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Investigation of the Superconductor Application in Medium Distribution Networks to Meet the Future Demand

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Abstract

Renewable energies (REs) and electric vehicles (EVs) are seen to be an alternating solution to reduce CO_2 emissions in the UK. However, increasing numbers of EVs in the future will be considered as additional power demand which may cause voltage drop issues with distribution networks. To meet the future demand in conventional distribution networks in the UK, several REs such as wind farms need to be connected as distributed generation (DGs) with distribution networks to meet such future demand and to reduce CO_2 emissions. However, operating many DGs in the distribution network causes voltage regulation problems. In addition, increased delivery of power using the existing distribution networks is challenging when considering conventional power system technologies such as conductors and transformers. In this context, this paper investigates the impact of future EVs load on voltage profiles on the existing UK medium voltage (MV) distribution networks using high temperature superconducting (HTS) technology. Existing MV conventional power systems and those containing AC HTS conductors are compared and conclusions drawn regarding the likely impact of HTS technologies on the capital cost and operation of future power systems.

Index Terms: Conventional networks, superconductor networks, voltage control, renewable energies, electrical vehicles and capital cost.

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1. Introduction

REs and electrical vehicles (EVs) are seen to be part of the solution to reduce CO_2 emissions in the UK [1]. By 2020, the UK government proposes to have increased the electricity demand to 13.1TWh for EVs while sourcing 20% energy from REs [2, 3]. However, increasing numbers of electrical vehicle (EV) sources and heat pumps (HPs) in the future may lead to increased voltage drop issues in conventional distribution networks, and also will have an impact on the amount of power delivered into conventional distribution networks due to EVs and HPs charging from these networks. This will be considered as an additional power demand which may cause voltage drop issues and thermal overloads with conventional distribution networks in the future [4].

When considering targets to reduce CO_2 emissions and meeting future demand in conventional distribution networks in the UK, several RE sources such as wind farms need to be connected as distributed generation (DGs) to the existing distribution networks. Nevertheless, operating many DGs in the distribution network can increase problems of stability, power flow management, and voltage regulation [5]. There are many techniques currently implemented in distribution networks to reduce the voltage excursions such as sharing of reactive power between DGs, power factor control, capacitor placement and transformer tap change control [6]. Using these techniques with distribution networks is targeted to maintain voltage level in 20 kV conventional distribution networks within certain levels ± 6% [6,7]. However, these techniques often increase system capital and operational costs. In addition, the increased delivery of power to urban areas where distribution networks exist is challenging when considering conventional power system technologies such as conductors and transformers, especially in cases where space to install new cables and transformers is scarce. The voltage change in networks can be calculated from equation (1) which is shown below.

$$\Delta V = \frac{RP + XQ}{V} \pm j\frac{XP - RQ}{V} \qquad (1)$$

Where, ΔV is the voltage change in the system from sending to receiving end busbars; P and Q are the active and reactive power loads, R and X are resistance and reactance respectively and V is the sending end voltage.

A key research challenge is to discover new conductor and transformer winding material with significantly lower resistance in order to reduce impedance of distribution networks. Since High–Temperature Superconductor (HTS) materials provide very low resistance to AC currents when cooled to the boiling point of liquid nitrogen (77 Kelvin (K)), interest in using these materials for equipment in distribution power systems is growing rapidly [6]. HTS materials have been used in transformers and conductors to reduce the power losses (I^2R and I^2X) and to overcome voltage control problems that are associated with conventional cables and transformers. AC HTS cables can deliver significantly more power (3–5 times) than conventional cables and hence provide the opportunity to reduce grid congestion issues in urban areas [8]. Although implementing a conventional distribution network with HTS equipment results in AC power losses such as hysteretic losses and eddy current losses, these AC losses are still much lower than those resulting from conventional power system conductors [8]. Furthermore, HTS tapes are available for use in the windings of transformers. Using HTS materials in transformers provides several benefits over conventional transformers, including higher power density, lower operating losses, fault current limiting, lower impedance, and better voltage regulation [9.10].

This paper investigates the impact of future demand including EVs, HPs and future RE sources on voltage profiles with existing UK medium voltage (MV) conventional distribution networks. Moreover, the investigation will analysis the impact of future demand and future REs on voltage profiles with existing UK MV distribution networks which contain HTS cables and transformers. Existing MV conventional power systems and those containing HTS cables and transformers are compared and conclusions drawn regarding the likely impact of HTS technologies on the capital cost and the operation of future power systems.

2. Case Study Network

First step was to model existing UK 20kV conventional distribution network using Interactive Power System Analysis (IPSA) software. Moreover, onshore wind farms are planning to connect with this practical network in the future, therefore, it would be a good investigation to show how applied HTS technologies with this network could address the challenges which would face 20kV conventional distribution networks in the future in terms of reducing voltage regulator issues. Real parameters of each component of the 20kV conventional distribution network have been used to model the network. The voltage regulator (VR) and capacitor bank (CB) have been modelled to keep voltage in ± 6%. Also, transformers are modelled as on-load tap changer transformers (OLTCT). Each transformer can carry power up to 25MVA. Tap changers have 15 steps to maintain voltage in target BT-bus voltage (1.02 pu). The change of the tap position is carried out in discrete steps with each beginning at 1.5% of the normal ratio. Fig. 1 show the network which has been modelled.

3. Analysis of Voltage Change in 20 kV Conventional and Superconductor Distribution Network

In this work, sensitive analysis has been performed to determine the voltage change in conventional network and proposed network with HTS cables for the same present demand. Furthermore, an investigation has been accomplished to find out the impact of onshore wind farms on voltage change in conventional networks, and on the proposed one which contains HTS cables.

3.1 Peak demand

This case investigated the voltage changes in the 20 kV conventional distribution network at early evening peak demand. Demand reaches peak value in the summer and winter seasons [11]. In UK, June, July and August are considered the summer peak demand and December, January and February as the winter peak demand, therefore, in this study, the highest demand has been taken to investigate the voltage changes that occur in the 20kV superconductor and conventional distribution networks at the current peak demand, which is 31 MVA in this network case study [11]. Then a comparison between the two distribution systems has been made.

A collaboration of tap changer transformers, CB and VR, are required to maintain voltage level within required limits in the conventional distribution network. Table 1 shows the voltage change in the 20 kV conventional distribution network at peak demand.

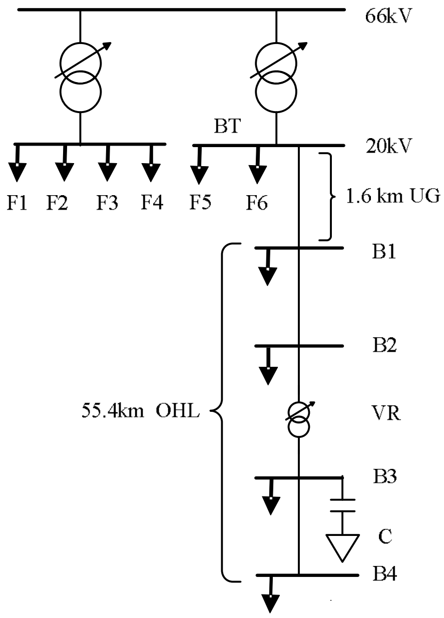

Fig. 1: The existing 20kv distribution Network model.

Table 1: The Voltage Change in the 20 KV Conventional Distribution Network at Peak Demand.

Busbars	BT (pu)	B1(pu)	B2(pu)	B3(pu)	B4(pu)
Voltage (pu)	1.020	1.0071	0.9715	0.9902	0.9575

Table 2 shows the voltage change in the 20 kV proposed distribution networks which contains HTS cables at peak demand.

Table 2: The Voltage Change in the 20 KV Proposed Distribution Network Contains HTS Cables at Peak Demand

Busbars	BT(pu)	B1(pu)	B2(pu)	B3(pu)	B4(pu)
Voltage (pu)	1.02	1.0199	1.0198	1.0197	1.0194

In 20 kV proposed distribution network which contains HTS cables, the voltage change is very small compared to the voltage change which occurred in 20 kV conventional distribution network at peak because impedances of HTS cables are very small. In addition, collaboration of OLTCT, CB and VR, are no longer needed to be implemented to keep voltage level within the required limit in the network when HTS cables are used. This will reduce the capital cost of the network.

At peak demand, the VR stepped up the voltage to 1 pu between B2 and B3 and also CB supplied 4MVAr to B3 in the 20kV conventional distribution network as shown in Fig. 1. Moreover, OLTCT operated to maintain the voltage level of busbar BT within the required limit ± 6%. Therefore, the collaboration of OLTCT, CB and VR are necessary in the 20 kV conventional distribution network to keep voltage levels within required limits as shown in table 1. The results in table 2 shows that the use of OLTCT, CB and VR are no longer needed in the 20kV distribution network when HTS cables are considered at peak demand.

3.2 Future demand case

In this case, the voltage changes in the 20 kV conventional distribution network has been evaluated when future demand (EVs and HPs) is considered. This investigation needs to be implemented to see whether the present conventional distribution network can cope with future demand without causing any voltage drop issues. The number of transformers needs to be increased in this case to meet the rating of power delivered to the network to meet future demand as shown in Fig. 2. EV and HP home charging are the most common and may be considered as a 4kW constant load on the network [11]. Therefore, the power consumption of EV and HP for each customer has added to the current peak demand to obtain the future demand for this case study, which is 50 MVA. Table 3 illustrates the results of this case which shows the voltage change in 20 kV conventional distribution network when future demand (EVs and HPs) is considered.

Table 3: The Voltage Change in the 20 KV Conventional Distribution Network when Future Demand Is Considered

Busbars	**BT (pu)**	**B1(pu)**	**B2(pu)**	**B3(pu)**	**B4(pu)**
Voltage (pu)	1.02	0.9976	0.9320	0.9824	0.9266

Based on these results, the voltage level in 20 kV conventional distribution network goes under the required limit (- 6%) at busbars B2 and B4 when future demand is considered. In addition, the collaboration of OLTCT changer, VR and CB, have operated in this case but they could not show that they could keep voltage level within required limit in the network. This indicates that the voltage drop issues will face the present conventional distribution network when future demand is considered. Consequently, more equipment is required to be installed in the present conventional network to maintain the voltage level within the required limit of ±6% which leads to an increase in the capital cost of the network.

In this case, the HTS transformer and HTS cables have replaced conventional cables and transformers in the 20 kV distribution network. HTS transformers have a higher MVA rating than conventional transformers. Therefore, only one HTS transformer was applied rather than three conventional transformers to cope with a rating of power needed to be delivered in the network to meet future demand. All parameters of HTS transformers are taken from [12] and [13] and then converted to per unit. The voltage level in the 20 kV superconductor distributing network is maintained within the required limit when future demand (EVs and HPs) was considered and without the need to implement OLTCT, CB and VR, in the network. Table 4 shows the result for this case which indicates the voltage change in 20 kV superconductor distribution networks at future demand.

Table 4: The Voltage Change in the 20 KV Superconductor Distribution Network when Future Demand Is Considered

Busbars	**BT (pu)**	**B1(pu)**	**B2(pu)**	**B3(pu)**	**B4(pu)**
Voltage (pu)	1.02	1.0199	1.01906	1.0188	1.0187

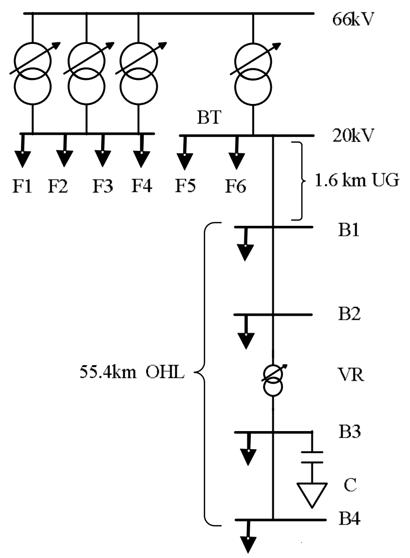

Fig. 2: The Conventional Distribution Network at Future Demand.

In addition, some research showed that EVs would impact negatively on the low voltage conventional distribution network. In [11] and [14], the impact of EV demand on the present 11kV conventional distribution network was investigated. They showed that EV demand would cause voltage drop issues in the present 11kV distribution network in the future. Therefore, the EV interface devices may be designed to minimize or even eliminate the effects of EVs on the conventional distribution networks in the future. This leads to an increased capital cost for the conventional distribution network. However, as shown in table 4, the future demand (including EVs and HPs) would not cause any voltage drop issues in the 20kV superconductor distribution network; therefore, the additional cost for EV interface devices and conventional control assets are no longer required to be installed in the future superconductor distribution networks.

3.3 Future onshore wind farm integration at minimum demand

An investigation into the possibility of integrating future onshore wind farms with the present conventional distribution network is required to evaluate how much power can be injected by future onshore wind farms before causing voltage regulation issues in network.

In this study, onshore wind farms have connected to 20 kV conventional distribution networks (Fig. 3) at unity power factor to find the maximum power that can be injected from future onshore wind farms before voltage regulator issues occur in the network. Large onshore wind farms capable of generating less than 1MW are normally connected on an 11kV network while the large onshore wind farms capable of generating above 5 MW are normally connected on a 33 kV network [15], therefore, the expectation of large onshore wind farms capable of generating between 1– 5MW in a 20 kV network. Based on obtained results for this case study network, the maximum power that can be injected from future onshore wind farms into the existing distribution network is 2.5 MW at minimum demands (6 MVA). The voltage level in 20 kV conventional distribution network goes over the required limit (+ 6%) at busbar B4 when power of onshore farms is increased more than 2.5 MW. Table 5 shows the voltage changes for maximum power which can be injected by future offshore wind with 20 kV conventional distribution network at minimum demand.

Table 5: The Voltage Change in the 20 KV Conventional Distribution Network at Minumum with Future Onshore Wind Generation.

Busbars	**BT (pu)**	**B1(pu)**	**B2(pu)**	**B3(pu)**	**B4(pu)**
Voltage (pu)	1.02	1.0195	1.094	1.026	1.06

The same investigation has been achieved with 20kV superconductor distribution network to find out the maximum power that can be injected at minimum demand by future onshore wind farms. Table 6 indicates that the 20 kV superconductor distribution network can deliver up to 40 MW from future onshore wind farms without causing any voltage regulator issues in the network. The reason for delivering just 40 MW from onshore wind farms was because the maximum power rating for HTS cables used in this study is 40 MVA. Table 6 shows the voltage change in the 20 kV superconductor distribution network at minimum demand with future onshore wind farm considered.

Table 6: The Voltage Change in the 20 KV Superconductor Distribution Network at Minumum Demand with Future Onshore Windfarm Considered

Busbars	BT (pu)	B1(pu)	B2(pu)	B3(pu)	B4(pu)
Voltage (pu)	1.02	1.0199	1.017	1.016	1.0146

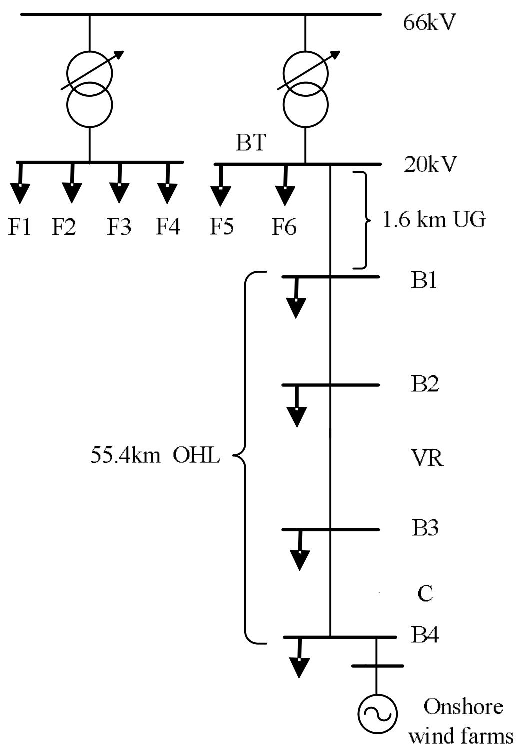

Fig. 3: The Onshore Windfarms Connected with the Case Study Network Conventional Distribution Networks.

The serious issue of integrating REs into the present 20 kV conventional distribution network is the ability of delivering power greater than 2.5 MW at minimum demand as shown in table 6. Therefore, wind energy convention control systems are required to be considered to control the output power from wind turbines to maintain the voltage level at required limits in critical demand periods. The wind energy convention control systems proposed in [14] to reduce the negative impact of integrating small onshore wind farms for the 11kV conventional distribution network which is also would result in an increase to the capital cost of conventional distribution network when REs are connected.

Based on the results in table 6, integrating large onshore wind farms into 20 kV superconductor distribution networks will not cause any voltage regulator issues in the network. Consequently, the use of wind energy convention control systems is no longer required for wind turbines when superconductor distribution networks are considered to maintain voltage within limits. The additional cost of equipment for future onshore farms is no longer required to be installed in the future superconductor distribution network. The voltage change behavior in the superconductor distribution network was found to be different from the voltage changes behavior in 20 kV conventional distribution network. This because HTS cable (40 MVA), used in this study has indicative reactance, which means they consume reactive power which leads to a rise in voltage level up.

This case study confirmed that HTS assets eliminate voltage regulation issues in distribution networks. Moreover, it proved that they can be implemented with MV distribution networks injecting more power from REs without causing any voltage regulation issues and without needing to use any special equipment in order to keep voltage within required limits. This will aid to reduce the capital cost of distribution networks in the future. However, the comparisons of 20 kV conventional and superconductor distribution networks are required to see how much capital cost can be reduced in the future when the superconductor equipment is applied with this present network.

4. Capital Cost Comparisons of Case Study Networks

The capital cost comparison of a 20 kV conventional and superconductor distribution networks have been evaluated in this study. Based on the assumptions in papers [16, 17], the present capital cost of a 20 kV distribution network which contains 57 km of HTS cables and one HTS transformer is £1141.2 Million (M) while the capital cost for a 20 kV conventional network is £5.3M. The future capital cost of a superconductor distribution network will be £115.1M based on the prices of HTS equipment which are indicated in papers [16, 17]. Based on these results, the capital cost of a 20 kV superconductor distribution network is much higher than a current 20 kV conventional distribution network. Although, the capital cost of the 20 kV superconductor network will be significantly decreased in the future but it is still higher by £109.8M from the present capital cost of a 20 kV conventional one in this case study network. This means, HTS cables and transformers will not be suitable to be implemented with small applications of distribution networks like this case study network, but it might be more beneficial to apply HTS equipment to large applications. This raises the question of finding a suitable application for applying HTS equipment with distribution networks in terms of reducing capital cost of the network. HTS technologies such as cables and transformers have proved their ability to overcome several issues, which are associated with existing conventional technologies, therefore, in the future, the HTS technologies are estimated to cover a total UK market value up to £96 billion by the year 2020 [18].

5. Conclusion

This paper aimed to answer the question of the impact of future demands and future RE sources on the existing MV conventional and superconductor distribution networks in terms of voltage regulator issues and capital cost. Applied HTS equipment with MV distribution networks leads to an elimination of the voltage regulation problems especially when future wind energies are connected. Additionally, the voltage control devices are no longer required to be implemented in an MV superconductor distribution network to keep voltage within the required limit. In this practical application, the capital cost of a 20 kV superconductor distribution network will be approximately higher in the future by £109.8M than the capital cost of 20 kV conventional distribution network. This means, more research must be undertaken in the next piece of work to find out the suitable application of applying HTS equipment with distribution networks to result in lower capital costs than the existing conventional distribution network design.

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Biographies

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Mahmoud Zaggout received his B.Sc. and M.Sc. degrees in Electrical and Electronic Engineering from Tripoli University, Libya in 2000 and 2008 and his PhD in Engineering from Durham University, UK, in 2013. Currently, he is a lecturer in Department of Electrical Engineering, Misurata University. His research field is renewable energy sources and wind turbine condition monitoring.

Kamal Ramadan Doud; IEEE member, received the M.Sc. and Ph.D. degree in electrical power engineering from University of Khartoum, Sudan, in 1996 and 2004, respectively. In 1991, he joined the Department of Electrical Engineering, University of Khartoum, as a Teaching assistant, and in 2005 became an Assistant professor. Since 2013, he has been with the Misruta University/Libya, where he is currently an assistant professor.

Elfadil Zakaria Yahia, received the B.sc., M.sc. and Ph.D. degrees from Sudan University of Science and Technology in 1997, 2002 and 2010 respectively, all in electrical engineering. He has 17 years of experience in electrical power system. Since 2011 he has been head of training and self–assessment (SUST). His interests are power system analysis, power quality and power economics. Dr. Elfadil is full member of (SESJ) Sudan Engineering Society Journal and (SEC) Sudan Engineering Council. Currently, he is assistance professor of electrical power at Misurata University, Libya.

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