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팬타그래프 전압제약조건을 고려한 AT급전계통 해석

Analysis Of AT Feeding Systems Considering The Voltage Constraint Conditions Of The Pantagraph

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Abstract

Constant load model is widely used for an electric train to perform the static analysis of AT (Auto Transformer) feeding systems. In this model, the train will be considered as a constant load model when it drives or as a constant source model when it applies regenerative brake. However there must be some constraints imposed on the pantagraph voltage in actual operations. These constraints are established for the reason of protecting the feeding facilities from excessive rise of regenerative braking voltage or guaranteeing the minimum traction power of train. In normal operating situation, the pantagraph voltage of the train should be maintained within these limits. Keeping these facts in minds, we suggest new methods of analyzing AT feeding systems using the constant power models with the conditions of voltage constraints. The simulation results from a sample system using the proposed method illustrate both the states of system variables and the supply-demand relation of power among the trains and the systems very clearly, so it is believed that the proposed method yields more accurate results than conventional methods do. The proposed methods are believed to contribute to the assessment of TCR-TSC for compensating reactive powers too.

Keywords : Electric train, AT feeding systems, Regenerative brake, Pantagraph, Voltage constraints

1. AT Feeding Systems

1.1 Simplification of Mutual Impedances

Considered from the point of potential differences, the AT feeding systems that consist of multiple conductors can be reduced to the 3-line feeding systems, the catenary, the rail and the feeder as shown in Fig. 1. All of them are electrically composed of self impedances and mutual impedances between them. Even though the mutual impedances are taken into account, there is no difficulty in analyzing the circuits, but it is unavoidable that the developing processes of their equations get complicated, so we substitute the self-impedances equivalent to the mutual impedances for them.

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There are two lines from a substation to the first AT, and three lines in the other sections.

2-line section, section 0

In this section the circuit can be expressed with the equivalent self-impedance Z_{C0} and Z_{F0} after the mutual impedances are eliminated as follows.

$$\begin{aligned} Z_{C0} &= Z_{CC0} - Z_{CF0} \\ Z_{F0} &= Z_{FF0} - Z_{CF0} \end{aligned} \tag{1}$$

The other 3-line sections

In the other sections except for the section 0, there are three lines, the catenary, the rail and the feeder. It is always true that $i_{Ck} + i_{Rk} + i_{Fk} = 0$ (k is a section number.) in these sections, so it is possible to make the circuit expressed with self-impedances only using the following equations.[1]

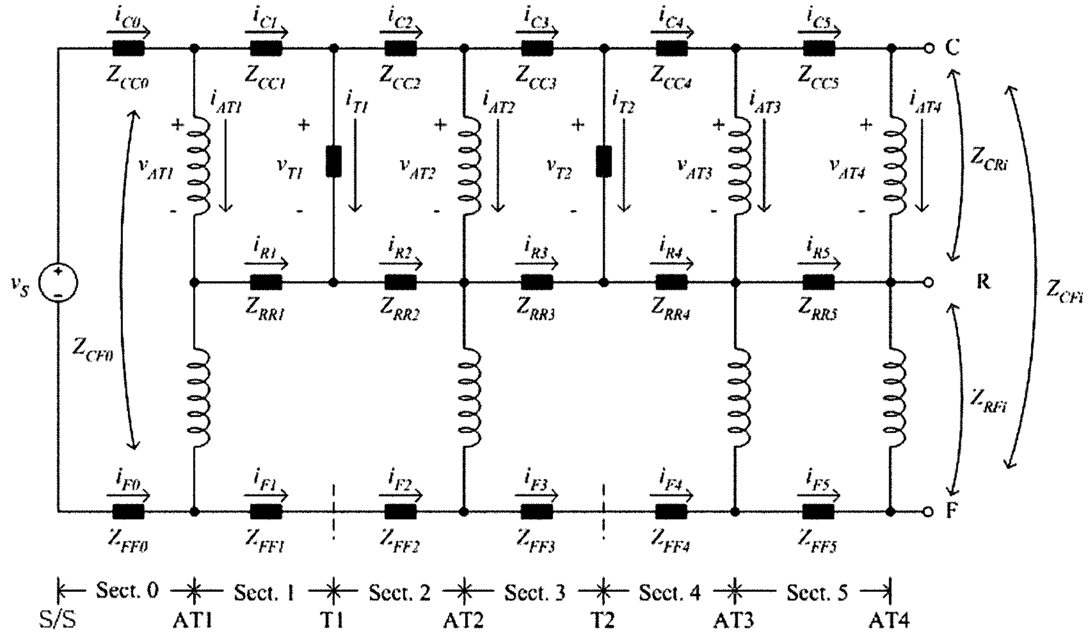


Fig. 1. AT feeding systems

$$
\begin{aligned}
Z_{Ck} &= Z_{CCk} + Z_{RFk} - Z_{CRk} - Z_{CFk} \\
Z_{Rk} &= Z_{RRk} + Z_{CFk} - Z_{RFk} - Z_{CRk} \\
Z_{Fk} &= Z_{FFk} + Z_{CRk} - Z_{CFk} - Z_{RFk}
\end{aligned}
\tag{2}
$$

(k is a section number, $k \neq 0$)

1.2 The Sections Where the Circuit Analysis is Unnecessary

A train is the variational load that changes as time passes. The topology of feeding systems gets changed according to the locations of the trains in the systems from the view of the circuit analysis. The circuit variables and the number of the related equations increase or decrease depending on the locations of the trains. For example, when the trains are located as shown in Fig. 1, the circuit is divided into 7 meshes. There is no wonder that the currents won't flow through the opposite sections of the source where the train doesn't exist (in this figure the section between AT3 and AT4, and the following sections after AT4), but it is easy to make a mistake of thinking that the currents flow through these sections when the train is considered as a constant current model. It can be confirmed by the examination as follows.

When i_{AT4} is the current that flows on AT4, in the upper mesh of section 5,

$$v_{AT3} = (Z_{C5} - 2Z_{R5}) i_{AT4} + v_{AT4} \tag{3}$$

and by the behavior of 1:1 current distribution in the half tap AT, in the lower mesh of section 5,

$$v_{AT3} = -(Z_{C5} + 2Z_{R5}) i_{AT4} + v_{AT4} \tag{4}$$

i_{AT4} must be equal to 0 to make both (3) and (4) true at the same time, and it is unnecessary to induce the circuit equations of section 5. It is true even if the train is considered as a constant current load.[2]

2. Constant Train Model

If the voltage applied to a train is v_T and the current is i_T each, the constant load model is represented as,

$$S_T = v_T \times i_T^* = S_T \cos\alpha + jS_T \sin\alpha \tag{5}$$

where α is the power factor angle of a vehicle and regarded as unchangeable when the static analysis is performed. The general power factor angles of a vehicle according to the

Table 1. Power factor angles according to the operating modes of a vehicle (α)

	Driving	Regenerative braking
Thyristor phase controlled vehicle	40°	120°
PWM controlled vehicle	0°	180°

control methods and the operating modes are gathered in Table 1.[3]

The pantagraph voltage of the train v_T may reach the upper limit, $V_{T\_\max}$, which can occur during the regenerative braking phase. As the opposite case the voltage v_T may reach the lower limit, $V_{T\_\min}$, which can occur during the full torque driving phase. However $V_{T\_\max}$ or $V_{T\_\min}$ are given numbers depending on the insulation level of the systems and the minimum required torque of the train, etc. Consequently the voltage v_T should be maintained between these numbers. When $|v_T| > V_{T\_\max}$ or $|v_T| < V_{T\_\min}$, the absolute value of the train voltage is fixed to,

$$|v_T| = V_{T\_\max} \quad \text{or} \quad |v_T| = V_{T\_\min} \tag{6}$$

and

$$\theta_{v_T} - \theta_{i_T} = \alpha \tag{7}$$

(θ_{v_T} is a voltage phase angle and θ_{i_T} is a current phase angle.)

If v_T and i_T are represented in the rectangular coordinate system as follows, $v_T = v_{Tre} + jv_{Tim}$, $i_T = i_{Tre} + ji_{Tim}$, (6) and (7) become

$$v_{Tre}^{\ 2} + v_{Tim}^{\ 2} = V_{T\_\max}^{\ 2} \ (\text{or } \ V_{T\_\min}^{\ 2}) \tag{8}$$

$$(v_{Tim} i_{Tre} - v_{Tre} i_{Tim}) / (v_{Tre} i_{Tre} + v_{Tim} i_{Tim}) = \tan\alpha \tag{9}$$

The train operating states are determined by the values that satisfy (5), (6) and (7). (otherwise (5), (8) and (9) in rectangular form)

3. System Equations

We select the currents on the ramified sides of the AT feeding systems as current state variables, namely the load currents of each train $i_{Tj}\,(j = 1, 2, ,..)$ and the AT currents $i_{ATk}\,(k = 2, 3, ,..)$. If so, we can express other currents on the catenary and the feeder by using i_{Tj}, i_{ATk} and the behavior of 1:1 current distribution in the half tap AT, which follows the conservation rule of the flux linkage. The current of the rail can be earned easily using $i_{Ci} + i_{Ri} + i_{Fi} = 0$ in 3-line sections.

① $i_{Ci}\,(i \neq 0) = \sum_{j,k}^{m,n} (i_{Tj} + i_{ATk})$

i_{Tj} is a vehicle current (m cars) and i_{ATk} is an AT current (n units) of the load side from section i.

② $i_{C0} = 1/2 \sum_{j}^{m} i_{Tj}$

i_{Tj} is a vehicle current (m cars) of the load side from section 0.

③ $i_{Fi}\,(i \neq 0) = \sum_{k}^{n} i_{ATk}$

i_{ATk} is an AT current (n units) of the load side from section i.

④ $i_{F0} = -i_{C0} = -1/2 \sum_{j}^{m} i_{Tj}$

i_{Tj} is a vehicle current (m cars) of the load side from section 0.

⑤ $i_{Ri} = -(i_{Ci} + i_{Fi})$
$= -\sum_{j,k}^{m,n} (i_{Tj} + 2i_{ATk})$

i_{Tj} is a vehicle current (m cars) and i_{ATk} is an AT current (n units) of the load side from section i. On the other side, we select the train voltage, v_{Tj} and the AT voltage, v_{ATk} as voltage state variables, and then the system equations can be easily made out in the system of Fig. 1.

4. Example Of AT Feeding Systems Analysis

As an illustrative example for the method, the AT feeding systems shown in Fig. 1 was chosen. Assuming that the locations of the trains are the same as shown in the figure, we set up the train and system data as follows.

① S/S & train load

Voltage at S/S : $v_S = 55(\text{kV}) \angle 0°$

(Train data)
Train control method : PWM
Required train load : 0~10.0 (MVA), variable
Required regenerative power of train : 0~10.0 (MVA), variable
Voltage rising limit : 27.5 (KV)

② Sectional distance (unit : kM)

Sect. 0	Sect. 1	Sect. 2	Secti. 3	Sect. 4
0.3	8.0	4.0	7.0	3.0

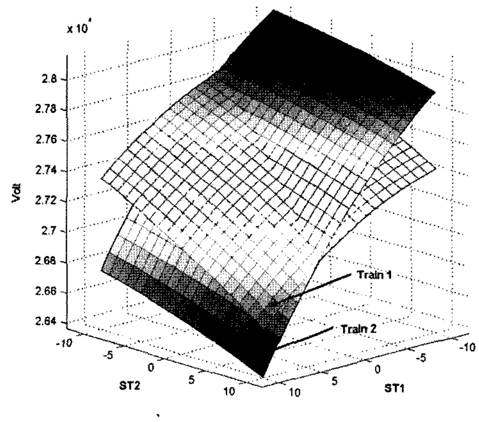
③ Line impedance (unit : Ω/kM)

Z_{CC}	$0.13+j0.82$	Z_{CR}	$0.06+j0.38$
Z_{RR}	$0.19+j0.72$	Z_{RF}	$0.06+j0.39$
Z_{FF}	$0.21+j0.95$	Z_{CF}	$0.07+j0.38$

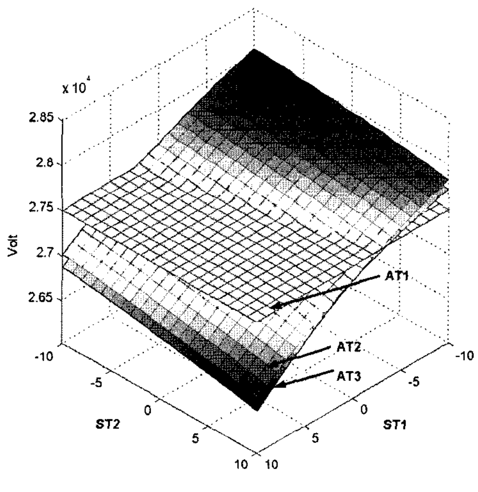
First of all, on the supposition that there are no voltage constraint conditions, the pantagraph voltages of T_1 and T_2 and the AT voltages are illustrated in Fig. 2. The figures were drawn according to the operating modes of each train. In the figure, when the regenerative braking demand (negative load) grows larger, the pantagraph voltage increases, but when the driving load (positive) grows larger, it decreases. Both the highest and the lowest voltage of the pantagraph are presented at T_2, which is the farthest load from the substation. The voltage becomes the lowest when the train loads of T_1 and T_2 are maximum and it becomes the highest when the regenerative braking demands are maximum.

Investigating the voltage sensitivities due to individual load variation, we know that $|\partial v_{T2}/\partial S_{T1}| > |\partial v_{T1}/\partial S_{T1}|$ (when S_{T2} is fixed) and $|\partial v_{T1}/\partial S_{T2}| > |\partial v_{T2}/\partial S_{T2}|$ (when S_{T1} is fixed). In other words, load variation of a certain train has more influences on the voltage of other trains than on the voltage of itself. This is the character of the constant loads supplied from a voltage source. The farther the auto transformer is located from the source, the more sensitive it becomes according to the load change. Since the voltage of the closest auto transformer to the source is most insensitive, AT1 plays a role like the slack bus in the load flow problem. These show that the results of the methods we suggest have physical validity.

When the required train load (S_{T2}) is 1.0 (MVA) and the required regenerative braking power (S_{T1}) is under -1.165 (MVA), $|v_{T1}|$ becomes smaller than the voltage rising limit of 27.5 (kV) and the regenerative brake can be successful. However, when S_{T1} is over -1.165 (MVA) (See Table. 2), $|v_{T1}|$ becomes suppressed below the voltage rising limit of 27.5 (kV) and the regenerative brake as much as the required demand becomes impossible. When $|v_{T1}|$ is suppressed below the limits, the regenerative braking demand of this train is constrained by the load of other train (S_{T2}). Table. 2 shows the possible maximum regenerative power of T_1 (S_{T1}) that is under regenerative braking when $|v_{T1}|$ is suppressed by the limits of 27.5 (kV). The regenerative power varies



(a) Train pantagraph voltages



(b) Auto Transformer (AT) voltages

Fig. 2. The voltages of the train and the system according to the power (MVA) of each operating mode

Table 2. The possible regenerative power of T_1 (S_{T1}) according to the train load (S_{T2}), when $|v_{T1}|$ = 27.5 (kV),

$\|v_{T1}\|$	S_{T2} (MVA)	S_{T1} (MVA)	$\|v_{T2}\|$ (kV)	$\|v_{AT1}\|$ (kV)	$\|v_{AT2}\|$ (kV)	$\|v_{AT3}\|$ (kV)
27.5 (kV)	1.0	-1.165	27.422	27.500	27.466	27.454
	2.0	-2.406	27.382	27.500	27.431	27.406
	3.0	-3.727	27.320	27.500	27.394	27.355
	4.0	-5.134	27.256	27.500	27.355	27.303
	5.0	-6.631	27.189	27.500	27.315	27.248
	6.0	-8.227	27.120	27.500	27.273	27.191
	7.0	-9.929	27.048	27.500	27.228	27.132

according to the train load,S_{T2}. For example, the regenerative brake is possible up to -3.727 (MVA) when S_{T2}=3.0 (MVA), but more regenerative braking demand must be judged to fail in the regenerative control or to need the increase of braking distance or braking time.

5. Conclusion

We have suggested new methods of analyzing the AT feeding systems using the constant power models with the voltage constraints on the pantagraph so far. The constant power models with the conditions of voltage constraints are more practical than the conventional models. The system equations including them can be simply induced and the convergence speed of calculation by the N-R method is fast enough. However, a trivial solution may be found in the calculating process because the constant voltage model is more nonlinear than the constant power model without constraints and gets more sensitive to the initial value in the N-R method. It is confirmed that the voltage, the current and the supply-demand relations of power in the AT feeding systems are physically and clearly explained by the results of simulation using the proposed method, so we can tell that the proposed method is more accurate than the conventional methods.

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