MAXIMUM REGENERATIVE BRAKING POWER TRANSFER CAPABILITY IN AC RAILWAY POWER FEEDING SYSTEMS

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Abstract - This paper proposes an approach to formulate the maximum power transfer capability of AC railway power feeding systems. The approach is based on the total reactance consideration between the two sources, in this paper the source at the feeder substation and another source is the train itself during the train braking instance. The study exhibits the calculation procedure and also provides one test system. The Suvanabhumi airport rail link, Bangkok, Thailand, was chosen as a test example to generate numerical results. As a result, this calculation concept can be extended to further investigate the problem of power system transient stability in AC railway power feeding systems.

Keywords - Ac Railway Power Feeding System, Power Angle Equation, Total Reactance, Single-Machine Connected to an Infinite Bus.

I. INTRODUCTION

Increasing of demands for long distance train journey in nationwide attracts a consideration of energy saving of the transport means. Mainline railway is one of a long distance services for passenger trains. Unlike mass rapid transit trains where frequent stops at platforms lead to the reuse of the regenerative braking power from arriving trains, mainline trains stop less due to longer distance between stopping platforms. Regenerative braking power can be transferred back to AC substation transformers and finally to HV power transmission system of a local utility grid.

In DC mass transit railways there is a possibility to regenerative braking energy and to exchange it between trains but there is no transferred to MV power systems of a local grid due to the blocking of rectifier traction substations. In AC electric railways, the feedback regenerative power to the local utility grid is enabled. An AC railway power feeding system is a single-end power circuit where only one source at a traction substation is existed. Along the feeder line of a long distance railway only a few trains is running and consuming power from the same supply source. In addition, a double track is a typical widely-used railway system. This represents a single source connected with a single machine, as characterized by on-board inverter-fed AC traction motors of the electric train. With the interconnection systems continually growing in size it is difficult to maintain synchronism between various parts of an AC railway power feeding system. Power flows in an AC railway power feeding system limited to the maximum power transfer capability of electric power transmission lines. This can imply that under a normal operating condition the phase angle of train's terminal voltage relates to an amount of power flowing through the feeder portion to the AC traction substation. A so-called power angle equation is formulated to exhibit how much power can be transferred from the train position to the substation terminal bus. This concept is a part of power system stability. In literature, a stability study of DC micro-grid for urban railway system was illustrated [1]. Lyapunov function and the backstepping method were employed to calculate and therefore evaluate the risk of system stability. Transient stability assessment of multi-chine multi-converter power systems was proposed in [2]. PV power plant integrating with utility grid-connected inverter was modelled and analyzed. DC-side dynamics and closed-loop controller's performances were investigated. In this paper, the concept of recovering train braking energy through a single-machine connected to an infinite bus (SMIB) [3-4] is first presented. The power angle equation of the system is then reviewed. A SMIB with constant power loading is studied and discussed. Special conditions in railway regenerative braking were included.

II. MAXIMUM POWER TRANSFER

A. SMIB Model

Power generated from generator associated with the generator rotor angle this can be explained with a generator that is connected to the infinite bus system as shown in Fig. 1.

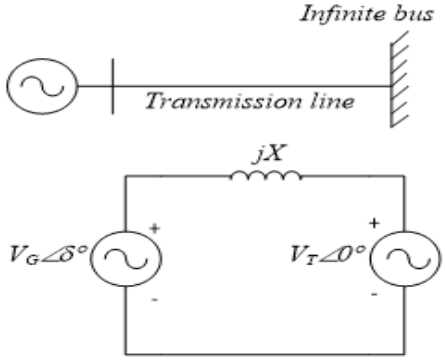


Fig. 1 SMIB

B. Power Angle Equation

By neglecting resistance in the generator and no losses

in network then the equation become (1). From this equation states that the relationship between the transmitted power depends on the angle and reactance and power angle δ. When the angle δ value is zero, no power is transmitted to the system and the maximum value when sin δ equal to 1.

$$P_G = \left|\frac{V_G V_T}{X}\right| \sin\delta = P_{\max} \sin\delta \qquad (1)$$

The graphical representation of P_G and the load angle δ is called the power angle curve. It is widely used in power system stability studies. The power angle curve is shown below in Fig.2.

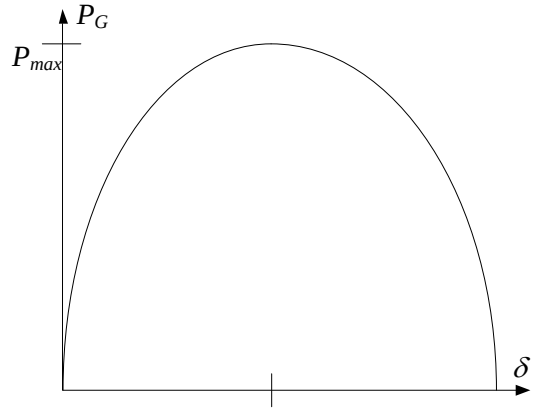


Fig. 2 power angle curve

Maximum power is transferred when δ = 90° . As the value of load angle δ is above 90, P_G decrease and becomes zero at δ = 180° . Above 180° , P_G becomes negative, which show that the direction of power flow is reversed, and the power is supplied from infinite bus to the generator. The value of P_G is often called pull out power. It is also called the steady-state limit. The total reactance between two voltage sources and X is called the transfer reactance. The maximum power limit is inversely proportion to the transfer reactance.

III. AC ELECTRIC RAILWAY POWER FEEDING SYSTEMS

A double-track railway usually involves running one track in each direction, compared to a single-track railway where trains in both directions share the same track. Double-track railways, especially older ones, may use each track exclusively in one direction. This arrangement simplifies the signalling systems, especially where the signalling is mechanical. Where the signals and points or rail switches (US) are power-operated, it can be worthwhile to signal each line in both directions, so that the double line becomes a pair of single lines. This allows trains to use one track where the other track is out of service due to track maintenance work, or a train failure, or for a fast train to overtake a slow train.

A. Case 1: No Track Section

Since three-phase to single-phase conversion is the main scheme for all mainline and long distance railway electrification systems, AC power feeding circuits is simplified as a per-phase circuit. A typical double-track AC railway power feeding system is shown in Fig. 3. For simplicity, a double-track feeding circuit with no track section is presented. This simple circuit scheme is used to formulate the maximum power transfer through a feeder portion varying with the train position.

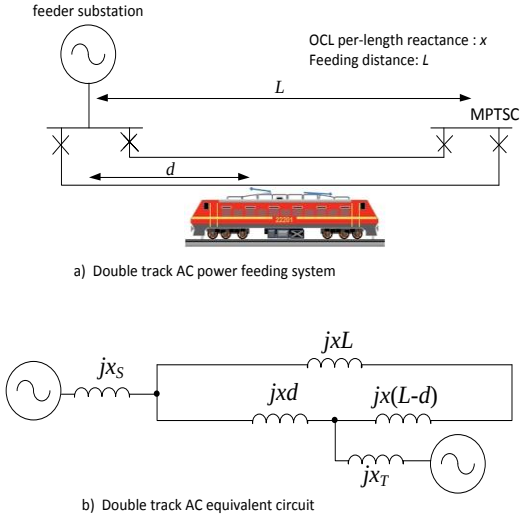


Fig. 3 SMIB model of a double track AC railway

The total reactance between the train terminal and substation source is a function of train position. This means that the maximum power transfer capability is varied with respect to the train position. The maximum power transfer is inversely proportional to this reactance. From Fig. 3-b), the total reactance seen between the two given sources can be expressed as the following equation.

$$X = x_S + x_T + \left(\frac{2L-d}{2L}\right)x \qquad (2)$$

Where

x_S denotes the short circuit reactance of the substation seen at MV side

x_T is the equivalent onboard reactance of the train

The maximum power transfer of this case can be calculated by applying (1) associated with (2).

B. Case 2: Intermediate Track Section

An intermediate track section (ITS) is always placed in multiple track railways to enable parallelize multiple power feeding line sections between the substation and the midpoint section. To depict this case, Fig. 4 is an example for a double track with one intermediate track section at the midpoint of the feeder length.

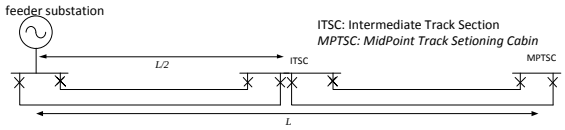


Fig. 4 AC power feeding system with ITSC

In fact, the position of ITSC is not necessary to divide the feeder section into a pairs of two equal sections. Nevertheless, in this paper, the two equal sections case is only presented and analyzed. As shown in Fig. 5, the first sub-case is the case where the train is located between the substation and the ITSC, called the near section (near the substation). As mention previously, the maximum power transfer is dependent upon the inverse of the total reactance. From Fig. 5-b), the total reactance seen between the two given sources can be expressed as in (3).

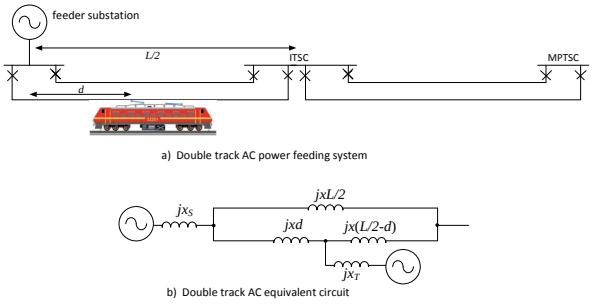


Fig. 5 A train located at the near section

$$X = x_S + x_T + d\left(\frac{L-d}{L}\right)x \qquad (3)$$

The second case is the train located in the far section.

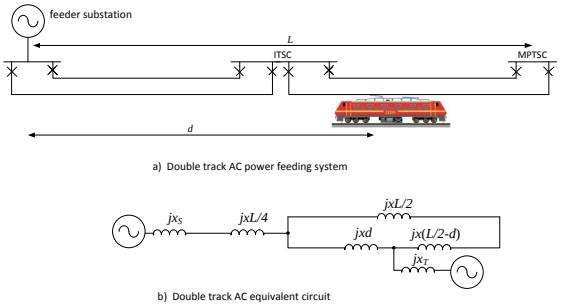


Fig. 6 A train located at the far section

The maximum power transfer is proportionally inversed to the total reactance. From Fig. 6-b), the total reactance seen between the two given sources can be expressed as in (4).

$$X = x_S + x_T + \frac{L}{4}x + \frac{\left(Ld - \frac{3}{4}L^2 - d^2\right)}{L}x \qquad (4)$$

IV. TEST AND RESULTS

In this paper, the Suvanabhumi airport rail link, Bangkok, Thailand as shown in Fig. 7, is used to exhibit the power feeding without ITC case. The test system is the existing AC railway line in Thailand with direct feeding configuration. This is to use as the test without ITC. From Fig. 7, the first study is the section from TPS position to Praya Thai station. The feeder length of this study is 8.0 km. The OCL system for this line is shown in Fig. 8. The Second test case is the study of AC power feeding system with ITC. The test system used for this case is the line section from TPS to the airport terminal 1, having 20 km feeding distance. In this study the ITSC is placed at the distance 10 km from TPS. Vehicle data for the test is the 3 car train set of city line service. Tare mass of the train set is 131 tons. The maximum deceleration n rate is 0.88 m/s^2. Assume that during a braking instance, the train terminal voltage is at the highest non-permanent voltage of 29 kV while the substation terminal voltage is kept at 25 kV for all the test case scenarios. The TPS data is 2.7 GVA, the minimum short circuit power at the point of common coupling. The substation transformer rating is 20 MVA with 12% reactance. The calculation of the total substation reactance from these information, x_S =3.98 □ . Assume that the onboard reactance of the train is neglected.

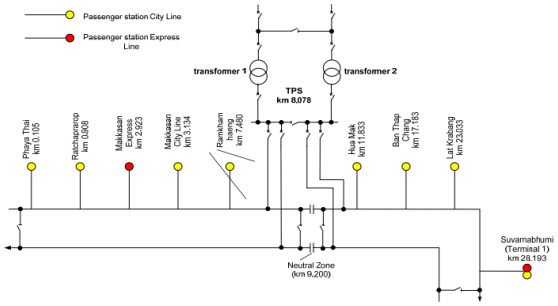


Fig. 7 Suvanabhumi airport rail link, Bangkok, Thailand

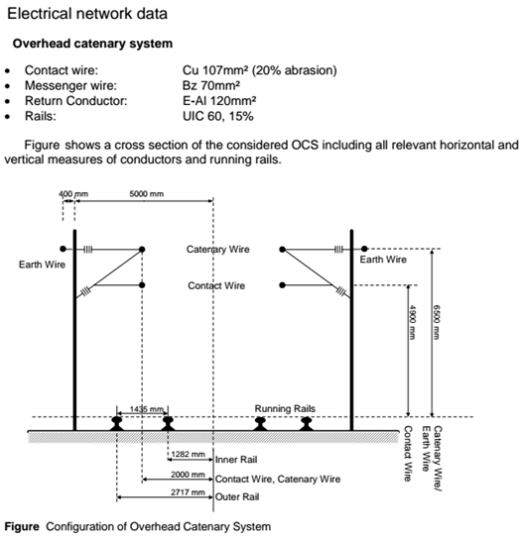


Fig. 8 OCL system of Fig. 7

A. Test Case 1: No Track Section

The simulation of the vehicle braking is conducted to investigate the maximum power transfer during the

braking. For this vehicle the maximum braking effort used is 150 kN with 32 km/h of base speed. This leads to a maximum braking power of 1300 kW. (2) is used to calculate the total reactance and together with (1) the power angle equation of this case can be computed. The maximum power transfer limit that is the magnitude of this equation, (1), is varied due to the train braking position. BY varying the train braking position from 0 to 8.0 km, the maximum power transfer capability of the train during its brake is depicted as shown in Fig. 9. As a result the maximum power transfer is in the range of 169.5 – 175.5 MW. However, the short-circuit level at the end line and the substation bus bar of this case are 114 MW and 157 MW respectively. This characterizes the ability to supply the fault power from the train braking without violating the maximum power transfer limit.

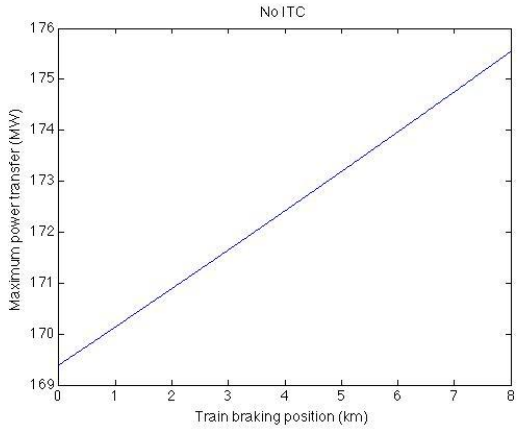


Fig. 9 Maximum power transfer of no ITC case

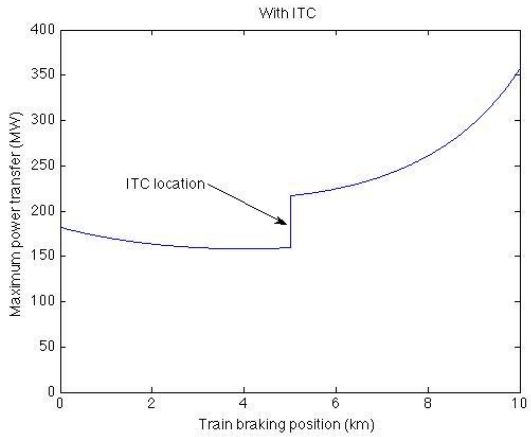


Fig. 10 Maximum power transfer of ITC case

B. Test Case 2: With Track Section (ITC)

The simulation of the vehicle braking is conducted to investigate the maximum power transfer during the braking. For this vehicle the maximum braking effort used is 150 kN with 32 km/h of base speed. This leads to a maximum braking power of 1300 kW. (3) and (4) are used to calculate the total reactance and together with (1) the power angle equation of this case can be computed. The maximum power transfer limit that is the magnitude of this equation, (1), is varied due to the train braking position. BY varying the train braking position from 0 to 10.0 km, the maximum power transfer capability of the train during its brake is depicted as shown in Fig. 10. As a result the maximum power transfer is in the range of 160 – 350 MW. However, the short-circuit level at the end line, ITC and the substation bus bar of this case are 114 MW, 132 MW and 157 MW respectively. This characterizes the ability to supply the fault power from the train braking without violating the maximum power transfer limit.

This is just a two example representing the approach to evaluate the ability of fault power handling. This is a basic concept and can be employed as a tool for further investigation of AC railway power feeding system. A study of transient power system in AC railway power feeding systems is therefore carried out. For example, a calculation of critical clearing time can be calculated and the risk of transient stability can be improved. However, this problem is risen during the train braking only and just a few train is running at the same power feeding section of a long distance railway electrified line. Multi-machine study of the transient stability is not necessary. Only a single-machine connected to an infinite bus model is sufficient for the extension.

V. CONCLUSION

This paper described the approach to calculate the maximum power transfer capability in AC railway power feeding systems of two typical widely-used configuration. The Suvanabhumi airport rail link is employed as a test system. The first test is the configuration that has no ITC. This configuration can allow 169.5 – 175.5 MW power transferring between the sources. The second test is the configuration with ITC installed at the mid of the line length. This case enables approximately 160 – 350 MW flowing through the AC railway feeder line portion.

REFERENCES

[1] S. Nasr, M. Petit, M. Iordache, and O Langlois, "Stability of DC micro-grid for urban railway systems", International Journal of Smart Grid and Clean Energy, vol. 4, no. 3, pp. 261 - 268, July 2015.

[2] N. Hugo, P. Villegas, and B.B. Johnson, “Transient stability assessment of multi-machine multi-converter power systems”, IEEE Trans. on Power Systems, vol. 34, no. 5, pp. 3504 – 3514, September 2019.

[3] J. Grainger , and W. Stevenson Jr., "Power system analysis", McGraw-Hill, 1994

[4] H. Saadat, “Power system analysis”, McGraw-Hill, Singapore, 2004

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