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Load Modeling of Electric Locomotive Using Parameter Identification

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Abstract – 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 that have static and dynamic characteristics. 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.

Keywords: Load modeling, Parameter, Traction power supply system

1. Introduction

Analysis of the traction power supply system indicates the calculation of the electrical quantities in railway systems. The traction power system in the electrified railway is comprised of a three-phase receiving unit, *facilities including Scott-transformer and auto-transformer* to transform voltage level and phase, and the train as consuming electric power. Therefore, the train is the electric load.

The circuit for analysis is made up of a three-phase voltage source represented by a three-phase receiving unit, load represented trains, and line impedance for catenary that is a transmission line for supplying electric power to the train.

Although the circuit element is determined like indicated above, the circuit is not determined due to the unknown state of the train (location, consumed power, and etc.). The location of the 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 the train based on time. The consumed power, however, is simply calculated by multiplying the mechanical power required for the train propulsion by the ratio in the TPS. This ratio is constant for converting the mechanical power into electric power. Thus, it could make some errors in analysis of the traction power system.

This paper presents the load modeling for the analysis of the 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 [1-2].

This paper proposes the load modeling of the electric locomotive by the parameter identification method. The electric locomotive load is represented as a combination of the static loads and the dynamic loads. The static load is described using polynomial equations and the dynamic load is described using the 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 the KTX (Korea Train eXpress) is performed.

2. Analysis of Traction Power System

Analysis of the traction power system indicates checking the electric state of the system in normal condition.

It is somewhat difficult to check the condition because the train of electric load repeats powering and breaking.

Fig. 1 illustrates a simplified configuration of the Korean electric railway. The system is supplied with three-phase, 154kV power from the Korea Electric Power Corp. (KEPCO), which is transformed to single-phase 55kV by a Scott-connected transformer. In this way the electric energy is supplied to the train. As mentioned previously, the consumed power of the train is changing rapidly due to the

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movement of the train. Therefore, TPS should be conducted for the analysis of the 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 the traction power system.

The analysis as mentioned above is the conventional method. TPS is mainly performed for the location and speed of the train. Therefore, the consumed power in the train, which is calculated in the conventional TPS, is inaccurate from an electrical point of view. This affects the analysis of the traction power supply system after all.

This paper presents the representation of load for the accurate analysis of the traction power supply system. If the proposed method is used, only the location and speed of the train is calculated from the TPS. The consumed power is not calculated from the TPS any more.

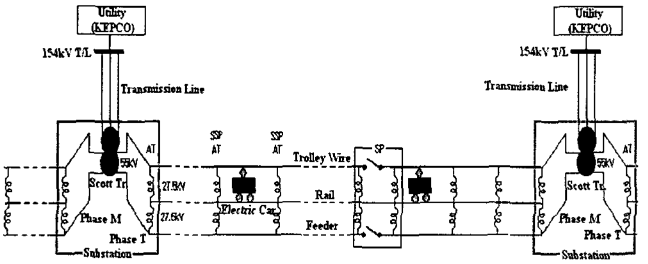

Fig. 1. Configure of traction power supply system

3. Load Modeling

In this paper, the proposed load modeling for the 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 using polynomial equations and the dynamic load is described using the equivalent induction motor. Fig. 2 indicates the electric locomotive load models that are represented by the summation of static and dynamic characteristic load at the trolley wire. The symbols in fig. 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).

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

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

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

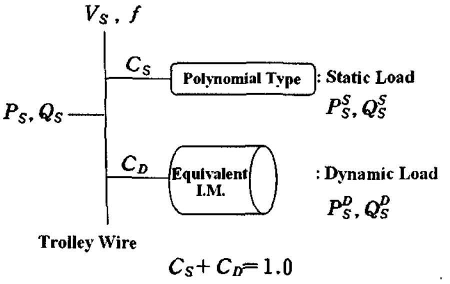

***Fig. 2.** Equivalent load models for electric traction*

3.2 Dynamic Load (Equivalent Induction Motor)

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

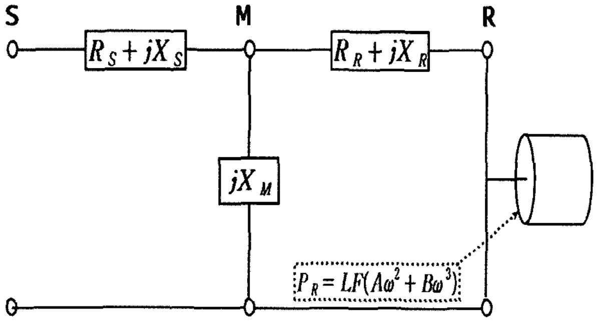

Fig. 3. Equivalent circuit of IM with rotating load

At the given equivalent circuit in Fig. 3, for the analysis, a direct solution of the circuit that is assumed as slip is usually employed. However, equivalent to the constant impedance, which is not appropriate, the load of constant impedance consumes power with the square of voltage, while the induction motor power shows constant. The slip varies depending upon the voltages and frequencies.

In this paper, for the analysis of the induction motor, the equivalent circuit of Fig. 3 is supposed by a 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 the dynamic characteristic model is represented by Eq. (2).

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

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 the 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 the 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 analysis of the inductive motor, besides conventional power flow calculation it requires the additional process of convergence from mechanical-electrical coupling. The rotation of rotor and the power depend on input voltages and frequencies.

3.3 Combined Load Model

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

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

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 the 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

When applying the recursive identification technique, the recursive least square method has some advantages, for 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).

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

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

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

where,

K: Gain matrix

N: Steps of identification

4.2 The Pattern Search Method

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

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

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 Fig. 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 the KTX, which is currently in service. Fig. 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.

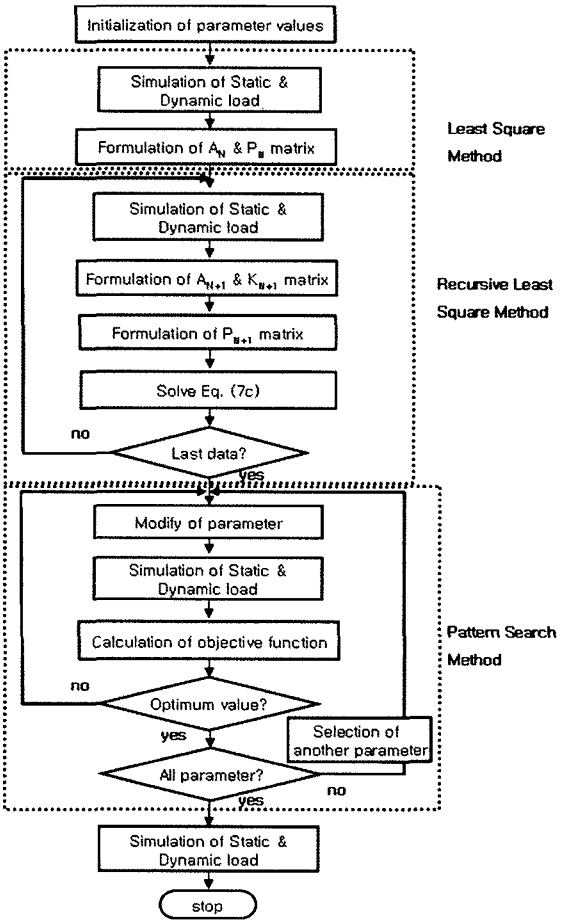

Fig. 4. Flowchart of parameter identification

5.2 Classification According to Running Mode

It is impossible to set up an integrated load model since the train moves with acceleration and deceleration repeatedly. The train has a different characteristic respectively, when it is accelerated or decelerated. When the train accelerates, electric power is absorbed into the train.

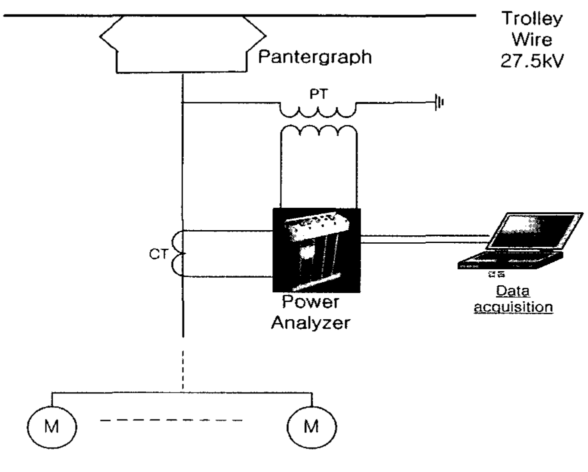

Fig. 5. The diagram for measuring in the KTX

The electric power, however, is generated in the train when it decelerates. Therefore, this paper presents each model of acceleration and retardation through the acceleration of the train calculated with speed.

5.3 Results of Load Modeling for Accelerating Mode

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

Fig. 6 indicates 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 presented in Fig. 7 and 8. It is seen that the load model by the proposed method is reasonable. The parameters of accelerating mode are shown in Table 1.

Table 1. The parameters of accelerating mode

Real power model		Reactive power model	
Coefficient	Parameter	Coefficient	Parameter
a_{p0}	4.73E-02	a_{q0}	5.33E-02
a_{p1}	7.52E-02	a_{q1}	-5.76E-02
a_{p2}	2.70E-01	a_{q2}	-1.42E+00
a_{p3}	-4.16E+01	a_{q3}	1.03E+02
a_{p4}	-6.30E+02	a_{q4}	2.26E+03
a_{p5}	-1.91E+03	a_{q5}	1.21E+04
a_{p6}	1.22E+02	a_{q6}	3.39E+01
a_{p7}	8.81E+02	a_{q7}	4.94E+02
a_{p8}	2.69E+00	a_{q8}	-1.07E-01

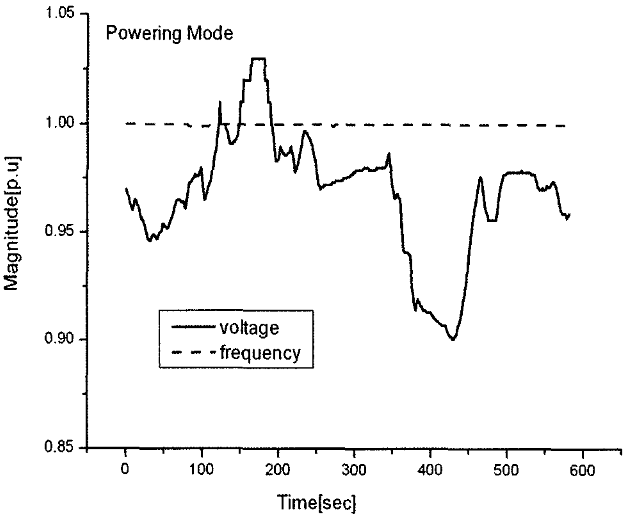

Fig. 6. Measurements of voltage and frequency in acceleration mode

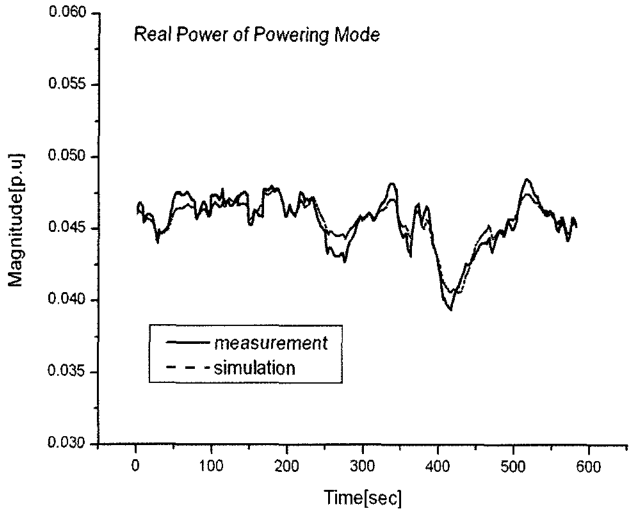

Fig. 7. Results of load model in accelerating mode (real power)

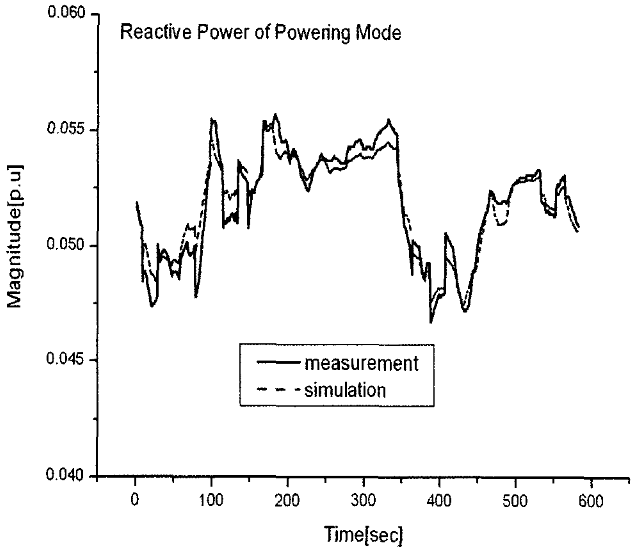

Fig. 8. Results of load model in powering mode (reactive power)

5.4 Results of Load Modeling for Deceleration Mode

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

Fig. 9 also shows the measured value of voltage and frequency. The voltage is fluctuant, but the frequency is not like the accelerating mode.

The results of simulation and measurements of real and reactive power are indicated in Fig. 10 and 11, and the parameters of accelerating mode are shown in Table 2.

Table 2. The parameters of deceleration mode

Real power model		Reactive power model	
Coefficient	Parameter	Coefficient	Parameter
a_{p0}	-8.80E-02	a_{q0}	4.67E-02
a_{p1}	2.89E-01	a_{q1}	-2.03E-01
a_{p2}	6.36E+01	a_{q2}	-1.98E+01
a_{p3}	3.97E+02	a_{q3}	-2.30E+02
a_{p4}	-3.35E+04	a_{q4}	7.39E+03
a_{p5}	-2.71E+05	a_{q5}	7.35E+04
a_{p6}	9.58E+01	a_{q6}	-1.81E+02
a_{p7}	5.92E+04	a_{q7}	-8.66E+03
a_{p8}	-5.49E+01	a_{q8}	-1.44E+01

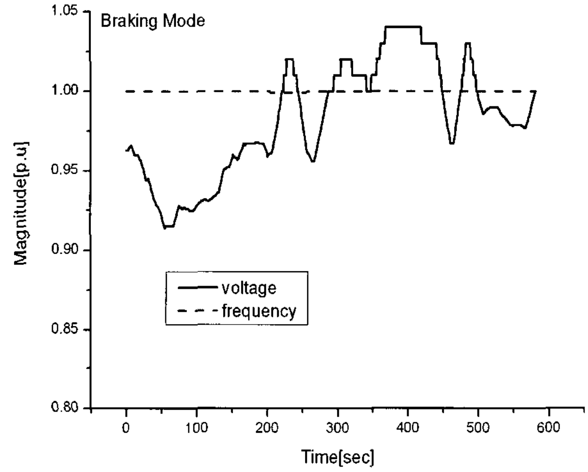

Fig. 9. Measurements of voltage and frequency in decelerating mode

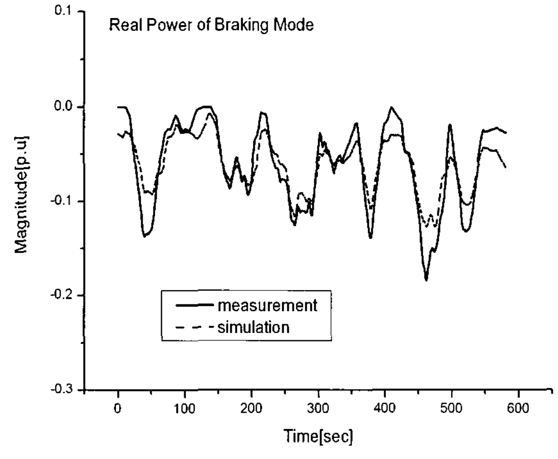

Fig. 10. The results of load modeling in decelerating mode (real power)

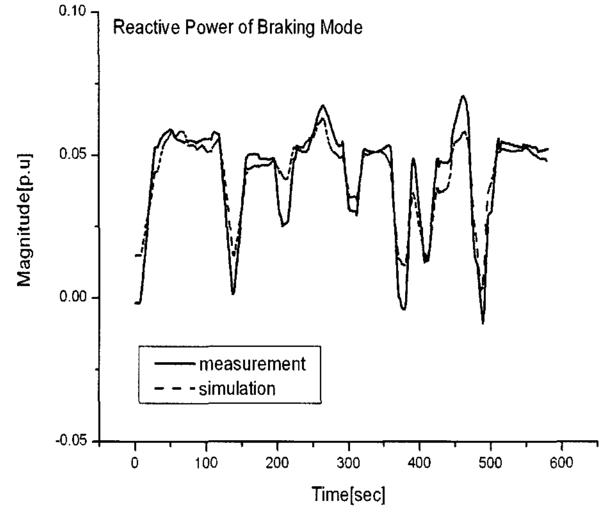

Fig. 11. The results of load modeling in decelerating mode (reactive power)

6. Conclusion

This paper presents the load modeling of the electric locomotive by the parameter identification method. In this paper, the parameter identification method is proposed by combining the recursive least square method (RLS) with the pattern search method (PS). The proposed method for load modeling is very simple and easy for application.

The 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 the 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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