Energy Saving Performance Analysis of An Inverter-based Regenerative Power Re-utilization Device for Urban Rail Transit

Jin Li, Zhiling Qiu and Leilei Hu
Nanjing APAITEK Technology Co. Ltd, Nanjing, China, 210000

Abstract. The inverter-based regenerative braking power utilization devices can re-utilize the regenerative energy, thus reduce the energy consumption of urban rail transit. In this paper the power absorption principle of the inverter-based device is introduced, then the key influencing factors of energy saving performance are analyzed based on the absorption model. The field operation data verified that the control DC voltage plays an important role and lower control DC voltage yields more energy saving. Also, the one year energy saving performance data of an inverter-based re-utilization device located in NanJing S8 line is provided, and more than 1.2 million kWh energy is recovered in the one year operation.

1. Introduction
Recently, the urban rail transit gains rapid development due to its high capacity, punctuality and absence of emission. However, the urban rail transit consumes huge amount of power in its operation, and the energy saving issue has become an important topic for the sustainable development of urban rail transit.

During the regenerative braking of the urban rail transit train, the kinetic energy is converted into regenerative energy and fed back to the DC traction network. The regenerative energy, which accounts for about 30%-50% of the total traction energy consumption and offers the greatest energy saving potential[1-2], could boost the DC traction network voltage and may cause the regenerative braking failure so that it is required to be absorbed or utilized[3].

There are two state-of-art regenerative energy utilization devices, one is the storage-based device which stores the regenerative energy in the energy storage medium like super capacitors when the train is braking, and release the energy when the train is accelerating[4-5]. The other one is the inverter-based utilization device which can feedback the regenerative energy into the AC medium-voltage ring network and provide the power to the other metro line loads like traction system, environment control system, and etc. The inverter-based device becomes popular in China due to its features of higher power, smaller occupation and better performance cost ratio compared with storage-based utilization.
device[6-7]. In this paper, the inverter-based device is analyzed in terms of working principle, power absorption model, energy-saving performance.

2. Working principle and modeling

2.1. The principle of regenerative power utilization

As shown in the Figure 1, the inverter-based device is interfaced with the DC traction network and the medium voltage AC grid, and is parallel with the traction rectifier device. When the train is braking, a part of the regenerative power can be absorbed by the adjacent accelerating trains, and the rest of the power is fed back to the AC grid by the inverter and utilized by other loads.

![Figure 1. The system structure of substation with inverter-based utilization device](image)

As shown in Figure 2 the control objectives of the inverter-based utilization device are to control the overhead line DC voltage and regulate the current injected into the AC grid. Seen from the DC traction network the inverter-based device behaves as a DC voltage source, while seen from the AC grid, the device behaves as a AC current source.

![Figure 2. the control strategy of inverter-based device](image)

In some cases, the on-board resistor-based devices as well as the inverter-based devices are equipped in the metro line. Since the DC control threshold voltage of the inverter-based device $V_{th_{\text{inverter}}}$ is set be lower than that of the resistor-based device $V_{th_{\text{resistor}}}$, the inverter-based device has the priority to absorb the power. Figure 3 shows the typical power absorption process waveform, at $t_0$ instant, the inverter-based device starts to absorb the power. During the $t_0$-$t_1$ interval, the regenerative power is within the rated power of the inverter-based device, so the device can absorb all the regenerative energy and control the DC line voltage independently. At $t_1$ instant, the regenerative power exceed the rated power of the inverter-based device, then the inverter-based device keeps outputting its rated power, and the exceeding power boosts the the DC overhead line voltage and reaches $V_{th_{\text{resistor}}}$ and the
resistor-based device start to absorb the excessive power and stabilize the overhead line DC voltage. During t2-t3 interval, the regenerative power drops within the rated power of the inverter-based device, then the resistor-based device quits and all of the power is absorbed by the inverter-based device.

**Figure 3.** The typical waveform of power absorption process

### 2.2. Modeling of DC line regenerative power absorption model

As stated in the last section, the inverter-based utilization device is controlled as a DC voltage source, and the braking train can be modeled as a current injection into the overhead DC line. Since there are resistance between the braking train and the inverter-based utilization device located substation, the injection current could incur a voltage drop across the overhead DC line and rail track. Figure 4 shows the flowing path of the regenerative current $I_{cl}$. As shown, the control DC voltage of the inverter-based device located substation is $U_{dc}$, and the DC voltage of the braking train $U_{cl}$ can be expressed in equation (1), where $\mu_a$ and $\mu_b$ are the resistance rate of the overhead line and the rail track respectively where $\mu_a$ is 0.007Ω/km, $\mu_b$ is 0.009Ω/km, and $d$ is the the distance between the braking train and the substation.

$$U_{cl} = U_{dc} + I_{cl} \cdot (\mu_a + \mu_b) \cdot d$$

**Figure 4.** The regenerative current flowing path

So the inverter-based device regenerative absorption power is

$$P_{cl} = U_{dc} \cdot I_{cl}$$
It is assumed that the maximum allowable DC voltage for the regenerative braking train is 1800V, and the maximum absorption power of inverter-based device can be derived as equation (3).

\[
P_{cl_{-max}} = \frac{1800 - U_{dc}}{(\mu_a + \mu_b) \cdot d} U_{dc}
\]  

(3)

There are two key factors influencing the maximum absorption regenerative power, one is the control DC voltage of the inverter-based utilization device, the other one is the distance between the braking train and the substation.

Figure 5 shows the relationship of the maximum absorption power and the distance between the braking train and the substation with different control DC voltages of 1750V and 1700V. The lower control DC voltage results in higher absorption power, the maximum absorption power is about 6.7MW at 0.5kM braking distance with the control DC voltage of 1700V, while with the control DC voltage of 1750V the maximum absorption power is only 3.5MW. At the same braking distance of 4km, the maximum absorption power is 840kw with control DC voltage of 1700V, while with control DC voltage of 1750V the maximum absorption power is only 430kW.

3. Field operation performance

3.1. System configuration

A inverter-based utilization device of 2.5MW power rating is installed in a substation of Nanjing S8 line which is also equipped with the on-board resistor-based utilization device. As shown in Figure 6, the 2.5MW inverter-based device is installed in station B, and within the 5kM distance there are three other stations, namely StationA, StationC, StationD. As stated in the last section, the inverter-based device can recover the regenerative power from the braking train not only at the station B but also the adjacent stations.

Table 1 shows the recovered energy with different control DC voltages, and the lower control DC voltage yields more saved energy. Considering there should be enough margin to ensure the control DC voltage is higher than the floating voltage of diode rectifier device, so the control DC voltage is set to be 1730V for the field operation.
Figure 6. The adjacent stations condition of the inverter-based device

Table 1. Saved energy at different control DC voltage

| Control DC voltage | Utilization energy per day (kWh) |
|--------------------|----------------------------------|
| 1770V              | 2310                             |
| 1750V              | 3115                             |
| 1730V              | 4130                             |
| 1710V              | 5355                             |

3.2. The DC line voltage stabilization

The inverter-based utilization device can effectively reduce the fluctuation of the overhead DC line voltage. As shown in Figure 7(a), the overhead DC line voltage fluctuates greatly without the inverter-based device, when the train is braking the overhead DC line voltage rises to about 1800V and when the train is accelerating the overhead DC line voltage drops to about 1500V, while Figure 7(b) shows that the maximum DC line voltage decrease to about 1730V with the inverter-based utilization device, the inverter-based utilization device reduced DC voltage fluctuation.

Figure 7. The overhead DC line voltage stabilization

3.3. Energy saving performance

The energy recover performance is related with many operation factors like train model, braking speed, timetable, passenger onboard rate, and etc. In this case, a model B metro train with 2 motor cars and 2
trails is used in this line, the train braking speed is 80km/h, and on the work days there are 268 train departure per day while on the off days there are 228 train departure per day. In one year operation the inverter-based utilization device with the control DC voltage of 1730V recovered more than 1.2 million kWh, and more than 100000 kWh per month averagely. The monthly and daily energy saving data are shown in Figure 8.

![Figure 8. Energy saving data](image)

(a) Monthly data (kWh)  (b) Daily data (kWh)

4. Conclusion

The inverter-based regenerative power utilization device can effectively stabilize the overhead line DC voltage and recover the regenerative energy. Several key influencing factors like control DC voltage, braking distance are analyzed based on the absorption model, and the field data verified the lower control DC voltage can yield more saving energy. The field operation data of energy saving performance and the overhead DC voltage stabilization effect of an inverter-based power utilization device installed in NanJing S8 line are given, in the one year operation the device recovered more than 1.2 million kWh energy, at the same time the overhead DC voltage maximum value is constrained and reduced from 1800V to 1745V.

Reference

[1] Yang Jian, Huang Hou-ming, Fang yu. Energy Consumption of Trains on Shanghai Metro Line 2[J]. Diesel Locomotives, 2009,(4):23-25.

[2] LIU Baolin. Analysis on Energy Consumption of Metro Train[J]. Electric Locomotives and Mass Transit Vehicles. 2007,30(4):65-70.

[3] ZHOU Jian-bin, SU Jun, He Yong-bin. Utilization of Train’s Regenerative Energy in Metro System [J]. Urban Metro Transit, 2004, 7(4): 33-35.

[4] ZHAO Li-feng, Zhang Fa-ming. Regenerative Energy Absorption Devices in Beijing Metro Line 5[J]. Modern Urban Transit, 2008, 2(1): 6-8.

[5] RUFER A, BARRADE P, HOTELLIER D. Power Electronics Interface for a Supercapacitor-based Energy Storage Substation in DC Transportation Networks [J]. European Power Electronics and Drives Journal, 2004, 14(4): 43-49.

[6] Yang G. Analysis of Urban Rail Transit Train Regenerative Braking Energy Feedback utilization Device[J]. Construction & Design for Engineering, 2016.

[7] Zeng Jianjun, Lin zhiming, Guo wanling. The regenerative braking energy absorption devices[J]. Electrified railway , 2008(6): 44-47.