DC-DC Converter Control Method for High Voltage DC Feeding System to Improve Use of Regenerative Power

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A high voltage DC feeding system, which consists of higher-voltage feeders and DC-DC converters in addition to an existing feeding circuit, is assumed to improve the performance of power supply to trains without changing the nominal voltage of contact lines and onboard traction systems. In this system, the method for controlling the converter is an important element which must be taken into consideration to maximize energy savings. In this paper, we propose a converter control method to make the voltage ratio constant between the contact line and the higher-voltage feeder. In this paper, the high voltage DC feeding system with this converter control method is called a “DC-AT feeding system.” We evaluated the energy savings of this system through simulation, and case studies on a model line confirmed that this system can reduce energy consumption by 4.5% at most, and on average 3.5%, compared to conventional DC feeding systems.

Key words: DC feeding system, high-voltage DC feeding system, DC-DC converter, regenerative power, energy saving, auto-transformer

1. Introduction

DC electric railways are generally low-voltage and high-current systems for the amount of power they should supply. For this reason, there are problems such as voltage drops and Joule loss, due to the resistance of contact lines, due to the large resistance of contact lines, feeders and rails, and poor utilization of regenerative braking power.

In Japan, to solve these problems proposals have been made on several occasions until now to change the standard voltages of the contact line from 1500 volts to 3000 volts. However, implementation of this proposals was too difficult: not only because of the high cost and time required for renovating contact line supports and substations, but also because of the need for expensive dual voltage motor cars that can operate under multiple DC voltages used while construction of the system was underway.

This led to the idea of a “high-voltage DC feeding system,” shown in Fig. 1. This idea has been examined in various fields for some time [2, 3]. One of the purposes of this system is to obtain the same advantages as raising the standard voltage of contact lines, by installed “high voltage feeders” with a higher voltage than that of the contact line. With this method, existing 1500 V trains can continue to operate, and construction can be advanced in stages. However, in order for the system to function effectively, one particular issue had to be overcome: how to control power converters that transfer power between the contact line and the high-voltage feeder.

Therefore, we examined a new control method for the converters used in this system. The new method can promote the interchange of regenerative power, and significant energy savings can be obtained. This paper describes the details of the control method, and simulation case studies conducted to verify energy savings achieved with this system by implementing this method.

2. High-voltage DC feeding system

2.1 Outline configuration of high-voltage DC feeding system and its expected effects

In the high-voltage DC feeding system, the voltage of the contact line (hereinafter referred to as T; including existing feeder) is not changed, but a high-voltage feeder (F) is added to operate at a higher voltage than T, and DC-DC converters (hereinafter referred to as converters) are installed at traction substations (hereinafter referred to as SS) and track sectioning cabins (hereinafter referred to as SP). The converters transfer power between the T side and the F side, and the power flow between substations and loads (trains) are divided appropriately between the T side and the F side.

One significant advantage of this system is that it can achieve the same effect as raising the contact line voltage while continuing to use existing vehicles. Control methods and circuit methods of the converters are important factors to determine the effectiveness of the high voltage feeder system.

2.2 Solving the problems of DC electric railways with a high voltage DC feeding system

Silicon diode rectifiers (hereinafter referred to as diode rectifiers) are generally used in DC electric railways. The power flow of diode rectifiers is unidirectional from AC to DC. Therefore, in order to save energy, the regenerative power generated by a decelerating train using regenerative braking (regenerating train) should be used.
better within the feeding circuit, that is, it should be smoothly transferred to another accelerating train (powering train).

However, compared to the peak power flow up to several megawatts per train in acceleration or deceleration, the nominal value of 1.5 kV is sometimes considered not high enough to ensure sufficient power transfer capability. One of the examples is restriction of regenerative braking. When there is a large distance between a regenerating train and a powering train, the transferable current between them is limited due to line resistance to avoid excessive voltage not allowed by the insulation design or traction circuit design. In such cases, the reuse rate of kinetic energy is low because mechanical brakes or onboard brake resistors are used to secure braking force.

With the larger power transfer capability obtained from adding high-voltage feeders, we expect that the high-voltage DC feeding system will be able to promote regenerative power interchange between trains and bring significant energy savings. However, previous studies have examined the high-voltage DC feeding system only from the perspective of improving the efficiency of power supply from substations to trains, and there have been few specific studies of the effect of promoting regenerative power interchange [2, 3]. Therefore, we did research focused on this point.

3. DC-DC converter control methods

There can be innumerable control methods for power transfer between the T side and the F side of converters. One of extremely advanced examples is when each converter is controlled in real time according to certain information, such as position and load status of each train, which is collected in a facility such as an operations control center. However here, we attached greater importance to finding a method which would be more feasible, easier to implement, easier to operate and fast to install. Consequently, the control method would ideally not require control information obtained remotely from other locations other than where each converter was installed — for example from the central processing equipment in the operations control center, and so on. Each converter should be able to operate stand-alone, using only the measurements of voltage and current with sensors in each converter itself.

Such simple controls that satisfy the above-mentioned conditions could be as follows:

- Constant control of the F side voltage \( V_f \)
- Constant control of the T side voltage \( V_t \)
- Emulating an output characteristic of existing diode rectifiers and inverters in substations (e.g., \( V_f \) drops linearly according to current output to contact line, while \( V_t \) is constant when the current is drawn from the contact line)
- Constant control of the voltage ratio \( N = V_f / V_t \)

In the high-voltage DC feeding system, plural converters are installed in multiple locations, such as each substation and each track sectioning cabin. Also, they should be controlled as a group of converters with any or several of the above control methods. There are also countless configurations for group control, but the following requirements should be satisfied in order to demonstrate energy savings:

- Distributing appropriate currents between the T-side and the F-side
- Promoting regenerative power interchange
- Suppressing circulating currents

Since there is no external power supply on the F side, there must be at least one converter that directly controls the \( V_f \) in order to stabilize the \( V_f \) in a steady state. And it should be noted that the power sent to the F side by one converter must be returned to the T side by another converter, minus losses.

4. DC-AT feeding system

4.1 Basic characteristics

We devised a method to meet the requirements of group converter control described in Section 3, to ensure constant control of the voltage ratio \( N \) to all the converters in the line (Fig. 2 (b)). This idea is based on the circuit topology of AT feeding systems (Fig. 2 (a)) which is one of the common configurations for AC feeding systems. Similar to high-voltage DC feeding systems, AT feeding systems aim to reduce voltage drops and perform long-distance power transmission by applying higher transmission line voltage than contact line voltage.

Although the connection relationship of T, F, and R is slightly different, a similarity in the geometric configuration of the circuit can be found between the autotransformer (AT) of the AT feeding system in Fig. 2(a) and the converter in Fig. 2(b). For this reason, we named the feeding system in Fig. 2 (b) a “DC-AT feeding system,” in the sense that it is a system composed of “Autotransformers operating in a DC circuit.”

Figure 3 shows the power flow and potential gradient in the DC-AT feeding system. There are following features of this system:

- Between adjacent converters, directions of potential gradient between the T side and the F sides are the same; i.e., basically, no circulating current is generated.
- The load condition of T side is accurately reflected on the F side since the variation of \( V_f \) is proportional to the variation of \( V_t \) due to the load current.
- A stable circuit can be constructed by simulating AT, which is a linear passive element.

4.2 Effect of improving regenerative power interchange

As mentioned previously, regenerative brake force is available only when the regenerative power is consumed by nearby loads, such as powering trains, etc. The \( V_t \) just at the point of a regenerating train must be higher than the \( V_t \) at the points of adjacent power-
ing trains or SSs to enable a transfer of the regenerative power through contact lines. In contrast, vehicle’s onboard traction converters have generally implementation of a restricting control that limits regenerative braking when $V_T$ exceeds a fixed voltage, in order to prevent damage to vehicles and feeding systems due to over-voltage. Therefore, the distance at which sufficient regenerative power can be interchanged is limited by voltage drops due to resistance of the feeding circuit and the restricting control described above. In other words, the farther a powering train and a regenerating train are apart, the more insufficient the regenerative braking power will be. As a result, the mechanical braking ratio increases, and more kinetic energy of a regenerating train is lost as thermal energy.

Here, focusing again on the characteristics of DC-AT feeding systems, converters with the constant control of the voltage ratio $N$ can be regarded as impedance converters as well as transformers. Therefore, the resistance of a high-voltage feeder $r_F$ is seen as $r_F' = r_F/N^2$ when referred to the T-side circuit. For example, assuming $N = 4$, it is equivalent to adding a somewhat unrealistic low resistance feeder which has a 16 times larger cross-sectional area than that of an ordinary one in conventional DC feeding systems (Fig. 4).

As a result, as shown in Fig. 5, the electrical distance between SS and trains or between trains is greatly shortened, which results in significant energy savings such as reduction of power transmission loss and increase in regenerative power interchange.

5. Verification of energy savings by simulation

5.1 Simulation conditions

Trains move around on rails; magnitude and direction of its current also changes greatly and rapidly. Therefore, the power flow of the entire circuit, consisting of multiple substations, DC-AT converters and trains, is very complicated and involves large time-dependent changes.

In order to verify energy savings of the proposed system compared to conventional DC feeding systems (hereafter referred to as “conventional systems”), it is essential to determine change in power consumption of an entire circuit with difficult characteristics. In other words, it is necessary to calculate the power flow at each moment in time sequentially and integrate them as they change from time to time. An analysis based on a state of the circuit at a certain moment in time or an analysis that treats each electric quantity as an average value alone will not provide a correct evaluation.

Therefore, we used the DC traction power supply simulation tool [4] that can evaluate the continuous time variation of electrical and dynamic behavior of trains, similar to that of an actual feeding circuit. Here, we assumed that the DC-AT feeding system to be applied to a double-track model line electrified by the conventional system as shown in Fig. 6, which is based on an actual line. The speed limit and gradient were set in accordance with a certain real commuter line. Calculation steps are at 1-second intervals.

The train characteristics used in the simulation were based on those of a typical commuter train (7-car train) in operation on that certain line. The restricting control described in Section 2.2 was also taken into account as a characteristic that starts restricting at $V_T = 1700$ V and decreases linearly with the $V_T$ until the regenerative braking effort reaches zero at $V_T = 1830$ V.

The high-voltage feeder was common to both up and down lines. The converters were installed in all SSs and SPs, and the voltage ratio $N$ was set to 4. The conversion efficiency of the converters was assumed to be 97% regardless of the current magnitude. Other circuit constants are shown in Table 1 and Table 2.

The train timetables for the simulation had to be set with care. In this research, we focused only on a comparison of power flow trends between DC-AT feeding systems and conventional systems. So we used a very simple assumption that all trains are operated with the same type and configuration, stop at every station, with a departure interval of 7 minutes and 30 seconds for both up track and down track (Fig. 7). Herein, the amount of interchanged regenerative power is strongly affected by the chances of an overlap of accelerating trains and decelerating trains. This is highly dependent on train timetables; executing simulation with only one particular train timetable is not enough to get a fair judgement of energy savings of
the proposed DC-AT feeding system compared to conventional systems. Therefore, we executed a total of 8 simulations with different train timetables: departure times of the down trains from the first station was fixed but departure times of the up trains was shifted in the step of 1 minutes from zero to 7 minutes (hereafter “shift time”).

5.2 Evaluation of the effect of energy saving

Figure 8(a) shows comparison results of the total amount of energy supplied (energy consumed) from all SSs to the model line in 30 min. for each train timetable between a conventional system (circuit without the red line part of Fig. 6) and the DC-AT feeding system. When a regenerative power is reused by other trains, the total amount of energy supplied from SSs, that is, the total energy consumption, decreases. Fig. 8(b) shows the change in the amount of energy consumption for each train timetable, normalized it of the conventional system as 100.

It can be seen from Fig. 8(a) that the energy consumption varies widely depending on each train timetable in both cases of the conventional system and the DC-AT feeding system. This is because the opportunities of the overlap of acceleration and deceleration vary depending on “time shifts.” Figure 8(b) shows that the DC-AT feeding system can reduce the energy consumption in all cases of shift time settings. The reduction in energy consumption reached 4.5% at most, and on average 3.5%. It should be noted that since these figures are affected by the condition of the lines, trains, timetables, and so on, the magnitude itself cannot be generalized.

Basically, the larger \( N \), the higher the energy savings, however there is a trade-off between the higher savings and higher cost of responding to increases in rated voltage.

5.3 Verification of the effect of promoting the regenerative power interchanging

As shown in Fig. 8, the reduction in energy consumption by the DC-AT feeding system tended to be higher in the cases of train timetables which produced relatively large energy consumption on the conventional system (shift time: 1 min., 6 min.) compared to the other cases. This is probably because the effect of shortening the electrical distance becomes more obvious due to the DC-AT feeding system which reduces the power loss between substations and powering trains and promotes regenerative power interchanging.

Figure 9 shows the voltage and current at each location of the model line with the shift time: 6 min., and at the time: 558 seconds, as an example of how regenerative power interchange can be improved. Figure. 9(a) shows the case of a conventional system and Fig. 9(b) shows the case of the DC-AT feeding system. In Fig. 9, trains shown with a red arrow and a positive current value are powering trains, and trains shown with a blue arrow and a negative current value are regenerating trains. The converters shown with a red arrow and a positive current value are in powering mode (power flow: F side to T side), and the converters shown with a blue arrow and a negative current value are in regenerative mode (power flow: T side to F side). Voltage values shown at the top of Fig. 9(a) represent output voltages of rectifiers in substations. Voltage values shown at the top of Fig. 9(b) are \( V_f \) (upper) and \( V_f \) (lower) of the

<table>
<thead>
<tr>
<th>Substation</th>
<th>Rated Power (kW)</th>
<th>Voltage drop (%)</th>
<th>No-load voltage (V)</th>
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<tbody>
<tr>
<td>SS1</td>
<td>4000</td>
<td>5</td>
<td>1575</td>
</tr>
<tr>
<td>SS2</td>
<td>6000</td>
<td>5</td>
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<tr>
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<tr>
<td>SS5</td>
<td>6000</td>
<td>8</td>
<td>1620</td>
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</table>

<table>
<thead>
<tr>
<th>Line name</th>
<th>Resistance (( \Omega )/km)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact line (T)</td>
<td>0.0238</td>
<td>GT110 mm² + St90 mm² + HAI510 mm² × 2</td>
</tr>
<tr>
<td>Rail (R)</td>
<td>0.017</td>
<td>JIS 50 kgN</td>
</tr>
<tr>
<td>High voltage</td>
<td>0.04845</td>
<td>HAI300 mm² × 2</td>
</tr>
</tbody>
</table>

GT: Copper grooved contact wires (JIS E 2101)
St: Zinc-coated steel wires strands (JIS G 3537)
HAI: Hard-drawn aluminum stranded conductors (JIS C 3109)
converters. For converters placed in substations, \( V_T \) equals to the DC output voltage of the corresponding rectifier.

There are powering trains between SP-2 and SP-3 and total load current is 6000 A. At the same time, there are two regenerating trains nearby SS-2 and total regenerative current is 2400 A. In the case of the conventional system (Fig. 9(a)), the regenerative current is limited due to the restricting control, because \( V_T \) of these trains reached 1700 V or higher, which exceeds the threshold at which the control starts. That means, despite sufficient energy demand, the regenerative power interchange was limited due to the electrical distance and a large amount of energy expected to be regenerated was lost. As a result, a current of approximately 3200 A is supplied from SS-3 to the powering trains; which leads to an increase in power received from the power grid.

On the other hand, in case of the DC-AT feeding system, \( V_T \) of regenerating trains decreased to 1709 V (the train on down track), 1731 V (the train on up track) respectively and the total regenerative current increased by 80% to about 4400 A. Of this regenerative current, 3300 A or more was sent to the F side by the converter within SS-2, and returned to the T side from the converters within SP-2 and SP-3. In this way, regenerative current can be smoothly sent over a long distance by the high-voltage feeder, and as a result, the current from SS-3 decreases to about 1400 A, which is less than half.

6. Conclusion

This paper focused on high-voltage DC feeding systems consisting of high-voltage feeders and converters that transfer power between contact lines and high-voltage feeders in addition to conventional DC feeding system as a way of saving energy on DC electric railways. We proposed a new converter control method to make the voltage ratio between the contact lines and the higher-voltage feeders constant. Then we named the high-voltage DC feeding system with this method implemented in all the converters a “DC-AT feeding system,” which improves regenerative power interchange. We evaluated the energy savings of this system through simulation, and a case study on a model line confirmed that this system can reduce energy consumption by 4.5% at most, and on average 3.5%, compared to conventional DC feeding systems.

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