Power flow analysis of a 5-bus 10 kV power system with high temperature superconducting cable

Bangzhu Wang¹,*, Ni Yang¹,³, Ziheng Hu², Bin Zhang², Wei Wang², Shaotao Dai¹

¹School of Electrical Engineering, Beijing Jiaotong University, Beijing, China
²Shenzhen Power Supply Bureau Co., Ltd., Shenzhen, China
³China Railway Nanning Bureau Group Co., Ltd., Nanning, China

*Corresponding author e-mail: bzwang@bjtu.edu.cn

Abstract. High temperature superconducting (HTS) power cable provides a promising solution for the challenges the power grids confront. As most of the existing HTS cable projects operated the cable in an isolated system, we have little knowledge about the power flow of the system when HTS cable integrated, which is essential for planning, operation, and protection of a power system containing HTS cable. In the paper, we build a 10 kV 5-bus power system with one HTS cable line and the same line with normal cable is as the benchmark. We solve the model and analyse the power flow of the system under normal operation, line disconnection, source power off, and load growing conditions. The results show that HTS cable tends to undertake more transmission energy and makes the connected buses more robust in terms of voltage drop. As HTS cable’s behaviour is different, it is necessary to readjust the settings and configurations of the secondary side apparatus of power system.

1. Introduction

High temperature superconducting (HTS) power cable, with the hallmarks of low transmission loss, high power density, and environmentally friendly, provides a promising solution for the challenges the power grids confront. In the past two decades, several HTS power cable projects in the world were carried out and demonstrated the feasibility for power transmission in the power system[1-4]. Although HTS cable technology has made tremendous advancement, few projects were integrated into the grid as ‘no-special’ line, i.e. the HTS cable’s operation was isolated in the grid to some extent. Thus, we have little knowledge about the influence of HTS cable on the power system[5, 6]. However, for planning, operation, and protection of HTS cable, power flow analysis is the first and basic step and has significant meanings for these works a) electric equipment selection; b) fault current handle and relay protection configurations; c) system operation mode selection; d) power flow forecasting; and et al.

In the paper, we build a 10 kV 5-bus power system with one HTS cable line and analyze its power flow under several normal operation, line disconnection, source power off, and load growing conditions. The results will be used for 10 kV HTS cable system design in Shenzhen City and they have reference value for other related projects.
2. Model and configuration
For simplification and to obtain the common sense of the power flow characteristics, we use a 10 kV 5-bus system as the analysis benchmark[7, 8]. The single line diagram of the 5-bus system is as Figure 1.

![Figure 1. single line diagram of 10 kV 5-bus system](image)

The system has two generator, five buses, and three loads. Any two buses are connected by a transmission line. Bus-1 is a PV and bus-2 swing. All loads are PQ and Y-grounded. Line parameters are listed as Table 1[9].

| Line | Impedance/Ω | Admittance/S | Line | Impedance/Ω | Admittance/S |
|------|-------------|--------------|------|-------------|--------------|
| 1-2  | 0.04+j0.25  | 0.03         | 2-5  | 0.06+j0.2 (normal) | 0.015     |
| 1-3  | 0.1+j0.35   | 0.025        | 2-5  | 0.0001+j0.00006 (HTS) | 0.01      |
| 2-3  | 0.08+j0.3   | 0.02         | 3-4  | 0.02+j0.15  | 0.025      |
| 2-4  | 0.09+j0.2   | 0.02         | 4-5  | 0.1+j0.3    |            |

To solve the model, MATLAB/Simulink is used as Figure 2. Every block’s parameters are configured as above given.

![Figure 2. model implementation using MATLAB/Simulink](image)

3. Simulation analysis and discussion
Using the model, we analyze the power flow under four different conditions. For comparisons, line 2-5 will use normal line and HTS cable line, respectively.
3.1. Normal operation condition
First the system with and without HTS cable, i.e. line 2-5 is connected with a normal power line or HTS cable, are studied. The results without HTS cable are regarded as the benchmark reference values. Table 2 shows the comparison values. We can see that due to HTS cable’s integration, system flow changes, especially for node 5 and its neighbour node 4. The current of line 2-5 is 4.03 kA for normal state. The results in Table 5 show that the increased power of load 2 is preferably obtained through 6.86 kA for HTS cable.

Table 2. Power flow under normal operation condition

| Node | P/MW | Q/Mvar | V/pu | Phase/° |
|------|------|--------|------|---------|
|      | Normal | HTS | Normal | HTS | Normal | HTS | Normal | HTS | Normal | HTS |
| 1    | 286.95 | 291.47 | 203.60 | 202.67 | 1.06 | 1.06 | 0 | 0 |
| 2    | 500 | 500 | 40.26 | 29.33 | 1.00 | 1.00 | 33.93 | 33.67 |
| 3    | 125.52 | 132.22 | 44.55 | 42.12 | 0.94 | 0.95 | 18.79 | 19.83 |
| 4    | 87.72 | 100.65 | 16.66 | 12.96 | 0.93 | 0.95 | 23.64 | 25.71 |
| 5    | 69.31 | 100.17 | 10.00 | 15.46 | 0.93 | 1.00 | 25.58 | 32.69 |

3.2. G1 power off
If G1 is power off because its fault or any other reasons, the only source of the system would be G2. As HTS cable is connected to bus 2, it may undertake severe power transmission condition. Table 3 gives the power flow redistribution results of both normal and HTS line 2-5 under G1 power off condition. In terms of voltage of buses, system with HTS cable drops less. The current of line 2-5 is 3.52 kA for normal cable while 5.17 kA for HTS cable.

Table 3. Power flow with G1 power off

| Node | P/MW | Q/Mvar | V/pu | Phase/° |
|------|------|--------|------|---------|
|      | Normal | HTS | Normal | HTS | Normal | HTS | Normal | HTS | Normal | HTS |
| 1    | 178.44 | 174.92 | 79.44 | 66.93 | 1.06 | 1.06 | 0 | 0 |
| 2    | 97.30 | 99.07 | 27.97 | 23.02 | 0.92 | 0.94 | -14.18 | -13.37 |
| 3    | 73.88 | 67.33 | 18.38 | 15.00 | 0.90 | 0.93 | -17.13 | -15.46 |
| 4    | 53.90 | 40.00 | 7.08 | 6.48 | 0.88 | 0.95 | -19.98 | -14.47 |
| 5    | 60.00 | 65.69 | 10.00 | 11.79 | 0.93 | 0.95 | -13.75 | -13.76 |

3.3. Line 2-4 disconnection
When a line is under fault, system will use breaker to disconnect the line. If reclosing fails, the line will be drop out. Here, we consider this situation and drop line 2-4 out. We can figure out that as line 2-4 disconnected, bus 4’s active power and voltage drop while bus 5 raise. As expected, HTS one drops less and raise more. For comparison, the current of line 2-5 is 5.02 kA for normal cable while 6.86 kA for HTS cable.

Table 4. Power flow with line 2-4 disconnection

| Node | P/MW | Q/Mvar | V/pu | Phase/° |
|------|------|--------|------|---------|
|      | Normal | HTS | Normal | HTS | Normal | HTS | Normal | HTS |
| 1    | 281.41 | 288.61 | 209.21 | 202.85 | 1.06 | 1.06 | 0 | 0 |
| 2    | 500 | 500 | 74.81 | 52.39 | 1.00 | 1.00 | 36.62 | 35.35 |
| 3    | 105.61 | 118.70 | 50.66 | 31.00 | 0.91 | 0.94 | 15.06 | 17.56 |
| 4    | 40.00 | 68.67 | 15.80 | 13.54 | 0.89 | 0.92 | 15.03 | 20.56 |
| 5    | 99.91 | 134.29 | 10.00 | 18.32 | 0.91 | 1.00 | 23.94 | 34.04 |

3.4. Load 2 power demand growing
Load growing is common in power grid. We triple the load 2 and study the power flow in steady state. The results in Table 5 show that the increased power of load 2 is preferably obtained through HTS cable and HTS cable keeps the bus voltages more robust.
Table 5. Power flow with load 2 power demand growing

| Node | P/MW  | Q/Mvar | V/pu | Phase/° |
|------|-------|--------|------|---------|
|      | Normal | HTS | Normal | HTS | Normal | HTS | Normal | HTS |
| 1    | 255.92 | 26.025 | 175.81 | 174.71 | 1.06 | 1.06 | 0 | 0 |
| 2    | 500    | 500   | 33.12 | 24.11 | 1.00 | 1.00 | 30.01 | 29.77 |
| 3    | 113.87 | 120.23 | 43.32 | 41.13 | 0.95 | 0.96 | 16.12 | 17.11 |
| 4    | 81.67  | 94.17  | 17.27 | 13.43 | 0.94 | 0.95 | 20.31 | 22.31 |
| 5    | 67.46  | 97.38  | 10 | 14.19  | 0.94 | 1.00 | 21.90 | 28.81 |

4. Conclusion
Having very low resistance and inductance, HTS cable changes or redistributes the power flow when it is integrated into the power system. In the paper, we build a 10 kV 5-bus power system and analyze the power flow of normal cable and HTS cable under normal operation, source power off, line disconnection, and load growing conditions. From the simulation results, we can draw these conclusions:

(1) HTS cable tends to undertake more transmission energy. However it has current carrying capacity limits. For HTS cable design, one should consider not only the rated current but also the potential maximum current determined by the integrated whole system;

(2) HTS cable makes the connected buses more robust in terms of voltage drop, which is merciful for the grid. But think in turn, after the system adjusts based on HTS cable behaviors, the system would be less robust when HTS cable is forced to drop out.

(3) Thought only one HTS cable line is introduced into the system, we can see that the power flow of all nodes changes more or less. It is necessary to readjust the settings and configurations of the secondary side apparatus of power system.

Acknowledgments
This work was financially supported by Natural Science Foundation of China (51477165), China Southern Power Grid Major Science and Technology Program (SZKJXM20170410) and Fundamental Research Funds for the Central Universities (2016JBZ011 and 2017RC009).

References
[1] P.M. Grant, Superconducting Lines for the Transmission of Large Amounts of Electrical Power Over Great Distances: Garwin–Matisoo Revisited Forty Years Later, IEEE Transactions on Applied Superconductivity 17 (2007) 1641-1647.
[2] D. Kottonau, E. Shabagin, M. Noe, and S. Grohmann, Opportunities for High-Voltage AC Superconducting Cables as Part of New Long-Distance Transmission Lines, IEEE Transactions on Applied Superconductivity 27 (2017), 2483648.
[3] H.C. Lee, Y.G. Roh, and B.J. Jung, A Study for Control Power System Load Flow by Shield Control of High-TC Superconducting Cable, Indian Journal of science and technology 9 (2016).
[4] S.R. Lee, J. Lee, J. Yoon, Y. Kang, and J. Hur, Impact of 154-kV HTS Cable to Protection Systems of the Power Grid in South Korea, IEEE Transactions on Applied Superconductivity 26 (2016), 1-4.
[5] Z. Liu, Z. Lin, Z. Zhang, and S. Yang, Feasibility research for underground power transmission application of HTS cable, Taiwan Electric Power Corporation, 2012.
[6] P. Manuel, F.X. Camescasse, M. Coevoet, V. Leitloff, F. Lesur, E. Serres, P. Suau, and J.A. Muraz, Prospects for application of high temperature superconductors to electric power networks, Physica C: Superconductivity 372–376 (2002), 1591-1597.
[7] S. Parvathy, K.C.S. Thampatty, and T.N.P. Nambiar, Response of voltage source model of UPFC in an IEEE 5 bus system for power flow enhancement, in: 2017 International Conference on Technological Advancesments in Power and Energy (TAP Energy), 2017, pp. 1-5.
[8] H. Thomas, A. Marian, A. Chervyakov, Stefan Stückrad, D. Salmieri, and Carlo Rubbia, Superconducting transmission lines – Sustainable electric energy transfer with higher public acceptance?, Renewable and Sustainable Energy Reviews 55 (2016), 59–72.

[9] D. Wu, R. Wu, Z. Chen, W. Xie, and X. Huang, Power Flow Analysis and Visualization in Smart Grid, Springer Berlin Heidelberg, Berlin, 2014.