complementarities in time-space, the electric vehicle charging stations or the energy storage system may also be connected to different levels of DC loop busbars in order to increase the stability of the total power supply on the loop busbars. Fifthly, it is need to connect the distributed power sources of smaller power and electricity users (for example, 10MW and below) to the DC loop busbars of the level VI loop to configure into a small-scale distributed power grid, while connecting the distributed power sources of larger power and large-scale electricity users (for example, 10-100MW) to the DC loop busbars of the V and even IV level grid to configure into a larger distributed power grid. Take China's national conditions as an example, the multi-level DC loop grid constructed is shown in Fig. 2.

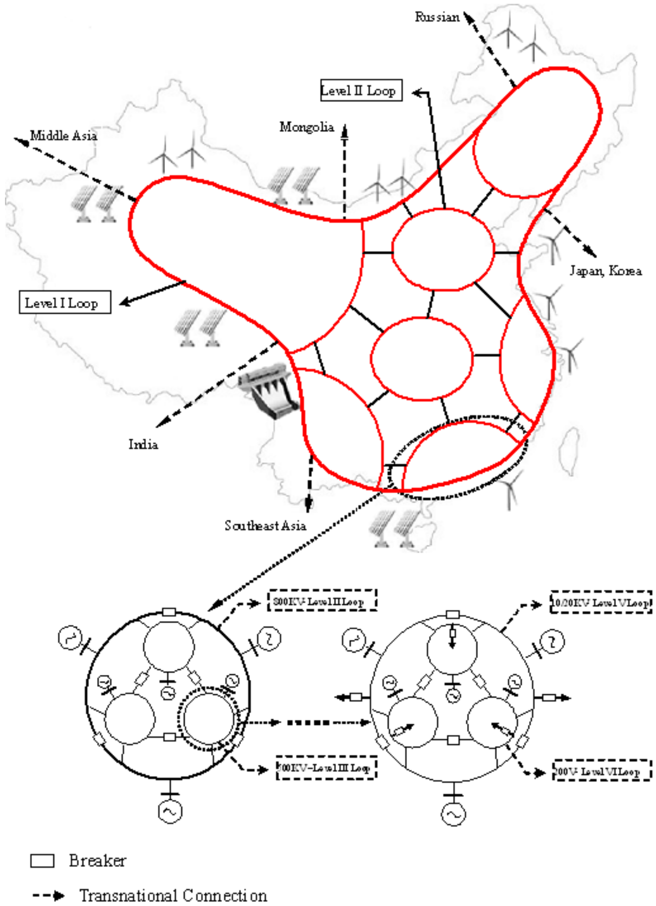

Fig.2. Multiple-level DC loop grids of China in the future

III. HTS Power cable for Future DC Power Grid

For the multiple-level DC loops, they will transport Giga-watts or even tens of Giga-watts of renewable power. For examples, the loop for a city will transport Giga-watts of power, and the loop for a certain area which covers several states or provinces will transport tens or Giga-watts of power. Then, the high Tc superconducting power cable is a very competitive candidate for the DC loop. Compared with the conventional overhead transmission line, the HTS power cable is very low in losses, high in efficiency and compact in structure.

According to a report from EPRI [16], if the cost of HTS wires would be in 50$/kA.m, the total construction cost and losses (for a term of 30 years) of HTS DC cable with length up 1500 miles would be competitive over the traditional transmission technology. For this reason, the HTS DC power cable would be promising for the construction of the loops of the multiple-level DC loop grid. In Europe, a super-grid has been in proposal [15], and the Grid2030 [17] for US power grid was also proposed. These possible wide-area power grids would transport large-capacity of energy in long distance, and thus leading to a potential application for the HTS DC power cable in the future.

Recently, a group leaded by Prof. Yamaguchi at Chubu University, Japan has successfully fabricated and demonstrated a HTS DC power cable with length of 200m, rated voltage of ±10kV and rated current of 2kA [18]. In the United States, the Tres Amigas Project, which is the nation's first renewable energy market hub, planned to use transmission-level DC superconductor power cables. The Tres Amigas renewable energy market hub will be a multi-mile, triangular electricity pathway of superconducting power cable capable of transferring and balancing many Giga-watts of renewable power between the three Interconnections [19].

A. *Design of a 10kA/360m HTS DC Power Cable* [20]

The 10kA/360m HTS DC power cable is a warm-dielectric type, it consists of a cable conductor, a cryogenic envelope, two terminations and a refrigeration system.

The cable conductor consists of the former, the HTS tapes, the inter-layer insulation tapes and the skid wires. Bi-2223 HTS tapes are used for the conductor of the cable. In order to test the design to use different types within a cable conductor, the cable conductor consists of 5 layers of HTS tapes, in which one layer is fabricated with the HTS tapes from InnoST, and four layers are fabricated with the HTS tapes supplied by SEI. The inner and outer diameters of the cable conductor are 41.0mm and 46.2mm, respectively. The design parameters of the cable conductor are listed in Table I.

The cryogenic envelope which hosts the cable conductor is composed of two concentric corrugated stainless steel tubes. Table II lists the main parameters of the cryogenic envelope. Testing shows that heat loss of the cryogenic envelope is about 1.0W/m. The cryogenic envelope is fabricated by jointing 8 segments, joint between 2 segments is performed by means of a dual vacuum layer insertion, leading a lower thermal loss of 3W for each joint. This kind of jointing technique for cryogenic envelope would be useful in the development of long distance HTS cable in the future.

TABLE I
Main Parameters of the Cable Conductor

Items	Value
Outer diameter of the former (mm)	41.0
Critical current of the HTS tapes used (A)	150/90
Minimum tensile stress of the HTS tapes (MPa)	250/100
Outer diameter of the conductor (mm)	46.2
Layer of conductors	5
Pieces of HTS tapes	115
Total length of HTS tapes used (km)	46

TABLE II
Main Parameters of the Cryogenic Envelop

Items	Value
Inner diameter (mm)	62
Outer diameter without steel textile (mm)	131
Outer diameter with steel textile (mm)	133
Outer diameter with insulation (mm)	151
Operational pressure with (bar)	1-5
Minimum bending radius (m)	1.2
Operational temperature (K)	70-77
Vacuum (pa)	$\leq 10^{-2}$

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Fig.3. The refrigeration system for the 360m/10kA HTS DC cable.

Fig.4. An overview of the 10kA HTS DC power cable after installation.

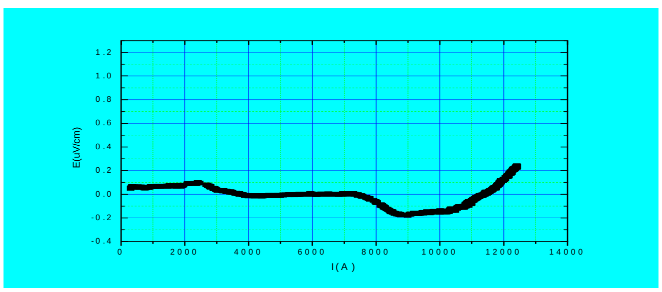


Fig.5. Critical Current Tests for the 360m/10kA HTS DC cable.

The termination consists of a main body, a current lead, and a chamber which are designed and manufactured separately, so that it can be easily transported and integrated. For the 10kA current lead, the ratio of length to cross section is 318.5m^{-1} and the length is 2.9m, this design can reduce the heat losses of lead to 43W/kA..

The sub-cooled liquid nitrogen of about 70K is used to cool the cable system. In order to keep a temperature difference within 70-77K, the system's pressure is in the range of 1-5bar, and then the backward liquid nitrogen is cooled down by a four-cylinder Stirling refrigerator whose cooling power is 4kW at 77K and about 3.3kW at 70K. The refrigeration system is shown in Fig. 3 after installation.

B. Installation and Test

The power cable is installed at Henan Zhongfu Industrial Co. LTD., which is a company to produce aluminum. The power cable, which connects the substation and the bus-bar of an aluminum electrolyzing workshop, will be used to serve for the power supply of the factory together with the conventional transmission conductor. In order to test the bending performance of the cable, the installation of the HTS DC cable is designed to be bended 9 times, among which three are vertical bending and six are horizontal bending, and the minimum bending radius is 3m. An overview of the installed cable is shown in Fig.4. After installation, the test for the cable has been performed. At 77K, the Ic by 1μm/cm is up to 12.0kA, the test result is shown in Fig. 5, the voltage drop in the cable is changed as the current is increased, and repeated tests show the same result. 2 hours of operation at 10.0kA shows that the voltage drop in the cable is stable.

IV. HTS Fault Current Limiter for DC Power Grid

For the multiple-level DC loop grid, the multiple-terminal DC (MTDC) transmission technology will be employed. In the DC grid, the fault current does not have the zero-crossing point as the AC current has, it is difficult to open the fault transmission line. Besides, as the energy storage in the fault transmission line should be absorbed before the it is cut, then it is critical to prevent the overvoltage during breaking, moreover, the breaking should be completed quickly in order to protect the other transmission line from the damage of the fault, usually it is the breaker to open within milliseconds or even microseconds.

For above reasons, it has been a difficult job to develop the DC breaker for MTDC system [21]. Recently, the DC breaker developed by ABB can break a 16kA fault current within 2 milliseconds while its rated voltage is 320kV, and Alstom has developed a DC breaker to break a 7.5kA fault current within 1.6 milliseconds (the rated voltage is 120kV) [22]. However, the fault current of the DC loops with rated voltage up to ±800kV will reach to tens of kilo-amperes. Then, it would be very helpful to reduce the fault current by fault current limiter (FCL).

Although there are many types of fault current limiters have been developed for the AC system, not all of them can be used for DC system. The promising FCL for DC power grid is the HTS resistive type FCL which can significantly reduce the fault current quickly because it can response the change of fault current immediately.

A. Design of a HTS Resistive Fault Current Limiting unit

The HTS resistive fault current limiter can be made of the matrix of fault current limiting unit, each unit can be made of non-inductive coil. In order to fabricate an non-inductive coil with reasonable interturn-voltage, an "ying-yang" type structure was employed as Fig. 6a, and a prototype non-inductive coil made of YBCO tapes is shown in Fig. 6b. In order to test the performances of the non-inductive coil, 4 prototype coils are fabricated. The parameters of the coils are listed in Table III. Tests show that the 4 coils show good homogeneity.

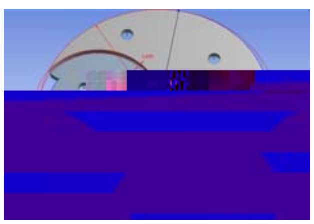
Based on above study, a non-inductive unit coil for a HTS resistive FCL which could be used for HVDC system has been designed. The design parameters of this unit are shown in Table IV. In order to develop a FCL for ±200kV/1.5kA DC transmission system, 8 non-inductive coils can be connected in parallel (as a coil-group) to achieve current capacity and safety margin, and 40 coil-groups can be connected in series to achieve resistance of about 15 ohm which is enough to limit the fault current down to the breaker's capacity. A concept view of the FCL is shown in Fig. 7.

TABLE III
DESIGN AND TEST VALUE OF THE 4 NON-INDUCTIVE COILS

Parameters	Coil 1#	Coil 2#	Coil 3#	Coil 4#
Length of YBCO Tape (m)	11.35	10.56	10.65	10.72
Inductance (μH)	1~2	1~2	1~2	1~2
Critical Current (A)	91.0	89.0	90.0	89.0
N Value	27.0	28.0	33.0	30.0
Resistance/meter at 300K (Ω)	0.275	0.307	0.293	0.302
Total Resistance at 300K (Ω)	3.119	3.241	3.120	3.238

TABLE IV
MAIN PARAMETERS OF THE CURRENT-LIMITING UNIT

Items	Value
Length of YBCO Tape (m)	54
ID (mm)	200
OD (mm)	870
Interturn Gap (mm)	5
Resistance (Ω)	1.28Ω@100K 2.98Ω@300K
N Value (0.1-1μV/cm)	38.6
Rated Voltage (kV)	3.0
Break-Down Voltage (kV)	15.0
Rated Current (A)	200.0
Peak current (A, with duration of 100ms)	900.0
Safety Temperature Limit (K)	300.0



(6a) (6b)

Fig.6. Design of a HTS resistive fault current limiting unit.

Fig.7. A conceptual view of a HTS DC resistive fault current limiter.

V. SUMMARY

With the revolutionary change of the energy, it can be expected that the primary energy will be dominated by the renewable energy and the terminal energy will be based on the electric power. This change will bring serious challenges for the power grid. In order to deal with these challenges, it would be necessary to develop a DC power grid with multiple-level loop structure. For this DC loop grid, the HTS DC power transmission cable and HTS DC resistive fault current limiter would be helpful for the construction of the new grid. In this paper, the progress of a 360m/10kA HTS DC power cable is reported, and a design for a resistive FCL unit is also presented.

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