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LOAD MODELING OF ELECTRIC LOCOMOTIVE USING PARAMETER IDENTIFICATION

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ABSTRACT
The electric load components have different characteristics according to the variation of voltage and frequency. This paper presents the load modeling of an electric locomotive by the parameter identification method. The proposed method for load modeling is very simple and easy for application. The proposed load model of the electric locomotive is represented by the combination of the loads which have static and dynamic characteristic. This load modeling is applied to the KTX in Korea to verify the effectiveness of the proposed method. The results of proposed load modeling by the parameter identification follow the field measurements very exactly.

KEY WORDS
Load modeling, Traction power supply system, Parameter Identification

1. Introduction

The analysis of traction power supply system indicates the calculation of the electrical quantities in railway system. The traction power system in the electrified railway is made up of three-phase receiving unit, the facilities including Scott-transformer and auto-transformer to transform voltage level and phase and train as consuming electric power. Therefore, train is the electric load.
The circuit for analysis is made up of a three-phase voltage source represented three-phase receiving unit, the loads represented trains, line impedance for catenary which is transmission line for supplying electric power to train.
Although the circuit element is determined like above, the circuit is not composed yet. Because the state of train (location, consumed power, and etc.) is not known. The location of train decides the position of load and the consumed power indicates the capacity of load in the circuit. Therefore, Train Performance Simulation (TPS) is used to calculate the consumed power, location and speed of train based on the time. The consumed power, however, is just calculated by multiplying mechanical power required for propulsion of train by the ratio in TPS. This ratio is constant for converting the mechanical power into electric power. Thus, it could lead some errors in analysis of traction power system because of the process above simple calculation.
This paper presents the load modeling for the analysis of electric railway system. The electric load components have different characteristics according to the variation of voltage and frequency. The methods for setting up load modeling may be classified into two categories; the first one is to find an aggregation of each component load modeling, and the other approach is to find parameters to represent load characteristics from field tests, if any [1], [2].
This paper proposes the load modeling of electric locomotive by the parameter identification method. The electric locomotive load is represented as combination of the static loads and the dynamic loads. The static load is described as polynomial equations and the dynamic load is described as equivalent induction motor. And the sum of composition rates of each load type is unity.
The pattern search method (PSM) [3] and the recursive least square method (RLS) [4] are applied to the parameter identification methods for the load modeling of an electric locomotive, in this paper. To demonstrate the potentiality of the proposed method for load modeling, actual field measurements from KTX (Korea Train eXpress) is performed.

2. Analysis of Traction Power System

The analysis of traction power system indicates checking electric state of system in normal condition.
It is somewhat difficult to check the condition because the train of electric load repeats powering and breaking.

Figure 1 illustrates a simplified configuration of Korean electric railway. System is supplied with three-phase, 154kV power from the Korea Electric Power Corp. (KEPCO), which is transformed to single-phase 55kV by Scott-connected transformer. And the electric energy is supplied to train. As mentioned above that, the consumed power of train is changing rapidly due to the movement of train. Therefore, TPS should be conducted the analysis of traction power system. It is a simulation to calculate the train location, speed and consumed power with time lapse. After TPS is performed, A circuit network can be formed to analyze traction power system.
The analysis as mentioned above is conventional method. TPS is mainly performed for the location and speed of train. Therefore, the consumed power in train, which is calculated in conventional TPS, is inaccurate from a electrical point of view. This affects the analysis of traction power supply system after all.
This paper presents the representation of load for the accurate analysis of traction power supply system. If proposed method is used, only the location and speed of train is calculated from TPS. The consumed power is not calculated from TPS any more.

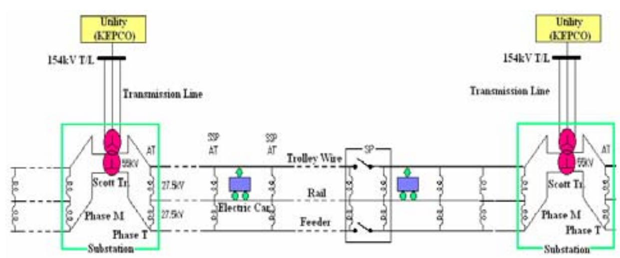

Figure 1 Configure of traction power supply system

3. Load Modeling

In this paper, the proposed load modeling for electric locomotive is to express the load characteristics according to the voltage and frequency by means of a numerical formula. The electric locomotive load is represented as the combination of the static loads and the dynamic loads. The static load is described as polynomial equations and the dynamic load is described as equivalent induction motor. Figure 2 shows the electric locomotive load models which are represented by the summation of static and dynamic characteristic load at the trolley wire(catenary). The symbols in figure 2 are represented in Eq. (5).

3.1 Static Load (Polynomial type)

The static characteristics load is given by the polynomial type in Eq. (1).

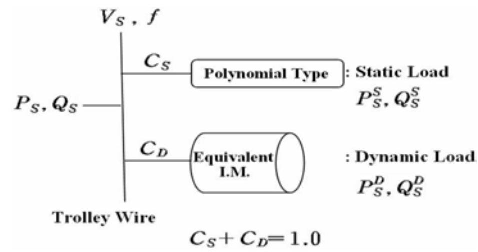

Figure 2 Equivalent load models for electric traction

$$P_S^S(V,f) = a_{p0} + a_{p1}\Delta V + a_{p2}\Delta V^2 + a_{p3}\Delta V^3 + a_{p4}\Delta V^4 + a_{p5}\Delta V^5 + a_{p6}\Delta V\Delta f + a_{p7}\Delta V^2\Delta f + a_{p8}\Delta f^2 \quad (1)$$

$$Q_S^S(V,f) = a_{q0} + a_{q1}\Delta V + a_{q2}\Delta V^2 + a_{q3}\Delta V^3 + a_{q4}\Delta V^4 + a_{q5}\Delta V^5 + a_{q6}\Delta V\Delta f + a_{q7}\Delta V^2\Delta f + a_{q8}\Delta f^2$$

where,

P_S^S : Real power [p.u] of static load

Q_S^S : Reactive power [p.u]] of static load

ΔV : Deviation from the nominal voltage [p.u]

Δf : Deviation from the nominal frequency [p.u]

$a_{p0,} \ldots, a_{p8}$: Parameters of real power

$a_{q0,} \ldots, a_{q8}$: Parameters of reactive power

3.2 Dynamic Load (Equivalent Induction Motor)

The dynamic load is represented by the equivalent induction motor in this paper. Figure 3 shows the equivalent circuit of induction motor with the rotating load.

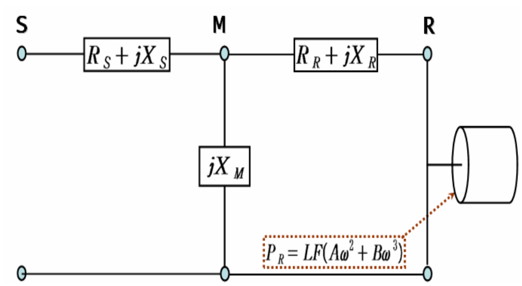

Figure 3 Equivalent circuit of IM with rotating load

At the given equivalent circuit at the Figure 3, for the analysis, a direct solution of the circuit which is assumed as slip is usually employed. However, equivalent to the constant impedance, which is not appropriate, since the load of constant impedance consumes power with square

of voltage, while induction motor power shows constant. Slip varies depending upon the voltages and frequencies.
In this paper, for the analysis of induction motor, equivalent circuit of Figure 3 is supposed by small power system with 3 buses as S, M and R. In each bus, real and reactive power can be solved. From this assumption, the load of dynamic characteristic model is represented by Eq. (2).

$$P_S^D = f(V_S, f, Z)$$
$$Q_S^D = f(V_S, f, Z) \tag{2}$$

where,

P_S^D : Real power [p.u] of dynamic load

Q_S^D : Reactive power [p.u] of dynamic load

V_S : Input voltage [p.u]

f : Input frequency [p.u]

Z : Parameter of induction motor [p.u]

Let rotating speed of induction motor be ω_m, magnitude of load is given by

$$P_L = -P_R = LF\left(A\omega_m^2 + B\omega_m^3\right) \tag{3}$$

where,

P_L : Mechanical load

LF : Loading factor [p.u]

A, B : Mechanical coefficient

Then rotating speed of induction motor is given by Eq. (4) from mechanical-electrical coupling.

$$\omega_m = \left(\frac{\omega_0}{V_R^2}\right)\left[1 - LF\left(A\omega_m^2 + B\omega_m^3\right)\right] \tag{4}$$

Accordingly, for the analysis of inductive motor, besides conventional power flow calculation it is needed only additional process of convergence from mechanical-electrical coupling. Because the revolution of rotor and the power depend on input voltages and frequencies.

3.3 Combined Load Model

Proposed load model is the combined load of the static and dynamic characteristic load in this paper. Then, real and reactive power of combined load model about the variation of voltages and frequencies for the electric locomotive is represented by

$$P_S^{model}(V_S, f, X) = C_D P_S^D + C_S P_S^S$$
$$Q_S^{model}(V_S, f, X) = C_D Q_S^D + C_S Q_S^S \tag{5}$$

where,

P_S^D , Q_S^D : Real and reactive power of dynamic load

P_S^S , Q_S^S : Real and reactive power of static load

V_S : System voltage [p.u]

f: Frequency [p.u]

X : Parameter set of combined load

C_D : Composition ratio of dynamic load

C_S : Composition ratio of static load

4. Parameter Identification

In order to apply the combined load modeling to the analysis of electric railway system, the parameters for static and dynamic load model are estimated respectively. These should be identified from field measurement data according to the variation of voltage and frequency. This paper is interested in the load modeling of an electric locomotive by identification parameters.
For the parameter identification of the combined load modeling, the recursive least method and the pattern search method are used in this paper.

4.1 The Recursive Least Square Method

To apply recursive identification technique, the recursive least square method has some advantages, which the required memory for computation is quite modest, though not all data are stored. And this method can be easily modified into real time algorithm.
Using the recursive least identification method, combined load model of electric locomotive can be rearranged to take a suitable amount of measurement data as

$$Y_N = A_N X_N + E_N \tag{6}$$

where,

Y_N : Measurement vector

X_N : Parameter vector

A_N : Model matrix

E_N : Error vector

The recursive least square method can be applied and other formulations are required as Eq.(7).

$$P_N = \left(A_N^T A_N\right)^{-1} \tag{7a}$$

$$K_{N+1} = P_N A_{N+1}^T \left(I + A_{N+1} P_N A_{N+1}\right)^{-1} \quad (7b)$$

$$X_{N+1} = X_N + K_{N+1}\left(Y_{N+1} - A_{N+1} X_N\right) \quad (7c)$$

where,

K : Gain matrix

N : Steps of identification

4.2 The Pattern Search Method

Pattern search method is used widely to calculate unknown variables as one of the optimization techniques. The objective function to establish load model of electric locomotive in advance minimizes the difference between measured and calculated value. The objective function for pattern search method is defined as

$$J = \sum_{i=1}^{n}\left[\left(P_{S,i}^{model}(X) - P_{S,i}^{mes}\right)^2 + \left(Q_{S,i}^{model}(X) - Q_{S,i}^{mes}\right)^2\right] \quad (8)$$

where,

$P_{S,i}^{model}$: Simulated value of real power

$Q_{S,i}^{model}$: Simulated value of reactive power

X : Set of parameter

$P_{S,i}^{mes}$: Measured value of real power

$Q_{S,i}^{mes}$: Measured value of reactive power

n: Number of measured value

4.3 Flow of Parameter Identification

The flow of the proposed electric locomotive load modeling by parameter identification is shown in Figure 4.

5. Case Studies

The proposed electric locomotive load modeling is applied to the KTX system in Korea to verify the effectiveness of the method.

5.1 Measurement

In order to set up a load modeling, data was gathered from KTX which is currently in service. Figure 5 illustrates a diagram to measure the voltage, current, frequency, and etc.. The train speed is measured using DAQCard-6062E of National Instrument. Data is collected and recorded by using LabView.

5.2 Classification According to Running Mode

It is impossible to set up integrated load model since train moves with acceleration and deceleration repeatedly. The train has a different characteristic respectively, when it is accelerated or decelerated. When train accelerates, electric power is absorbed into the train. The electric power, however, is generated in train when it decelerates. Therefore, this paper presents each model of acceleration and retardation through the acceleration of the train calculated with speed.

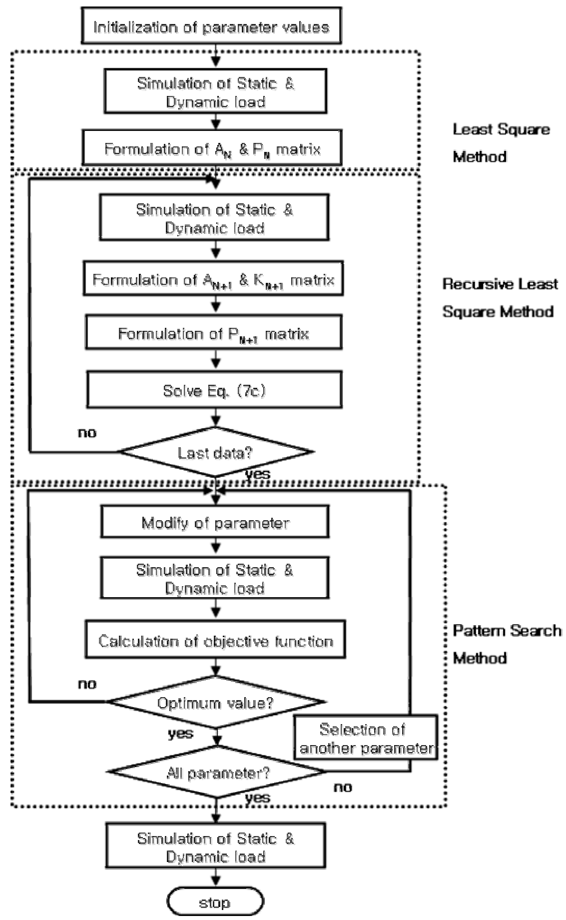

Fig. 4 Flowchart of parameter identification

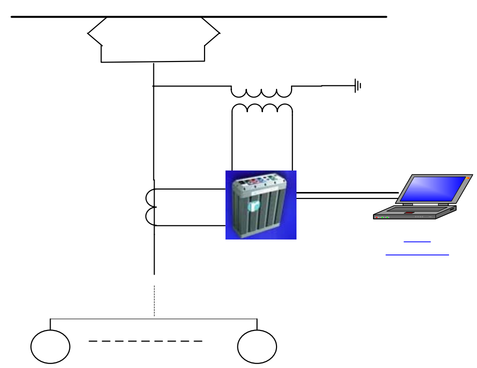

Figure 5 The diagram for measuring in KTX

5.3 Results of Load Modeling for Accelerating mode

When train accelerates, it consumes electric energy in the powering mode.

Figure 6 shows the value of voltage and frequency by the measurement. The voltage is fluctuant, but frequency is not.

The results of simulation and measurements of real and reactive power are shown in Figure 7 and 8. It is seen that the load model by the proposed method is reasonable

5.4 Results of Load Modeling in the Deceleration Mode

The decelerating mode means that the electric locomotive reduces speed. At this state, the electric power is generated by regenerative braking.

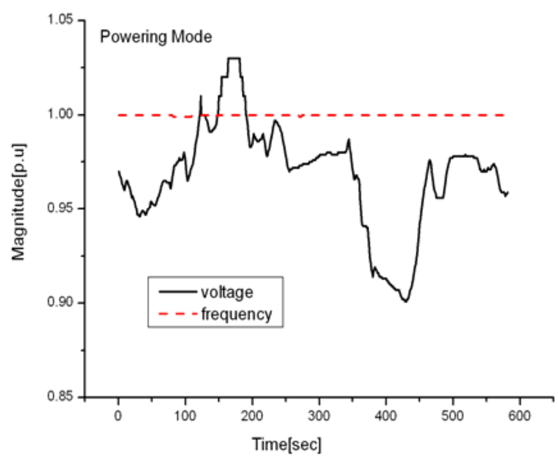

Figure 6 Measurements of voltage and frequency in accelerating mode

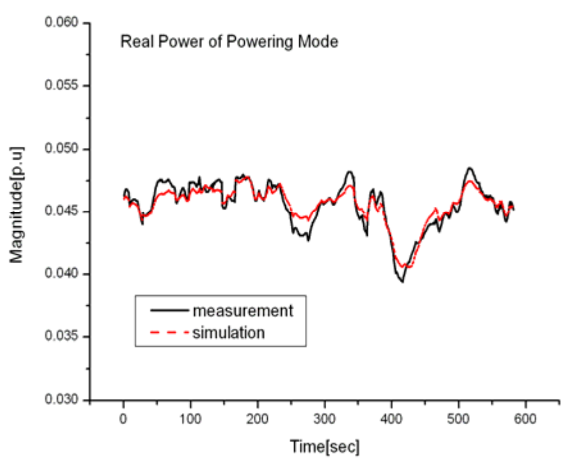

Figure 7 The results of load modeling in accelerating mode (real power)

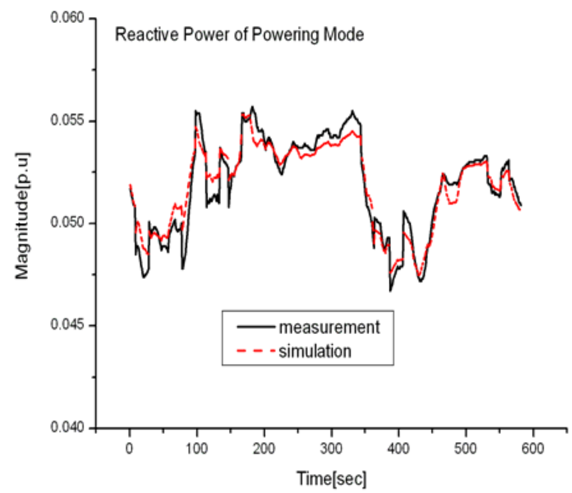

Figure 8 The results of load modeling in powering mode (reactive power)

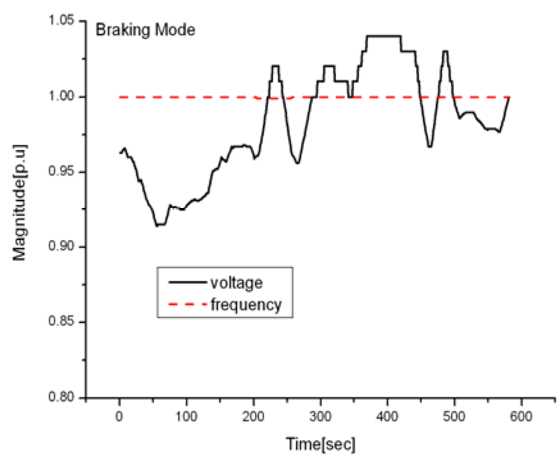

Figure 9 Measurements of voltage and frequency in decelerating mode

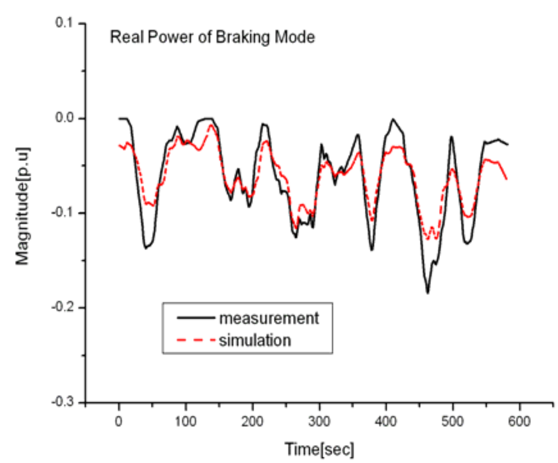

Figure 10 The results of load modeling in decelerating mode (real power)

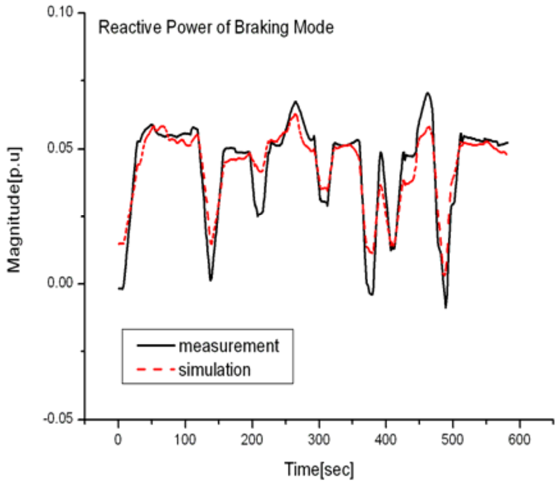

Figure 11 The results of load modeling in decelerating mode (reactive power)

Figure 9 shows value of voltage and frequency by the measurement in decelerating mode. Similarly in the accelerating mode, voltage is fluctuant, but frequency is not.
The results of simulation and measurements of real and reactive powers are shown in Figure 10 and 11. As results in accelerating mode, It is seen that the load model by the proposed method is quite comparable with results of the real simulations. And the proposed method for the electric locomotive load modeling is simple in concept and easy for the implementation.

6. Conclusion

This paper presents the load modeling of electric locomotive by the parameter identification method. In this paper, parameter identification method is proposed by combining recursive least square method (RLS) with pattern search method (PS). Proposed method for load modeling is very simple and easy for application.
Proposed load model of the electric locomotive is the combined load of the static and dynamic characteristic load. The static load is represented by polynomial type, and the dynamic load is represented by equivalent induction motor.
This load modeling is applied to the KTX system in Korea to verify the effectiveness of the proposed method. The results of the proposed load modeling by parameter identification follow the field measurements very exactly.

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