Feasibility Assessment of the New Configuration of an Electric Power Grid with 23 kV Tri-axial HTS Power Cables for an Urban Power Supply

C Lee⁵, H Yang⁴, J Choi³, M Park⁴, M Iwakuma⁵

¹ Korea Electric Power Co., Naju 58217, South Korea
² Korea Electric Power Research Institute, Daejeon 34056, South Korea
³ Supercoil Co., Ltd., Changwon, 51140, South Korea
⁴ Department of Electrical Engineering, Changwon National University, Changwon 51140, South Korea
⁵ Research Institute of Superconductor and Systems, Kyushu University, Fukuoka 819-0395, Japan

chulhyu.lee@kepco.co.kr

Abstract. The advantage of high temperature superconducting (HTS) power cables is that they can transmit large amounts of power at relatively low voltages, which can be used to reduce the number of lines in transmission cables or to configure a power grid at lower voltages. Because the commercial operation of 23 kV HTS power cables has begun, the optimal configuration between the 154 kV transformer substations and the 23 kV switching stations connected by the 23 kV HTS cables must be reviewed. In this paper, the new power supply model using 23 kV tri-axial HTS cables is presented for an urban power supply, and the economic feasibility is reviewed to present the appropriate cable capacity selection that matches the 23 kV switching stations.

1. Introduction

A long-term transmission expansion plan, including the construction of new substations and transmission lines, has been established based on various factors, such as economic growth rate, population changes, urban development policies, etc. The construction of power facilities is promoted so that loads can be supplied at the right time; however, during such a process, serious construction delays are often caused by public opposition, or the project itself is aborted. To overcome these challenges, there was an attempt to increase the size of the substation rather than increasing the number of substations, but unfortunately, the project was not carried out because it was difficult to secure a site for a large substation in the downtown area and to connect the several dozens of distribution feeders due to the corridor constraints [1].

The advantages of superconducting cables, which have been rapidly developed in recent years, are greatly highlighted by the fact that they can transmit five to 10 times more capacity than feeders of the same size, which makes them an excellent means to cancel or to relocate substations outside of the city center and to overcome difficulties that have not been resolved due to technological constraints. The first commercialization project of 23 kV HTS power cables was carried out in Shingal, Korea under the leadership of the Korea Electric Power Corporation (KEPCO), and commercial operation began in the second half of 2019. It is assessed that this project has successfully demonstrated that the spare capacity of the two substations can be shared by linking the secondary buses of the existing substations with the 23 kV HTS cables rather than new substation construction [2][3].
Consequently, the use of superconducting cables can make it more realistic to refrain from the construction of 154 kV substations in urban areas or to move them out of urban areas. Therefore, consideration should be given to the new configuration of power supply system and proper capacity selection of 23 kV HTS cables considering the load supply capacity of 23 kV switching stations for an urban power supply.

In our previous study [3], the economic effects of 23 kV tri-axial HTS cables application were compared with the conventional method in radial configuration. It showed that 154 kV substations can be relocated far from urban areas depending on how the 23 kV HTS cables is implemented into the actual power system. In this paper, we extend this radial configuration into the closed loop network replaced with 23 kV HTS power cables. This paper reviews the configuration and proper capacity of the switching stations considering the load density of the target site in urban areas and presents the appropriate capacity selection of the HTS cables from an economic perspective.

It is expected that the study results will be reflected in the design of 23 kV switching stations linked with 23 kV tri-axial HTS cables between 154 kV substations in Seoul, Korea, which will be another demonstration project by KEPCO.

2. Description of HTS Power Platform with 23 kV HTS Cables

2.1. Configuration of HTS power platform

Recently, 23 kV HTS power cables have been developed so rapidly that they can send the capacity of power transmission cables in the near future. Therefore, 154 kV substations can be installed on the outskirts of downtown areas, and two or more 23 kV switching stations with smaller space in urban areas can do the same tasks instead of 154 kV substations. Figure 1 shows a new power system configuration for power supply in urban areas. Two or three 23 kV switch stations are installed near the load center, and they are connected to 154 kV transformer substations with 23 kV HTS cables. The power supply to the individual load is made through the 23 kV distribution feeders from the substation or switching stations. This configuration is called the HTS Power Platform. The conventional method requires cable boxes or cable tunnels for the transmission cables, but the 23 kV HTS cable can be installed in conduits. This is highly effective in enhancing not only the economic efficiency of the superconducting cable but also the construction workability.

![Figure 1. HTS power platform with two 23 kV switching stations](image-url)
2.2. Load density and distance between substations

It appears that the distance between 154 kV substations in urban areas where higher load density than that of rural areas or outskirts, is distributed within about 3-6 km, as shown in figure 2, which shows the frequency of the 154 kV transmission cables of KEPCO’s power system by distance. Figure 3 shows the load density of the 154 kV substations. The load density of the urban or industrial complex is as high as 10 ~ 30 MW per km². Therefore, it might be reasonable for the HTS power platform to have a total load supply capacity of 240 MVA to 360 MVA including the capacity of interconnected substations, which corresponds to the size of two 154 kV substations.

![Figure 2. The number of transmission cables by distance](image)

![Figure 3. Load density of 154 kV substations by supply area](image)

2.3. Cost estimation of 23 kV tri-axial HTS cables considering the number of HTS tapes

The data on the statistically secured materials cost of power facilities, construction cost, and maintenance cost were sufficient; however, 23 kV HTS power cables are still being developed, and there are no prices available for various capacities through market procurement. Therefore, the cost of 23 kV tri-axial HTS cables with the capacity ranging from 60 MVA to 200 MVA, were estimated in the following ways.
Previous study estimated the HTS cable price by simply calculating the required number of HTS tapes matching to the capacity of HTS cables considering the design margin; however, if configured in the form of tri-axial cables, where three phases are wound on a single former, it is necessary to calculate the number of HTS tapes considering the size of copper stranded formers as well as the ratio of transport peak current to DC critical current below 40~60%. The loss of 23 kV HTS power cables can be largely divided into AC current loss and heat loss. In particular, AC loss is closely related to the ratio of the transport peak current $I_t$ and DC critical current $I_c$, which can be expressed using the Monoblock model equation (1) or Norris strip model [4]-[6].

$$P = \frac{fI_t^2\mu_0}{2\pi h^2} \left\{ \left( 2 - \frac{i_t}{I_c} h \right) \frac{I_t}{I_c} h + 2 \left( 1 - \frac{i_t}{I_c} h \right) \ln \left( 1 - \frac{i_t}{I_c} h \right) \right\}$$ \hspace{1cm} (1)

where $f$ is the frequency of the current, and $h$ is defined as

$$h = \frac{D_2^2 - D_1^2}{D_1^2}$$ \hspace{1cm} (2)

where, $D_1$ and $D_2$ are the outer and inner diameters of the superconducting cylinder, respectively. Also, it is necessary to optimize the tape-to-tape gap as small as possible when placing it around the former because AC losses appear to be highly affected by the tape-to-tape gap and layer spaces [5].

Figure 4 shows the result of the number of HTS tapes by the capacity of 23 kV tri-axial HTS cable. For some capacity ranges from 100 MVA to 150 MVA, it can be seen that the same number of HTS tapes appears. It is estimated that number of tapes may vary during optimization of cable design by manufacturers. The outer diameter of 23 kV HTS cables with capacity up to 200 MVA was shown not to exceed 150 mm, which is the installable upper limit of the ELP conduit with the diameter of 200 mm. In this analysis, the minimum DC critical current of HTS tapes is 150A at 77.3K, sf with the width of 4 mm, which is the same as those used in previous study.

![Figure 4. The number of HTS tapes and outer diameter of HTS cables by the capacity of 23 kV tri-axial HTS cables](image-url)
3. Economic Assessment of the HTS Power Platform

3.1. HTS Power Platform with two 23 kV switching stations

In the process of calculating the total investment cost of the HTS power platform as shown in Figure 1, it was considered to be composed of two 23 kV switching stations. It was assumed that the distance between the two switching stations and between the switching station and the 154 kV substation were 2 km and 1 km apart, respectively.

The load supply capacity of the 23 kV switching stations has changed from 60 MVA to 180 MVA, which is the maximum supply capacity of 154 kV substations. The number of 23 kV HTS cables required for this HTS power platform has been calculated to satisfy the deterministic reliability criterion N-1 contingency, which is widely used in practice for transmission expansion planning.

The total investment cost was calculated as the sum of the construction cost of substations, switching stations and HTS cable system including the conduits, which is shown as equation (3).

\[ TIC = C_{TS} + C_{STA} + \sum_{i=1}^{n}(N_{CCT}C_{HTS} + C_{DUCT})L_i \]  

where \( C_{TS}, C_{STA} \) is the construction cost of the 154 kV transformer substations and the 23 kV switching stations, respectively, \( N_{CCT} \) is the number of circuits of 23 kV HTS power cables, \( C_{HTS}, C_{DUCT} \) is the cost of the HTS cable system and duct construction, and \( L_i \) is the length of the i-th section of HTS cables between the substations.

Figure 5 shows the total investment cost of HTS power platform according to the capacity of 23 kV HTS cables in case the station’s supply capacity was set to 90 MVA, 120 MVA and 180 MVA, respectively. The lowest cost appeared when the platform was configured with HTS cables of 90 MVA in case the station’s load supply capacity was set to 90 MVA. If the station’s capacity is increased to 120 MVA, the capacity of HTS cables was found to be the most economical when configured as 120 MVA double circuits. Even when 180 MVA is applied as the station’s load supply capacity, it show that selecting the HTS cables with the capacity of 180 MVA equal to the station’s capacity is most optimal, confirming that it is desirable to maintain an equal station’s load supply capacity and the HTS cable’s capacity. When comparing the unit construction cost of the HTS power platform, it can be seen that the larger the station’s load supply capacity, the lower the unit construction cost. Therefore, the development of higher capacity HTS cables proportional to the platform capacity could contribute to improving power supply capabilities in urban areas.

![Figure 5. Total investment cost of HTS power platform with two 23 kV switching stations and unit investment cost per MVA](image-url)
3.2. HTS power platform with three 23 kV switching stations

The same as the previous platform, but by adding one more 23 kV switching station between the two stations, the total investment cost of the HTS power platform consisting of three switching stations was calculated using the same equation (3). The number of 23 kV HTS cables depends on the load supply capacity of the HTS power platform as well as the HTS cable’s capacity. Figure 6(a) and figure 6(b) show, for example, that on a platform consisting of three 90 MVA stations and 120 MVA stations, respectively, the number of HTS cables satisfy the reliability criterion N-1.

Each line in Figure 7 represents the total investment cost of HTS power platform consisting of 90MVA, 120 MVA, 150 MVA and 180 MVA of 23 kV switching stations by the capacity of HTS cables ranging from 60 MVA to 180 MVA capacity. For example, the bottom blue line represents the total investment cost of HTS power platform in case the switching station’s capacity is set to 90 MVA. Then, the total load supply capacity of this platform is 270 MVA since there are three switching stations. The HTS power platform appears to be the most economical when configured with HTS cables of 90 MVA. Similarly, for the HTS power platform consisting of three 180 MVA stations, the selection of the HTS cables with the capacity of 180 MVA are the most economical.

In case of 120 MVA HTS power platform, the HTS cables with the capacity of 120 MVA was expected to be the best, but the HTS cables of 90 MVA was found to be more economical. It is understood that this was caused by the sharp differences in the number of HTS tapes that make up the HTS cables. As shown in Figure 3, the number of HTS tapes in 90 MVA HTS cable and 100 MVA HTS cable makes a big difference. This phenomenon also occurred on HTS power platforms of higher load supply capacity, but its impact has not been relatively strong.

Figure 6(a). The HTS power platform with three switching stations of 90 MVA and HTS cables of 80 MVA

Figure 6(b). The HTS power platform with three switching stations of 120 MVA and HTS cables of 120 MVA
In order to compare the difference in the total investment costs between the conventional method and the HTS power platform, the land purchase cost for the 154 kV substations and 23 kV switching stations were reflected in the calculation of the total investment cost of the HTS power platform. It was assumed that the land price per m² in urban areas could be varied, but that the cost of the substation site on the outskirts would be set at a minimum of 1 million dollar which is equivalent to the $400/m².

For the land price of $1,000/m², the HTS power platform costs almost twice as much as the conventional method, as shown in Figure 8. On the other hand, if the unit land price is $13,000, there is a break-even price in which the total investment expense between the two methods is equal. Fortunately, it is encouraging that the land purchase expenses of the HTS power platform are significantly lower than conventional methods due to the much smaller space of 23 kV switching stations. If the number of 23 kV switching stations is two with 90 MVA or three with 60 MVA, i.e. the total load supply capacity of the HTS power platform remains the same, the total investment cost of the HTS power platforms with two stations is found to be relatively more advantageous. Figure 9 shows the comparison of the total investment cost between the conventional method and HTS power platform. HTS power platform shows that HTS cable cost accounts for the largest share and the cooling system is the second largest.
3.4. The cost effect of external single return pipe of LN$_2$

The 23 kV tri-axial HTS cables used for this economic evaluation study uses single external pipe as return path of liquid nitrogen for two circuits of HTS cables (2-Go 1-Return type). Thermo-hydraulic analysis was performed to determine operating conditions of 23 kV tri-axial HTS cables considering allowable operating temperature and pressure drop characteristics. [7]

Figure 10 illustrates the cost effect of external single return path of liquid nitrogen. The HTS power platform using 2 Go-1 Return type rather than 1 Go-1 Return type had investment cost savings of approximately 7% or more. For example, if two circuits of HTS cable are necessary, 1 Go -1 return HTS cable system need a total of 4 conduits. However, since the 2 Go-1 return uses only of three conduits, it has the advantage of one more conduit available for distribution feeders. Also, the size of cooling system and the number of monitoring and control systems can be optimized while maintaining the same reliability level. In terms of reliability, it still has the advantage of transmitting the same capacity as long as one of the two HTS cables is used as a return path of liquid nitrogen even in case of single contingency of external return pipe.

Figure 8. Total investment cost of HTS power platform by the land price
Figure 9. Cost comparison between conventional method and HTS power platform

Figure 10. Cost comparison of 1 Go-1 Return and 2 Go-1 return

4. Conclusion
In this paper, the material cost and construction cost have been calculated by both capacity and distance based on 23 kV tri-axial HTS cables, which require much less HTS tape than 3-phase in 1-cryostat HTS cables. During this process, HTS tape was placed around the former, keeping the Iop / Idc within 40 ~ 60% and appropriately controlling the gap to keep the loss below the design value. Rather than installing 154 kV substations in urban areas, an HTS cable utilization model has been presented to enable 23 kV switching stations to be installed near the load center and to supply power through them. It has also been confirmed that the appropriate capacity of the superconducting cable is closely related to the load supply capacity of 23 kV switching stations.

As KEPCO has been increasing the efficiency of power facility investments and operations by standardizing the capacity of substations and power transmission lines for a power supply, it is
expected that standardization measures can be established to form the HTS power platform through the relationship between switching station capacity and HTS cable capacity derived through this research. In the future, demonstration projects for a power supply in urban areas could be carried out during the process of installing 23 kV tri-axial HTS cables between the 154 kV substations in Seoul and the 23 kV switching stations in the middle.

5. References

[1] H. Oh, Y. Won, J. Hwang, “The long-term transmission & substation plan in Korea power system,” 2009 Transmission & Distribution Conference & Exposition: Asia and Pacific, Oct. 2009
[2] D. Koo, Y. Won, C. Ryu, et al., “World’s first commercial project for a superconducting cable system in Korea,” CIGRE 2018, B1-303, Aug. 2018
[3] C. Lee, J. Choi, H. Yang, M. Park, M. Iwakuma, “Economic evaluation of 23 kV tri-axial HTS cable application to a power system,” IEEE Trans. Appl. Supercond., vol. 29, no. 5, Aug. 2019
[4] N. Amemiya, Z. Jiang, M. Nakahata, et al., “AC loss reduction of superconducting power transmission cables composed of coated conductors,” IEEE Trans. Appl., vol. 17, no. 2, Jun. 2007
[5] S. Fukui, J. Ogawa, N. Suzuki, et al., “Numerical analysis of AC loss characteristics of a multi-layer HTS cable assembled by coated conductors,” IEEE Trans. Appl. Supercond., vol. 19, no. 3, Jun. 2009
[6] S. Kim, K. Sim, J. Cho, H. Jang, M. Park, “AC loss analysis of HTS power cable with RABiTS coated conductor,” IEEE Trans. Appl. Supercond., vol. 20, no. 3, Jun. 2010
[7] C. Lee, D. Kim, et. Al., “Thermo-hydraulic analysis on long three-phase coaxial HTS power cable of several kilometers,” IEEE Trans. Appl. Supercond., vol. 29, no. 5, Aug. 2019

Acknowledgments
This work was supported by Korea Electric Power Corporation