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# FEASIBILITY STUDY OF ULTRA LONG DISTANCE HVDC TRANSMISSION TO JAPAN

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**ABSTRACT**
The objective of the present paper is to study engineering feasibility of ultra long distance HVDC transmission lines (2500 km and 4000 km) to Japan. It has been shown that the loss of the lines ranges from 4 % for 800 kV and 2500 km to 17 % for 500 kV and 4000 km, depending on the voltage used and the line length needed. Usefulness of STATCOM has, then, been studied, where the power flow calculation and the transient stability analysis have been carried out to simulate the transient response of AC voltage after the three-phase ground fault or the DC line fault. It has been shown that STATCOM has an ability to keep the AC voltage high and to send full designed 5.0 GW of DC power. A comparison between the systems with and without STATCOM has shown that the recovered AC voltage after the three-phase ground fault becomes higher, as the node connected with STATCOM is nearer to the inverter. It is also found that the difference between the systems with and without STATCOM becomes small for the DC line fault compared with the AC fault.

**KEY WORDS**
Ultra long distance HVDC transmission lines, DC-AC inverter, STATCOM, AC and DC line faults

## 1. Introduction

Most of energy supply has depended on fossil fuels in Japan. There is a possibility that in some future it will become difficult to supply energy to Japan due to exhaustion of fossil fuels. Ishikawa, one of the authors, has proposed the import of natural energy from Tugursk in Russia to Kanto region in Japan (route 1) and from Yakutsk to Kansai region (route 2) with High Voltage Direct Current (HVDC) [1]-[3]. This is called 'ultra long distance HVDC transmission'. Figure 1 shows the proposed routes of the ultra long distance HVDC transmission lines. When transmission lines are long, HVDC is lower in costs and more stable than AC. It has been shown that the losses of DC transmission lines are 11% from Tugursk to Kanto region and 17.4% from Yakutsk to Kansai region under the condition of DC voltage of 500 kV, and 4.2% from Tugursk to Kanto region and 7.4 % from Yakutsk to Kansai region under the condition of DC voltage of 800 kV [4],[5]. The loss is relatively low with high voltage, so that there is possibility to realize the ultra long distance HVDC transmission lines. Shimizu, Ishikawa and others have carried out a study of engineering feasibility of ultra long distance HVDC transmission lines. They have also studied effects of Static Synchronous Compensator (STATCOM) on the ultra long distance HVDC transmission lines. It has shown that fluctuation of the AC voltage with STATCOM is smaller than that without STATCOM [5],[6]. Low Short Circuit Ratio (SCR), however, reduces the AC voltage at the node connected with the DC-AC inverter after the three-phase ground fault, because one of AC parallel transmission lines is of no use and the reactive power is in short supply there. There has not been a study exploring the possibility that STATCOM makes the AC voltage recover at the node connected with the DC-AC inverter. The present paper in tends to show engineering feasibility of ultra long distance HVDC transmission lines (2500 km and 4000 km) to Japan.


Figure 1 Routes of ultra long distance HVDC transmission lines

## 2. Simulation Results

### 2.1 Model System

Figure 2 shows a model system of the ultra long distance HVDC transmission line of the route 1, where a simplified electric power network is used. For example, the route 1 of the network has the Tugursk system on the sending side and the Kanto region system on the receiving side, while the ultra long distance HVDC transmission lines are connected between the Tugursk system and the Kanto region system. The Tugursk system consists of a synchronous generator of 5.0 GW, a transformer, and an AC-DC converter. The generator is assumed to be a unified large one. The transformer controls the AC voltage of the Tugursk system, and the AC-DC converter is assumed to be a line-commutated converter. The Kanto region system consists of a DC-AC inverter, STATCOM, AC parallel transmission lines, a transformer, a synchronous generator of 57 GW, and a load. It is assumed that DC-AC inverter is a line-commutated inverter and STATCOM is linked at some node. The transformer controls the AC voltage of the Kanto region system. The generator is also assumed to be a unified large one and the load consumes the effective power of 57 GW. Static Var Compensator (SVC) with a forced-commutated converter is called 'Static Synchronous Compensator (STATCOM)'.

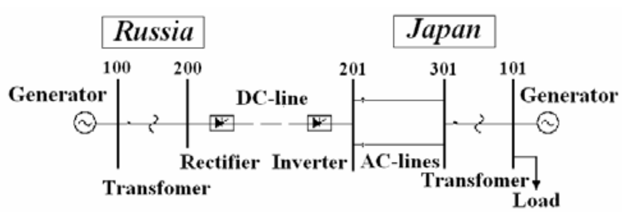


Figure 2. Model system of route 1

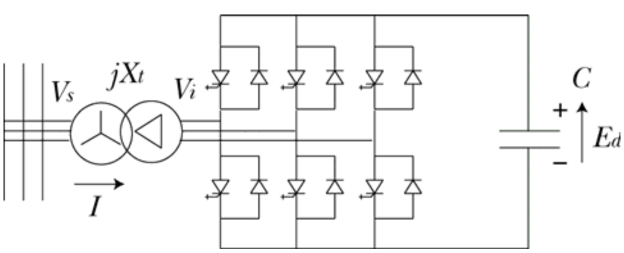


Figure 3. Model of STATCOM

Figure 3 shows a model of STATCOM, which has ability to control the reactive power by itself and is treated as an AC voltage source. The DC capacitor voltage $E_d$ generates the inverter output voltage $V_i$, when $V_i$ is higher than the system voltage $V_s$, whereas STATCOM consumes the reactive power when $V_i$ is lower than system voltage $V_s$. In AC system, it is required to keep the voltage high because the voltage reduction causes voltage instability. In this study, the AC voltage is kept to be 95 % of the rated voltage by using STATCOM.

### 2.2 Analysis Conditions

Table 1 lists the data used for the power flow calculation.

Table 1
Data used for analyses

| | |
|---|---|
| Rated DC voltage | 500 [kV], 800 [kV] |
| Transmission line resistance | 0.00227 [Ω/km] |
| Transmission line inductance | 0.0001844 [H/km] |
| Transmission line capacitance | 0.0069776 [μF/km] |
| Sending DC power | 5.0 [GW] |
| Phase-control angle of rectifier | 19 [degree] |
| DC voltage of inverter | 0.89 [p.u.] (500 kV) |
| | 0.96 [p.u.] (800 kV) |
| Phase-control angle of inverter | 135 [degree] |
| System reference capacity | 1000 [MVA] |
| Rated AC voltage | 500 [kV] |
| Power consumption in the point of demand | 57 [GW] |
| Short circuit Ratio | 2.0 – 5.0 |

### 2.3 Primary Power Flow

The present study adopts the L-method in order to obtain the power flow calculation, while the Y-method is used to carry out stability analysis. The L-method and the Y-method [8] have been developed by Central Research Institute of Electric Power Industry (CRIEPI), Japan, and have been used widely.

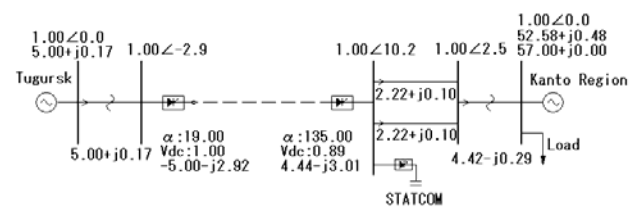


Figure 4. Power flow result for 500 kV, DC (route 1)

Figures 4 and 5 show results of the power flow calculation for the route 1, where Fig. 4 is the result obtained under the condition of 500 kV (DC) and Fig.5 is obtained for 800 kV, while SCR is 5.0. The results of the power flow calculation are used as the initial power flow for the three-phase ground fault analyses. As shown in Fig.4, the active power is 4.44 GW and the reactive power is –3.01 Gvar at the receiving side, whereas Fig.5 shows that the active power is 4.78 GW and the reactive power is –3.38 Gvar, indicating that the amount of consumption of the reactive power becomes larger, as the inverted active power is larger. More reactive power is, therefore, compensated in the system of the 800 kV DC transmission line than the system of the 500 kV DC transmission line.

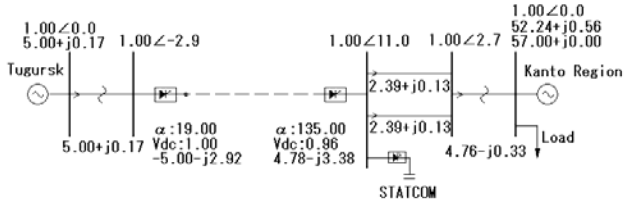


Figure 5. Power flow result for 800 kV, DC (route 1)

### 2.4 Transient response of AC voltage

Figures 6 and 7 show the transient responses of AC voltage at the three-phase ground fault in the cases without and with STATCOM, respectively. Conditions for the analyses are 3.1 for SCR, 500 kV for the DC voltage, and 5.0 GW for the sending DC power. As shown in Fig.6, the AC voltage in steady state without STATCOM becomes 0.90 p.u. after the three-phase ground fault, and on the other hand, Fig.7 indicates that the AC voltage with STATCOM becomes 0.95 p.u. in the steady state. Comparison of the results tells that the recovered AC voltage operated with STATCOM is higher than one without STATCOM after the three-phase ground fault for the present ultra long distance HVDC transmission lines. Both system can recover to the steady state at about 3 s after the three-phase ground fault.

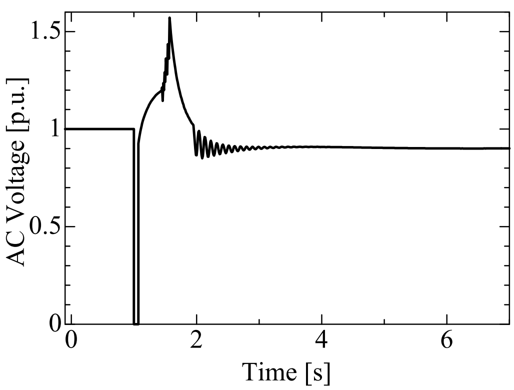


Figure 6 Transient response of AC voltage at ground fault without STATCOM (500kV, route 1)

These figures also show that the overvoltage occurs from about 1.0 s to 2.0 s. Without STATCOM the overvoltage is about 1.50 p.u., whereas the overvoltage becomes about 1.25 p.u. with STATCOM, demonstrating that STATCOM has an ability to restrain the overvoltage occurring after the three-phase ground fault. It should be noticed that the overvoltage has only one peak in the case without STATCOM, whereas the system with STATCOM has two peaks of the overvoltage, although the peak is lower compared with the case without STATCOM

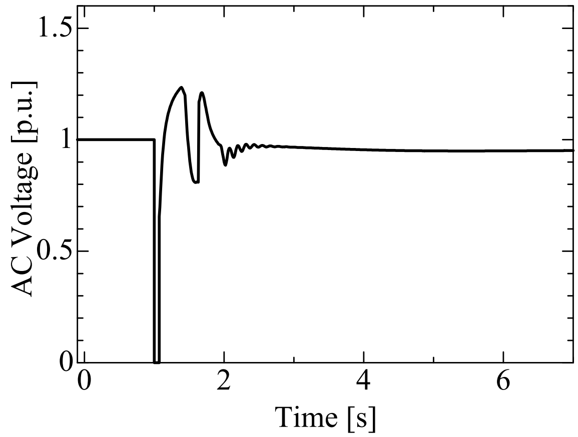


Figure 7 Transient response of AC voltage at ground fault with STATCOM (500 kV, route 1)

### 2.5 Recovery of AC voltage

Figures 8 and 9 depict the characteristics of SCR and AC voltage in the steady state after the three-phase ground fault. The conditions for Fig.8 are 500 kV for the DC voltage and 5.0 GW for the sending DC power, whereas the conditions for Fig.9 are 800 kV for the DC voltage with the same 5.0 GW for the sending DC power.

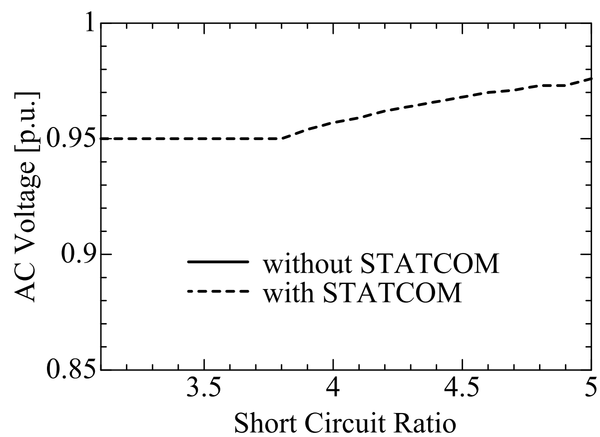


Figure 8. Characteristics of SCR and AC voltage for 500 kV, DC (route 1)

Without STATCOM, the AC voltage decreases as SCR decreases, because the reactance of AC transmission lines increases as SCR decreases. With STATCOM, AC voltage is kept 0.95 p.u. under the condition of the AC voltage without STATCOM less than 0.95 p.u., because STATCOM compensates the shortfall of the reactive power. The comparison indicates that STATCOM has an ability to keep AC voltage high, when SCR is low for the present ultra long distance HVDC transmission line. It should be noticed that the recovered voltage can become more than 0.95 p.u. in both cases, if the AC system is strong with SCR more than 4.

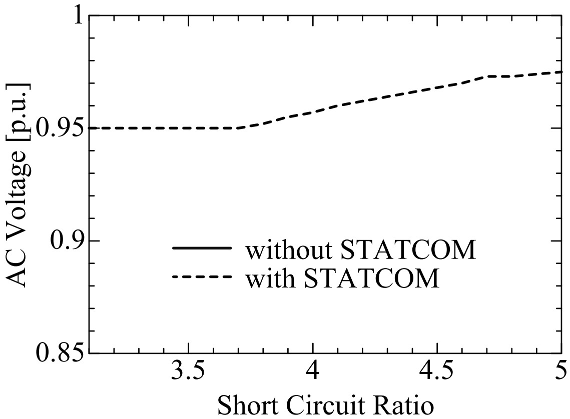


Figure 9. Characteristics of SCR and AC voltage for 800 kV, DC (route 1)

## 2.6 Operation limit of systems

Figures 10 and 11 show the operation limit of the systems, which means how much electric power can be sent at the maximum after the three-phase ground fault. The condition of the operation limit is 0.95 or over 0.95 of the AC voltage after the three-phase ground fault in both cases of Fig.10 (500 kV, DC voltage) and of Fig.11 (800 kV, DC voltage).

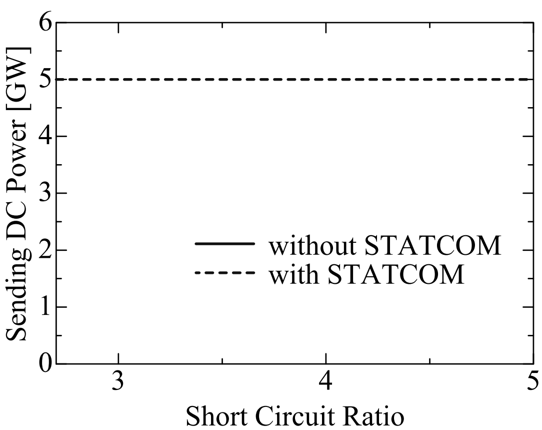


Figure 10 Operation limit for system of 500 kV (route 1)

Without STATCOM, the sending DC power decreases as SCR decreases when SCR is less than 3.8. Because line-commutated inverters need the reactive power which is about 60 % of active power, the sending DC power must be reduced, if the reactive power decreases at the node connected with the DC-AC inverter. With STATCOM, however, the sending DC power becomes 5.0 GW regardless of SCR, because STATCOM can compensate the reactive power that is consumed after the three-phase ground fault. The comparison of the results indicates that it is better to apply STATCOM to the ultra long distance HVDC transmission line sending 5.0 GW, when SCR is less than 3.8.

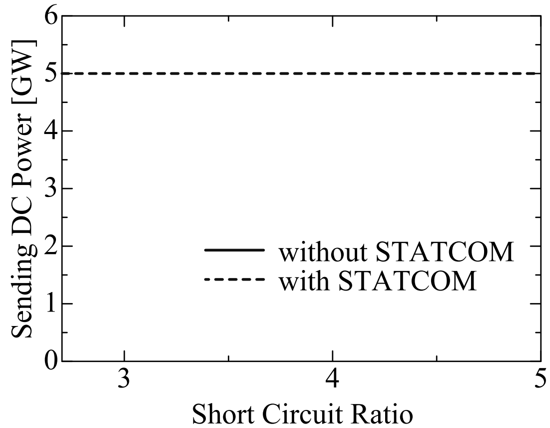


Figure 11. Operation limit for system of 800 kV (route 1)

## 2.7 Best node for STATCOM

In order to select the best node for STATCOM, the nodes 201, 301 and 302 in Fig.2 have been examined for the connection node of STATCOM, while the three-phase ground fault is assumed to occur at one of AC parallel transmission lines near the node 301. This section treats the results obtained for the route 2 under the condition of 500 kV, DC voltage and STATCOM of 340 Mvar.

Table 2
Relation of STATCOM Node and AC Voltage with Reactive Power at Node 201 with STATCOM of 340 Mvar for route 2

| *STATCOM* | *AC Voltage at node 201* | *Reactive Power at node 201* |
|---|---|---|
| *Without STATCOM* | *0.875 [p.u.]* | *0.001 [Gvar]* |
| *201* | *0.950 [p.u.]* | *0.269 [Gvar]* |
| *301* | *0.880 [p.u.]* | *0.013 [Gvar]* |
| *302* | *0.921 [p.u.]* | *0.166 [Gvar]* |

Table 2 shows the relation of the STATCOM node and the AC voltage with the reactive power at the node 201 after the three-phase ground fault. It has been found that the AC voltage at the node 201 becomes the highest with STATCOM connected at the node 201, which is the nearest to the node 201, and on the other hand, the AC voltage at node 201 becomes the lowest with STATCOM connected at the node 301, which is the furthest to the node 201. These results indicate that the AC voltage at the node 201 recovers higher as STATCOM is nearer to the node 201.

Figure 12 depicts the power flow, when the AC voltage at the node 201 drops, showing that the reactive power becomes lower as the node is nearer to the node of inverter and that STATCOM compensates more reactive power, as the node that is short of reactive power is nearer. It is, therefore, concluded that STATCOM is better to be connected with the node of inverter.

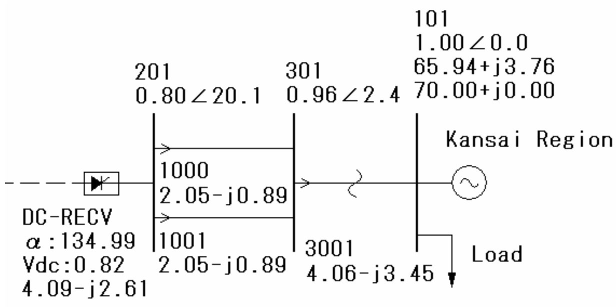


Figure 12. Power flow when AC voltage drops with STATCOM of 340 Mvar and 500 kV for route 2

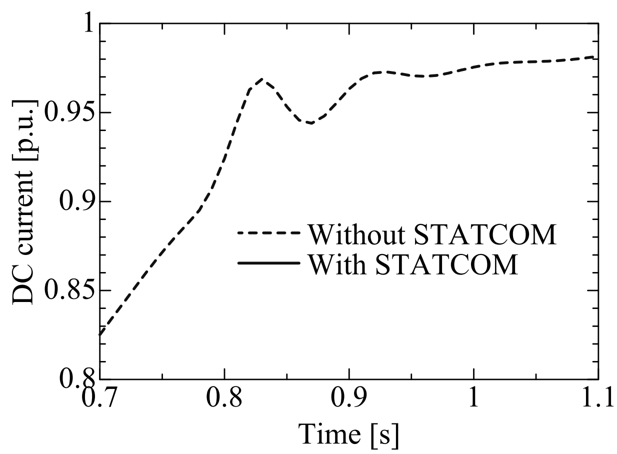


Figure 13. Transient Response of DC Current (from 0.70 s to 1.10 s) for route 2

### 2.8 Effects of STATCOM against DC Line Fault

STATCOM can control the AC voltage by producing or consuming the reactive power. The transient response of the AC voltage after the DC line fault for the route 2 operated with 500 kV indicates that the overvoltage occurs from about 0.00 s to about 0.06 s immediately after the DC line fault happens. It has been found that the AC voltage without STATCOM becomes about 1.30 p.u. and about 1.25 p.u. with STATCOM and that the overvoltage with STATCOM is lower than without one after the DC line fault. Thetransient response of the reactive power at the node 201 from 0.00 s to 0.08 s shows that the reactive power with STATCOM is lower than one without STATCOM, because STATCOM consumes excessive reactive power. The overvoltage with STATCOM, therefore, is kept lower than without STATCOM. It has been also found that the overvoltage occurs again from about 0.75 s to about 1.00 s, showing that the overvoltage with STATCOM is higher than without STATCOM. The response is opposite to the response of the overvoltage from about 0.00 s to about 0.06 s. The transient response of the reactive power at the node 201 from 0.70 s to 1.10 s indicates that the reactive power with STATCOM becomes higher than one without STATCOM. The transient response of the DC voltage for the route 2 with 500 kV after the DC line fault shows that there is a difference of behavior with and without STATCOM from about 0.75 s to about 1.10 s and the DC voltage with STATCOM is higher than without one.

The DC voltage depends on the AC voltage, the DC current, and the phase-control angle. Namely, the DC voltage of inverter becomes higher when the AC voltage becomes higher, the phase-control angle becomes larger, and the DC current becomes higher. The AC voltage with STATCOM becomes higher than one without STATCOM, resulting in the rise of the DC voltage with STATCOM.

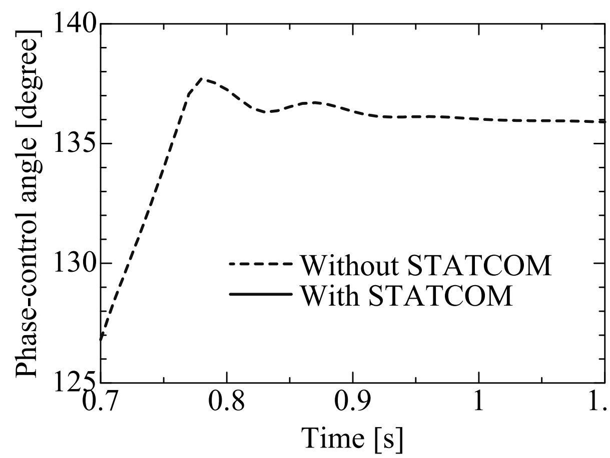


Figure 14. Transient Response of Phase-Control Angle (from 0.70 s to 1.10 s) for route 2

Figure 13 depicts the transient response of the DC current after the DC line fault, showing that the DC current with STATCOM is higher and lower than the DC current without STATCOM, depending on the period. Figure 14 shows the transient response of the phase-control angle from 0.70 s to 1.10 s, where the phase-control angle with STATCOM becomes higher than the angle without STATCOM after 0.8 s. The phase-control angle with STATCOM, therefore, leads to the rise of the DC voltage with STATCOM. It is then found that the rise of DC voltage with STATCOM depends on the AC voltage and the phase-control angle. It is also found that the AC voltage with STATCOM becomes better and worse to a small extent, and that the DC voltage with STATCOM becomes worse than without STATCOM in the case of the DC line fault. The difference of the AC or DC voltage between the cases with and without STATCOM is, however, little. It is, therefore, concluded that it is better to install STATCOM on the ultra long distance HVDC transmission lines from the viewpoint of recovery of the AC voltage after the three-phase ground fault.

## 3. Conclusion

The following results have been obtained.

It has been found that the ultra long distance HVDC transmission lines (2500km or 400 km long) can be stably operated, when operated with STATCOM.

STATCOM has ability to control the overvoltage of the ultra long distance HVDC transmission lines, when the three-phase ground fault happens.

STATCOM has ability to keep the AC voltage high on the ultra long distance HVDC transmission lines, even when SCR is low.

It has been found that SCR and the rated DC voltage are important parameters, when the capacity of STATCOM is decided for the ultra long distance HVDC transmission lines.

From the study of the best node for STATCOM, it is concluded that STATCOM is better to be connected with the inverter, because STATCOM compensates more reactive power as the node being short of reactive power is nearer.

The effects of STATCOM on the AC voltage and the DC voltage are rather small in the case of DC line fault, and therefore It is concluded that it is better to install STATCOM on the ultra long distance HVDC transmission lines.

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