Applying High-Temperature Superconductor Technologies into Power Systems

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Abstract — **implementing of distribution and transmission power systems for urban areas and for future renewable energy to meet future demand is a challenging task when conventional cables and transformers are considered. Therefore, there are several methods, that have applied in conational power systems to reduce power losses, voltage regulator issues , capital cost of whole system and increasing power delivering in urban areas and from offshore farms ,such as carefully sited and operated distributed generation (DG) and distributed control techniques. However, these techniques may raise others challenges in networks such as stability, voltage regulators issues and increasing capital cost of networks. Since High Temperature Superconductor (HTS) cables exhibit zero resistance when cooled to the boiling point of liquid nitrogen (77Keliven), they have the potential to be used to address these issues in distribution and transmission networks. Consequently, this paper reviews super-conductor power systems: the work previously achieved in the DC and AC superconductor power systems and describes the materials and methods which they used. In addition, it shows how the superconductor technologies can address these issues when they are used for distribution and transmission power systems.**

Index Terms — **HTS technologies, power losses, distributed generation.**

I. INTRODUCTION

Since High Temperature Superconductor (HTS) materials have zero resistance when cooled to the boiling point of liquid nitrogen 77 Kelvin (77K), interest in using HTS materials for power transmission is growing rapidly [1,2]. The aim of the research described in this paper is to investigate the potential benefits and challenges arising from the integration of HTS technologies into transmission and distribution power networks to address the issues that affect conventional transmission and distribution networks such as power losses issues, voltage regulator issues, reduce capital cost of network power systems and increasing delivering power in urban areas. This paper reviews superconductor power systems: the work previously achieved in the DC and AC superconductor power systems and describes the materials and methods which they used. In addition, it introduces the gaps and limitations in the research that needs to be considered for further papers.

II. REDUCE POWER LOSSES IN DISTRIBUTION AND TRANSMISSION POWER SYSTEMS

In papers [3-6], the comparison of power losses is introduce, and their economic impacts for high voltage DC transmission systems HVDC and DC HTS transmission systems over long distances (km). Power losses caused by these transmission systems have been studied using numerical simulations on Matlab/Simulink. These studies state that DC HTS cable can deliver power up to 10 times more than Thyristor-Based HVDC transmission systems. Additionally, DC HTS cables (without considering the power needs of refrigeration systems) have not resulted in any real losses ($I^2R=0$) due to their resistance being zero. The cost of high insulation and converter substations are reduced due the possibility of delivering high power density at a lower voltage level. Furthermore, the impact of harmonic current on steady state of DC HTS cables has been investigated [7,8]. The harmonic current does not impact on the steady state of DC HTS cable. In addition, the possibility the low voltage DC superconductor distribution to feed sensitive electric load such as office environment has been discussed in paper [7] and [9]. However, paper [7] proved that there is no need to apply rectifier or power factor correction(power factor correction for AC network sides) to reduce power losses in networks while paper [9] proposed the new control scheme of voltage source inverter (VSI) and proposed to allow the system to supply multiple passive loads without a central communication unit .There are some researchers who have concentrated on AC loss in HTS cable. Paper [10]is more specific, and focuses on AC losses and thermal considerations for AC super-conductor cables. AC superconductor power systems are not evaluated by their critical current density, but by the requirements for acceptable loss and reactive compensation. Operational limits for long length AC superconductor power systems depend upon: the cooling configuration; the AC superconducting cable loss, and the thermal loss. An analysis of liquid nitrogen cooling systems and electrical insulation contraction for AC superconducting cables is presented in [11].

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III. REDUCE CAPITAL COST IN DISTRIBUTION AND TRANSMISSION SYSTEMS

Other studies in papers [12-15], conducted research looking at the possibility of applying DC HTS cables to transmit high amounts of power (GW) over long distances (km). DC HTS transmission systems can be implemented with Voltage Source Converter at lower voltage to reduce costs of converter substations. The opportunity of using DC HTS transmission systems based on VSC provides the possibility of applying this technology to future offshore farms to deliver power over long distances. In [16] the optimum voltage level of converter substations in order to reduce cost was estimated as in range from 50kV to 100kV.New design topologies of distribution networks in urban areas can be achieved using AC HTS cables. In [17-20], the power can be supplied from 220kV down to low voltage levels such as 10kV, 20kV, 25kV or 35kV. These studies confirmed that implementing AC HTS cables to distribution power systems can reduce the cost of transformer-substations and switchgear. Investigating the reliability, power losses, and cost for new design of superconductor networks are introduced in these papers. However, the optimum application of implemented HTS cables and HTS transformers to urban areas has not been introduced in order to reduce power losses, voltage drop issues and reducing the cost of transformer-substations. Hence, the future demand in urban areas must be considered to show the AC HTS technologies can be covered coup with future issues which will be associated with conventional technologies such as power losses, voltage regulator issues and the cost of installing new cables and substations to meet such demand.[21]introduced an economic analysis to implement AC HTS cable in urban areas. This study consisted of six case studies, which applied AC HTS cable, and suggested the best choice among these studies by means of cost analysis.The conclusion is that applying AC HTS cables to the Seoul system will reduce the number of required underground cables by 25%, transmission losses by 3.5% and construction costs by $1.736 million by 2035 when compared to conventional cables. This study did not consider the cost of refrigeration systems and has not provided the prices of BSCCO materials which are major factors in dropping the price of AC HTS cable and HTS transformers. Furthermore, this study did not introduce a suitable price of AC HTS cables and HTS transformers when they will be competitive to conventional technologies based on the future price of Bi-2223. Therefore, the optimum application of applying HTS technologies to distribution networks needs to be introduced to result in lower capital cost than distribution conventional networks.

IV. INCREASING POWER DELIVERED IN URBAN AREAS

Other studies, for example in papers [22] and [23] provide the possibility of applying DC HTS cables to distribution power systems in urban areas. It is shown that implementing DC HTS cables into urban areas can eliminate real power losses, increase power density of each feeder and reduce the cost of converter stations and substations. Elsewhere, for example, in paper [24], the opportunity of operating low voltage DC super-conductor distribution networks in urban areas has been introduced. In addition, the method of power sharing control between rectifiers has been introduced in DC superconductor distributing networks including various distributed generators (DG_S).Several studies have concluded that AC HTS technologies such as HTS transformers and HTS cables can be ideal to implement in distribution power systems in urban areas. papers [25-28] proposed that HTS cables will be overcome on obstacles which face conventional technologies in urban areas such as reduced voltage drop, reduced power losses, reduced CO_2 emissions and increased power density. AC HTS cables can transmit bulk capacity with lower voltage (<50kV) and lower losses therefore they can reduce the need of high voltage substations which leads to reduced costs of substations in urban areas. The environment-friendly nature of the HTS cables is expected to bring huge environmental and social benefits including fewer civil petitions over environ-mental issues in urban areas. In paper [26] proved that there is an increasing interest in installing HTS cables to a highly populated metropolitan area to significantly improve power transmission capacity with minimal electrical loss. Also, this study calculated of the electrical losses of 100 kV, 50 km transmission lines where the load demands 100 MVA with 0.95 power factor. However, the power consumption of refrigeration systems for HTS cables have not been discussed in these studies due to the fact that power is considered a real power loss for AC HTS cables, consequently this gap must be considered when determining power losses for superconductor distribution networks. Furthermore, the power losses and voltage fluctuations in superconductor distribution networks need to be investigated when loads are a lagging, leading and unity power factor. Other studies have introduced the advantages of applying AC HTS transformers in urban areas over conventional transformers. In papers [29-32]it is emphasised that implementing HTS transformers to urban areas leads to an overcoming of issues which are associated with conventional transformers such as increased power density, reduced operating losses, lower impedance, smaller weight, smaller size and better voltage regulation.

V. ENHANCED THE VOLTAGE PERFORMANCE IN DISTRIBUTION NETWORKS

The impact of the unique characteristics of AC HTS cables on their power transfer performance and its needs for reactive compensation has been studied [33].The results show that the regulation voltage was better when AC HTS cables were considered. When overhead lines carry a small amount of power, the voltage profile along the line is uniform and requires little compensation. On the other hand, as the power increases in overhead lines, the capacitive compensation increases. In underground cables, the voltage profile along the line is higher than the normal value and therefore it requires inductive shunt compensation after 50km at intermediate points. However, a very low impedance of AC HTS cables provide better voltage regulation in the system, but the charging current for superconductor cables is large even though the voltage regulation is excellent. This study of AC HTS cables showed that cable lengths could reach over 175km before compensation was needed at intermediate points. Mathias Noe and et al. introduced several scenarios studies of superconductor networks to deliver power from extra high voltage level (380kV) to medium voltage level (30kV). This study introduced the notion that applying AC HTS cables to urban areas leads to reduce number of voltage levels, higher power rating per feeder, lower losses and high stability. Moreover, the n-1 criterion was considered for all investigations to guarantee the necessary reliability and redundancy. However, the risk study for superconductor distribution systems has not been introduced yet, therefore, it is necessary to evaluate risk levels in superconductor distribution networks and compare to conventional distribution systems. Papers [34] and [35]discuss the power control applications of low voltage DC superconductor mesh networks. The DC super-conductor cables can be applied to mesh networks at a low voltage (10-15kV). This leads to a decrease in the number of transformers required, and a subsequent reduction in the cost of high voltage insulation. Each of the nodes on a DC superconductor system reaches the same steady-state voltage level because the DC superconductor cables do not provide DC resistance to cause terminal voltage to vary with line current magnitudes. Thus, it is possible to use the voltage in a DC superconductor system as a signal to identify where the demand has increased in the mesh network loads. If the demand has decreased, then the voltage in the nodes has increased, and if the voltage in the nodes has decreased then the demand has increased.

VI. OVERCOMING THE FAULT LEVEL ISSUES IN NETWORK POWER SYSTEMS.

Due to the fact that HTS cables and transformers have very low impedances, the fault current level in the superconductor network is high. Using a conventional fault current as a solution in AC superconductor networks leads to unwanted side effects for the networks such as an increase in network losses, voltage regulation problems or compromised system stability [36]. Therefore, the superconducting fault current limiters (SFCL) can be used to limit the short-circuit current level in electrical transmission and distribution network. HTS materials have been used in order to enhance the performance of fault current devices. The matrix fault current limiter (MFCL) based on HTS materials which were introduced in papers[36-40]. MFCLs are designed to address fault current over-duty problems at a transmission voltage level of 138kV. MFCL devices consist of an HTS element variable resistor in parallel with a reactor. Under normal operating conditions, the peak current level of the power transmission is less than the critical current of the HTS element, and there is no voltages drop in the device because the resistance of the HTS elements is almost zero, which leads to a reduction in I^2R losses. When fault current occurs, the AC current will be higher than the critical current in the HTS element. This will result in creating a high resistance in the MFCL device, which will force the interruption of the fault current in the grid. Another application of MFCL devices in the power grid is when new a generator connects to the transmission grid, the fault current will increase. This requires upgrading conventional circuit breakers in the grid and this will be expensive and will include a voltage drop, with added power losses and stability problems in the grid. The MFLC devices can be connected directly to a new generator without upgrading the breakers in the grid [36]. The MFCL devices can clear the fault current without the need to open the breakers in the grid. Currently, there are many companies working on developing this device such as Superpower and Nexans Superconductors for utility transmission [36]. Paper [37] introduces also resistance type SFCL can be used with a transformer to reduce fault current level issues in the distribution networks. The resistive type of SFCL using a transformer consists of a transformer and an HTS element which is connected with the secondary winding of the transformer. It is a function of the turn number's ratio between primary and secondary winding to limit resistance of HTS element in a transformer to reduce fault level current issues in the network. In addition, SFCL devices can be applied to low voltage AC distribution grids. When a new generator connects to a distribution gird in order to meet increasing demand, the fault current level in the grid will increase. This requires the creation of a new configuration of substations and breaker circuits. In this case, conventional breaker circuits cannot interrupt the current fault due to its magnitude. Using resistive SFCL devices in the distribution grids requires a connection to the breaker circuit because resistive SFCL devices increase mitigating the fault current level to that breaker current handle it [39,40].

VII. THE POSSIBILITY OF USING HTS TECHNOLOGIES FOR FUTURE ELECTRICAL POWER SYSTEMS.

From the literature review, this paper shows the possibility of applying HTS technologies in future power systems to overcoming issues which will be exist in the future conventional power systems. Below is summarizing of advantages of using HTS technologies in distribution and transmission power systems.

- Reducing the power losses (I^2R) which are incurred in transmission and distribution networks.
- Overcoming voltage drop issues in urban areas combined with reducing the cost of installation requirements in distribution networks to maintain voltage within the required limits.
- Increase the ability of electrical distribution networks to deliver high power densities into critical urban areas whilst avoiding the need for heavy network reinforcement and additional assets.
- Introducing new topological designs of future superconducting distribution networks in the pursuit

of lower capital costs and lower power losses in comparison to conventional networks.

VIII. CONCLUSION

In light of the present review paper, the main research trends regarding the various relevant topics have been identified. Although some research has been achieved for applying HTS assets into power systems, but more necessary research is required to be considered for further papers to explore more about the opportunities and challenges of superconductor power systems. Further research needs to be carried out to address the research questions, which are obtained from the review paper, to introduce the opportunities of using HTS assets into power systems to overcome current and future obstacles which would face conventional power systems in the future.

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