The Rapid Transit System That Achieves Higher Performance with Lower Life-Cycle Costs*

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In the age of traction system made of inverter and ac traction motors, distributed traction system with pure electric brake of regenerative mode has been recognised very advantageous. This paper proposes a new system as the lowest life-cycle cost system for high performance rapid transit, a new architecture and optimum parameters of power feeding system, and a new running method of trains. In Japan, these components of this proposal, i.e. pure electric brake and various countermeasures of reducing loss of regeneration have been already popular but not as yet the new running method for better utilisation of the equipment and for lower life-cycle cost. One example of what are proposed in this paper will be made as Tsukuba Express, which is under construction as the most modern commuter railway in Greater Tokyo area.

Key Words: Regenerative Brake, Power Feeding System, Train Movement Control, Optimization

1. Introduction

In order to realise high performance rapid transit system, this paper proposes the lowest life-cycle cost system consist of introduction of pure electric braking to the trainset, a new architecture and optimum parameters of power feeding system, and a new running method of trains. In Japan, the components of this proposal, i.e. pure electric brake and various countermeasures of reducing loss of regeneration have been already discussed. And in recent years, the first step of pure electric braking is popular and power feeding system very near to ideal characteristics is being introduced to Tsukuba Express which will open in 2005.

This paper discusses the second step of pure electric brake, shows the energy consumption with relation to power feeding system, and proposes a new running method for better utilisation of the equipment and for lower life-cycle cost.

2. Pure Electric Brake

2.1 Background of braking system and life-cycle cost

To the contrary of dc motor traction system with chopper or rheostatic control, ac motor traction system requires no brush and commutator in traction motor and no contactor or changeover switch in control circuit other than for emergency purpose. This means much reduced maintenance requirement in traction system. In this situation, main source of required maintenance is related to friction brake; for brake lining, brake disc, reshaping of flat wheel etc.

Not a small part of life-cycle cost is energy cost for train operation. Small mass of the train and regenerative braking are most important for this purpose, and again ac motor traction is very favourable to these two factors. Out of the kinds of electric braking, regenerative braking is by far the best mode of braking with respect to the mass, heat generation and net energy consumption. Some people doubt the reliability of regenerative braking with some reasons including receptivity of the catenary system and inferior braking effort at high speed compared with rheostatic braking.

2.2 Basic requirement of braking system

In rapid transit system, reliability of regenerative braking can be high enough if characteristics of trainset and parameters of power feeding system have been carefully chosen as shown in later section of this paper.

If all kinetic energy at normal operation is to be absorbed by traction motor, maximum power at braking should be corresponding to maximum value of braking effort times train speed. This can easily be considerably higher than that of powering because of efficiency of the equipment, running resistance and difference of average voltage of catenary. To keep loss of braking effort due to wheel skid smaller than loss of traction effort due to wheel slip from the viewpoint of reliable train operation, ratio of motored axles may well be a little greater than required for
traction purpose only.

2.3 Performance of regenerative brake

Typical value of maximum traction and braking power at wheel rim can be around 40–50% bigger for braking than that of powering due to the factors shown above; overall efficiency from (to) inverter input (output) to (from) wheel rim through traction motor and transmission gears is around 85% for traction (braking) and average catenary voltage is at least 10% higher for braking. If maximum catenary current is chosen such as typical running of corrideric brake as far as possible and while braking excluding current for auxiliary equipment, maximum speed at which maximum power at wheel rim is attained is also 40–50% higher for braking than for powering. This condition is not far from typical operation of rapid transit where flat acceleration is up to 40% maximum speed, end of powering at 80% maximum speed and braking from 60% maximum speed. If low characteristics of traction system is chosen such as typical running of corresponding to flat acceleration up to 40%, end of powering at 100%, and braking at 80%, braking effort at high speed is not enough. Even if braking effort at the beginning of braking is not enough, weeker and longer time braking requires only a small addition of running time, for example one or two seconds, which can easily be compensated at a little higher braking effort at low speed. This is realised without sacrifice of ride comfort or without more probability of wheel slide thanks to much better controllability of electric brake than friction brake.

2.4 Development of pure electric brake

At the first stage of developing pure electric brake, technical development was concentrated to realise necessary braking effort down to complete standstill but not to restart backward. This was realised to use regenerative brake and backward running modes continuously and based upon the estimated time at which zero speed is attained jerk control for better riding comfort is made following to application of mechanical brake to keep the stopped train at standstill.

This method was called electric brake down to complete stop, or pure electric brake in broad sense, because in this stage brake of trailer cars was what they had been although some of the conventional trainsets had used electric brake as far as possible and while braking effort of the motor car is enough to decelerate the whole train, mechanical brake on trailer cars was not used.

After success of the first stage of pure electric brake in broad sense, real pure electric brake or pure electric brake in narrow sense is to realise where all braking effort in service brake is made electrically. Even in this case, mechanical brake equipment should not be removed because of emergency purpose or redundancy of braking equipment.

3. Distributed Traction System with Purely Regenerative Service Brake

There are very many rapid transit trainsets of distributed traction system and few using concentrated traction system. If dc traction motor is used concentrated traction system has advantage in maintenance of traction motors of fewer number. Also from the viewpoint of passengers’ safety, heat source of rheostat to be used as rheostatic control of dc traction motor or for dynamic braking is better to put as far from passengers space as possible. But in recent years, there is no reason to use locomotive for rapid transit.

Space and mass of ac traction system using regenerative braking is enough small to build double-decked EMU if necessary. From the viewpoint of reducing initial cost not all the axles should be motored but enough axles should be motored corresponding to maximum service braking force in the most adverse adhesion condition. Up to 18% of adhesion coefficient is known to be used reliably. So from this respect, it is enough to realise service brake electrically if half the axles are motored when maximum service brake is around 0.9 m/s² which is Japanese practice. If bigger, but acceptable from ride comfort of standing passengers, deceleration is normally used, around 60% of axles may be enough.

Distributed traction is also advantageous for less maximum axleload and for easier realisation of similar traction power per number of coaches with standardised traction unit. Traction unit can easily be made for two traction motors or half a motor car.

4. Power Feeding System for Regenerative Trains

4.1 Relationship between regenerative trains and power feeding system

Ability of regenerative trains can be effective only if regenerated power is absorbed by a load or loads near the braking train. Rectifier substation cannot absorb, or transmit back into ac grid, excess power. If loads are far from the braking train, voltage drop due to circuit resistance brings pantograph voltage of the braking train too high.

4.1.1 Squeezing characteristics of regenerative trains In order to keep pantograph voltage of a braking train below allowable maximum, typically 1 850 V for nominal 1.5 kV dc system, braking train itself should squeeze regenerating current at high pantograph voltage as shown in Fig. 1. When regenerative current is squeezed, another brake other than regenerative mode should be added to keep required braking force. This means loss of regeneration. The lost regenerative energy can be compensated through absorbing by a rheostat or by friction brake with sacrifice of additional mass and of additional maintenance cost. Rough estimation of the cost of lost energy is electric energy price, typically 15 JPY per kWh in
Japan for compensation by rheostatic brake, and double this value for friction brake.

4.1.2 No load voltage of substation  If this value is high, possibility of non-receptive condition and lost regenerative energy will increase and if low, pantograph voltage of powering trains will often too low to keep required running performance. This is also a source of increasing energy for train operation.

4.1.3 Voltage regulation of substation  Typical rectifier substation for dc rapid transit has voltage regulation of 6 to 8\% per rated output current. Normally overload of up to 300\% is allowed for varying train loads for a short period of time, typically one minute which corresponds to duration of acceleration from standstill to maximum speed, and this means around 20\% voltage drop at heavy train load at substation.

Pantograph voltage at powering train goes further down by voltage drop by circuit resistance.

4.1.4 Circuit resistance  It is very natural that the smaller of circuit resistance, the better. To reduce circuit resistance, parallel feeder cable with catenary is used and around 30 mΩ/km is attained but further reduction is not so easy because of resistance of running rails, to which addition of parallel conductor is difficult to keep function of track circuit for signalling.

4.1.5 Absorption at regenerated power at substation  Instead of applying on board additional brake, it is possible to put excess regenerated power absorbing device at substation. This is sometimes better for realising lighter and heat-free trains. In Japan, trains running on a long and steep gradient line or substations for this line have this kind of devices, controlled rheostat or inverter for returning excess energy to ac grid.

4.2 Ideal characteristics of substation  From discussions above, ideal characteristics of substation is flat regulation for powering and also flat voltage characteristics for accepting excess regenerated power as shown in Fig. 2. This can be made of a thyristor rectifier and a thyristor inverter connected in parallel and controlled in cooperation mode. But this arrangement brings other problems of harmonic currents and inferior power factor due to phase control. If pulse width modulated (PWM) converter, which is widely adopted in Japanese ac trains since Series 300 of Shinkansen made in 1991, is used, a single converter works as a rectifier and as an inverter according to situation with nearly ideal waveforms both in dc side, nearly flat without ripple, and ac side, nearly sinusoidal, balanced three phase current of unity power factor.

4.3 Effect of improved feeding system  Effectiveness of an improved power feeding system with reduced no load voltage, zero voltage regulation, reduced feeder circuit resistance and improved squeezing characteristics has been compared\(^{(1)}\). The present standard characteristics is shown in Fig. 3 and improved one in Fig. 4.

Improvement is clearly shown in Table 1.

4.4 Power feeding system of Tsukuba Express  Eight intermediate 4.5 MW and one end 3 MW PWM converters of insulated gate bipolar transistors (IGBT) of characteristics shown in Fig. 2 are used with mutual spacing of 3.1 to 6.8 km in 40 km long dc section out of to-

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(a) Preferred (b) Actual characteristics

Fig. 1 Squeezing characteristics

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4.1 No load voltage of substation

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4.2 Ideal characteristics of substation

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4.3 Effect of improved feeding system

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4.4 Power feeding system of Tsukuba Express

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Table 1

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Fig. 3 Standard model for regeneration in case of \(V_s \ll 1790\) V regeneration partly failures, actually if \(V_s \approx 1650\) in Fig. 1(a) regeneration almost stops

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Fig. 4 Improved model for regeneration in case of \(V_s > 1679\) V, easily realisable, full regeneration guaranteed

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Fig. 2 PWM converter substation
Table 1 Increased regenerated energy and decreased feeding loss

<table>
<thead>
<tr>
<th>No load voltage</th>
<th>Standard1</th>
<th>Standard2</th>
<th>Improved</th>
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<tbody>
<tr>
<td>Voltage regulation</td>
<td>1620V</td>
<td>1620V</td>
<td>1550V</td>
</tr>
<tr>
<td>Feeding resistance</td>
<td>8%</td>
<td>8%</td>
<td>0%</td>
</tr>
<tr>
<td>Squeezing characteristics</td>
<td>0.15Ω</td>
<td>0.15Ω</td>
<td>0.1Ω</td>
</tr>
<tr>
<td>Train voltage</td>
<td>Fig.1b</td>
<td>Fig.1a</td>
<td>Fig.1a</td>
</tr>
<tr>
<td>Train current</td>
<td>1=1650V, 1=1800V</td>
<td>1=1670V</td>
<td></td>
</tr>
<tr>
<td>Regenerated power</td>
<td>2240kW</td>
<td>2400kW</td>
<td></td>
</tr>
<tr>
<td>Loss of regeneration</td>
<td>100%</td>
<td>44%</td>
<td>0%</td>
</tr>
<tr>
<td>Feeding loss</td>
<td>130kW</td>
<td>286kW</td>
<td></td>
</tr>
<tr>
<td>Available power</td>
<td>2110kW</td>
<td>3710kW</td>
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</table>

total 58.3 km long Tsukuba Express Line. Maximum output current is set to 300% nominal value as is the standard case and maximum input current of 210% nominal value has been determined from double maximum regenerating current; two regenerating trains and no powering train at the same time is taken the worst case for regeneration failure. Voltage between regeneration and powering modes of 30 V has been set, not to make circulating current from one converter to another, but output voltage is still under discussion. Original idea was to set at 1 500 V as is the nominal voltage but later optimum voltage has been sought, and around 1 600 V is proposed to reduce overall cost for a long term.

4.5 Possibility of Further Improvement

If all substations of a line is made of PWM converter, various aspects of improvement of the system can be made by real time voltage and/or current control of each substation. For instance, minimum voltage of heavily powered train running far from substation can be increased, maximum output current of substation can be reduced, or energy loss of feeder circuit can be minimised at the given running time of the trains. At an abnormal condition, such as one substation out of use or extremely high density of train movement, safety limit of any part of the system can be kept with minimal additional delay of the trains.

If control of the movement of the trains in addition to the control of substations above is possible, much wider area of improvement can be made as shown in the next chapter.

5. Modification of Running Patterns of Trains for the Optimal Use of Regenerative Brakes

Although, as stated in section 4, it is now easy to allow bi-directional power flows at the dc substations, it is desirable to minimise the reverse power flows (from the railway power feeding network to the power system) for a number of reasons. Those include:

1. The price per kWh that the utility company pays to the railway company for such a reverse power flow is, in many cases, much lower than the normal power flow from utility to railway (in some cases it is even zero);
2. Excessive reverse flows will result in higher load peaks in normal power flows, which cause the required capacity of the equipment to be larger; and
3. When there is a flow of power between substation which simply goes into the power feeding network through one substation and goes out through the other, this will result in increased I^2R losses in the feeding network. Among these, (3) can be easily avoided by controlling the output voltages of substations adjacent to each other to be equal when the load is low, and is not discussed further in this paper.

5.1 Minimising Reverse Power Flows

The effect of cross-substation flows (problem (3) described above) can be ignored, the reverse power flow will only be seen when and where there is more regenerative power than the accelerating power. Therefore, to minimise reverse power flows, regenerative trains should coincide with other accelerating trains.

Figure 5 shows a simulation result of total substation input energy (energy that flowed into the railway power feeding network) per hour when the operational phase of trains running in different directions are changed. In this calculation, a 21.3 km-long, double-track line with the operating interval of 300 seconds is assumed. The operational phase is defined as x seconds when up train starts its originating station on one end of the line x seconds before the down train starts its originating station on the other end of the line. Because the operating interval is 300 seconds, phase = 0 and phase = 300 sec produces the same result. All substations along the line are equipped with conventional diode rectifiers, which means that the regenerative brakes become unavailible and replaced by mechanical brakes when the line is not receptive. As is clear from this graph, a little phase difference can result in large change in the input energy.

5.2 Traction Power Control of Trains to Further Optimise the Power Feeding System

Figure 5 suggests that a slight change in the running pattern of trains may result in great improvements from
Fig. 6 Reduction of tractive effort and the resulting train delay

Fig. 7 The effect of substation peak current suppression by traction power control

The point of view of the power feeding system.

If there is a couple of seconds of buffer time between a pair of adjacent stations, the running pattern between these stations can be changed fairly significantly. For example, in the simulation result shown in Fig. 6, the tractive effort of a train is reduced to 60% of the nominal (maximum) value when the train reached certain speed, for a duration of 10 seconds. The resulting delay, compared to the planned running pattern which assumes that the train always accelerates at maximum tractive effort, is only up to a couple of seconds, and is easily recovered until the train arrives at the next station.

Because of the small time deviation, the idea of controlling the traction power of trains will be a very effective way of optimising the power feeding system(3).

Figure 7 and Table 2 show an example. In this case, the trains are instructed to control power according to the following rules:

1. An accelerating train, running at relatively high speed, will lower the power when there are too many accelerating trains around it;
2. A coasting train, running at relatively high speed, will apply regenerative brake when there are too many accelerating trains around it; and
3. A coasting train will accelerate when there are too many regenerating trains around it.

The line voltage is used to find whether there are many accelerating or regenerating trains around it.

<table>
<thead>
<tr>
<th>Table 2 Improvements in other evaluation parameters</th>
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<tr>
<td>Substation input energy [MWh]</td>
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<tr>
<td>With control</td>
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<td>----------------</td>
</tr>
<tr>
<td>31.917</td>
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The simulation is carried out on the model, in which 11 substations, all with diode rectifiers, are located on the circular 34.5 km-long line, all double track and independent of all other railway network, on which 50 trains run at a time with the operating interval of 144 seconds. The result, shown in Fig. 7 and Table 2, it is clear that the control reduces the peak current significantly, almost eliminates the unreceptiveness of the line, and reduces the total input energy.

6. Conclusion

The recent developments in Japan in this field, conducted by rail operators and manufacturers alike, are expected to mark a major breakthrough, in which traction systems on board the trains and power feeding systems on the ground are re-designed to form a system that achieves higher performance, such as improved ride quality when braking, with lower life-cycle costs, especially through the introduction of pure electric brakes which will significantly reduce the needs for maintenance, as shown in this paper.

The new fleet recently introduced in Yamanote Line in central Tokyo, are fitted with traction equipment that has excessive capacity at higher speed region if pure electric brakes are not considered, which can be an example of how trains are designed in the new system. For the power feeding system, Tsukuba Express railway, with voltage-sourced converters used in all substations, will give an ideal example. Although both systems were not necessarily designed with pure electric brakes in mind in the first place, these will be the starting point from which subsequent improvements can and will be made.

References