Dynamic Calculation of a DC-Electrification of an Urban Railway for Studies on Control of Regenerative Brakes and Management of Their Electric Power

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Abstract**-- The authors describe a theory and numerical approach of transient calculations of a DC-electrification system containing multiple substations as well as moving trains. The tool has been developed based on generic software MATLAB and SIMULINK, which is easy-to-use for transient calculations and well-known by many engineers. A modification of the algorithm of on-board squeezing controls has resulted in improvement of several percent of regenerated energy in a field study. One can trace loci of transient electrical operating points using calculated data from the numerical transient analysis. Such dynamic simulation of transient behavior in a DC-electrification system is, therefore, useful in practice for redesign/relaxation of protection controls of regenerative braking trains for better usage of regeneration and total electrical energy.**

Index Terms**—DC-Electrification, electric, railway, power management, regenerative brake**

I. Introduction

The ratio of modern trains with regenerative braking function has been increased, and recent urban electric railways need new strategies both in electrification and train controls in order to take full advantages of the regenerative brakes effectively; setting lower no-load output voltage at substations, re-designing of protection algorithm of squeezing control of regenerative brakes, sophisticated braking management based on inter-train communication,and introduction of new energy management using electric power storage to be installed wayside as well as on-board. The protective switching from regenerative to mechanical brakes depends on instantaneous voltage at a train pantograph, that is to say, the usage and limitation of the regenerative electric braking mode strongly depends on transients of electric circuit for electrification. The authors, therefore, describe a theory and numerical approach of transient calculations of a DC-electrification system containing multiple substations as well as moving trains as shown in Fig. 1. The fundamental theory and algorithm will be explained in section II.

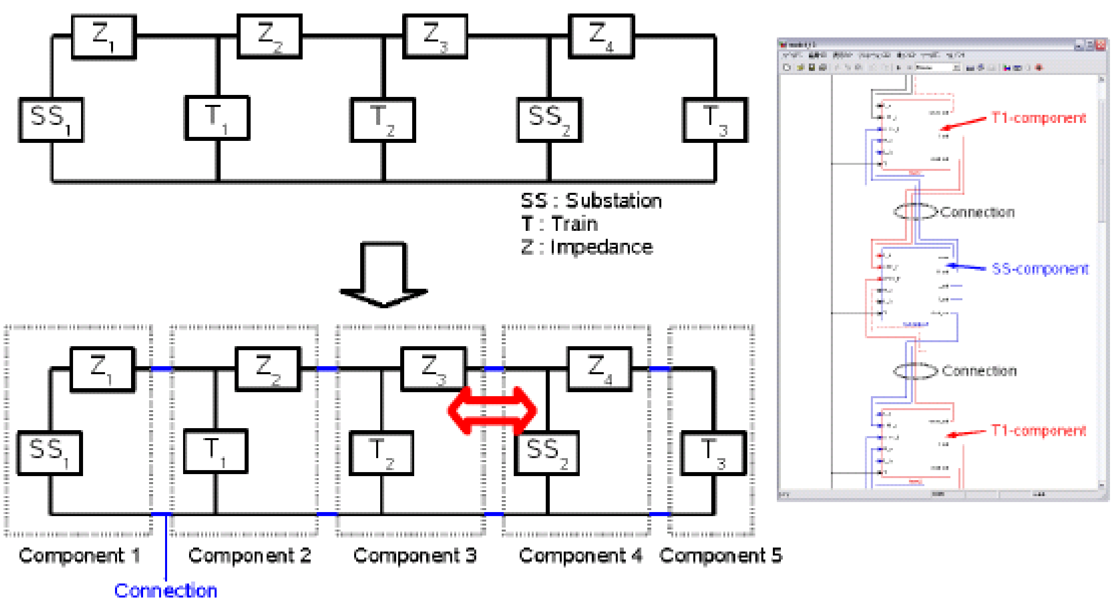


Fig. 1.Fundamental block for dividing a DC-electrification circuit to functional blocks for a transient simulator using MATLAB and SIMULINK.

The tool, whose fundamental structure is illustrated in Fig. 2, has been developed based on generic software MATLAB and SIMULINK, which is easy-to-use for transient calculations and well-known by many engineers. The effects of connecting feeding systems for both train-directions and introduction of wayside power storage devices are discussed based on numerical case studies. The problems for implementing moving trains and its solution will be described in section III.

This calculation tool is also useful for modification and improvement of conventional on-board electric braking controls. Problems in present systems and proposal for the improvement will be described in section IV.

One can trace loci of transient electrical operating points using calculated data from the numerical transient analysis. Such representation is useful to verify the functionality of protection algorithm and evaluation of energy-saving effect realized by regenerative braking. The calculated results will be discussed in section V.

II. Theoretical Basis for the Circuit Calculation

In spite that the authors' main target is calculation of a DC-electrification system, a transient calculation of an electric circuit is needed, since a protection of electric equipment is related to an instantaneous peak voltage. Authors have therefore prepare a transient simulator of electric circuit named *PSET: Power Simulator for Electric Trains*. The power reference value of each trainset is treated as input to the simulator, *i.e.*, it is assumed that the trainsets move completely subject to scheduled run-curve, and input/output corresponding pre-scheduled powers. This condition of “given power” means that one neglects fast transient in onboard electric circuits caused by deviation of line voltages.

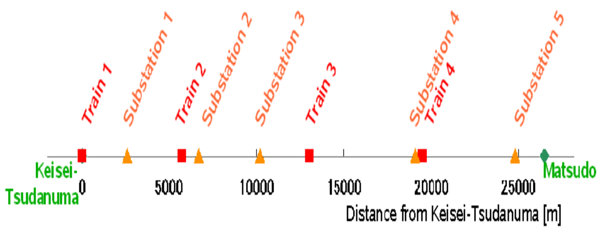


Fig. 2 An example of locations of substations and trains.

This problem has the following difficulties:

i. The circuit topology depends on actual number of trainsets,
ii. it also depends on the relationship of locations of trainsets and substations,
iii. the line impedance is time-dependent, since line-length between a substation and a trainset changes depending on trainset location, and
iv. the power flow from a silicon-substation is UNIDIRECTONAL, *i.e.,* the most substations can only output their power and never absorb: It results in strong nonlinearity in a circuit calculation.

III. Implementation Technique for Moving Trainsets

The dynamic calculation has been implemented by using MATLAB/SIMULINK. On account of the substantial characteristic of this circuit calculation discussed in the previous section, there was two technical difficulties in this implementation:

i. Nonlinearity of V-I characteristics of silicon-substations, and
ii. Changes of circuit topology depending on locations of trainsets.

The first problem was solved by stopping once the calculation, changing different modes of “Substation-ON” and “Substation-OFF” when the sign of the difference between the no-load output voltage and actual line voltage at a substation changes, in order to avoid numerical oscillations caused by sudden change of substations' output-impedances. Since trainsets run over the locations of substations, the circuit topology of total electrification system is changeable. In order to adapt the topology-changes, the authors have divided the circuit model in component functional blocks as shown in Fig. 1. the components *SS_n*, *T_n* and *Z_n* corresponds to models of substations, trainsets and line impedances between adjacent functional blocks. The power source and impedances in each component functional blocks are time-dependent. The time-profile of these time-dependent parameters have been prepared for an actual calculation. These annoying requirements for the implementation techniques were successfully fulfilled by using user-friendly interface of SIMULINK and authors' original control macros for controlling the prepared various circuit models corresponding to the different circuit topologies.

An example of the case-study model has already been illustrated in Fig. 2. This is a model for Shinkeisei-line, where the experimental field test, to be explained in section V, has been executed.

IV. A Strategy for Better Protection Control

Fig. 3 shows a result of measurement of regenerative powers as a function of train speed and equivalent deceleration provided by regenerative brakes. These data were measured in daytime on a spring day. The typical operating points of the regenerative brake were plotted in Fig. 4, where the bold line means the upper limit of the designed deceleration of the electric brake: The actual effective operating points were much lower than the intention of the designer. The effective operation strongly depends on the design of squeezing controller of regenerative brakes, which is a protector against excess of line-voltage.

Fig. 5 shows a typical electric components of a main circuit of an inverter-fed DC-electric train and the steady-state limit profile of the squeezing control. In conventional design, the parameters for the current limiter were set to , for example, V_1=1600 and V_2=1670 V which were much lower than the real limitation of line-voltage excess V_{max}=1900 V. This may seem a conservative design.

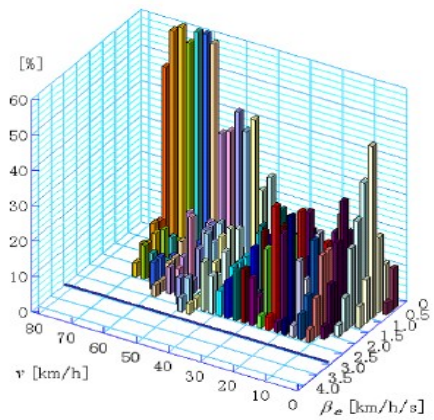


Fig. 3 Normalized frequency of measured electric brake-operating points.

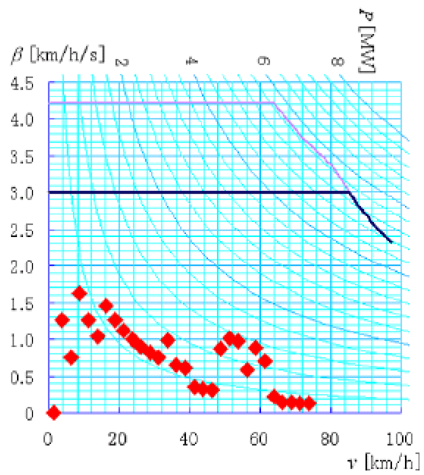
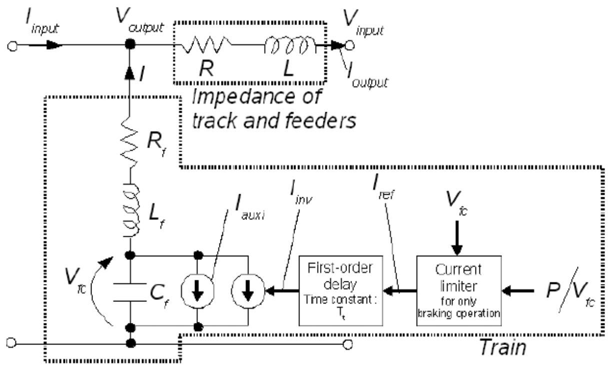
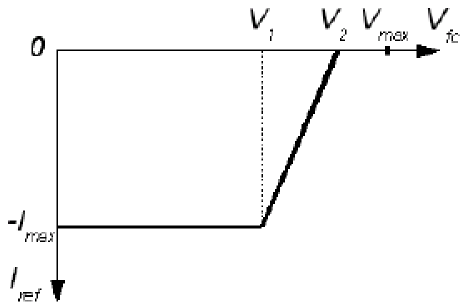


Fig. 4 Summary of measured electric braking operation.

The first simple idea may be to set higher values to the limitation parameters. What will happen if one sets relaxed limitation as shown in Fig. 6, where V_{max} can be selected arbitrarily by a new designer? Let's see a result of case study illustrated in Fig. 7. If the powering train is an inverter-fed modern one, which reduces the powering current relatively slowly in 100msec, the transient line voltage does not exceed 1900V even if you set V_{max}=1800V , but when the powering train is an old resistance-control one, which has two-step spontaneous current breaker, the transient behavior of the line voltage is quite different. A spontaneous jump of the line-voltage can be more than 200V [1] That is the reason for the conventional conservative design of the current limiter.



(a) Electric train



(b) Current limitation for a squeezing control

Fig. 5 Components and current limiter of an electric multiple unit.

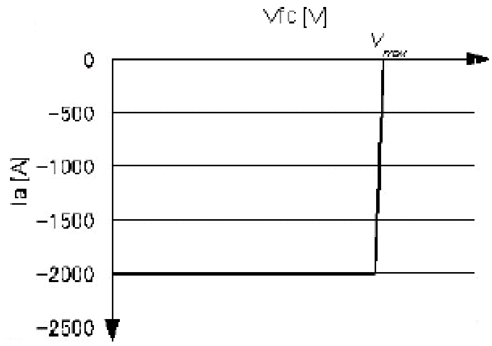


Fig. 6 Relaxed current limiter.

Taking this case study into account, the authors propose the following strategies for the modification of design concept of the current limiter based on Prof. Sone's investigation[2].

i. One checks the current of DC-intermediate circuit of traction inverter, which closely corresponds to actual electric braking power instead of motor current as a reference current in the squeezing control,
ii. one sets higher current limitation line named "steady limit line" whose parameters V_1 and V_2 are set higher values closed to V_{max} , when a braking train knows the property of the current control of adjacent trains and
iii. one sets a "waiting mode" between conventional "steady" and newly added "dynamic" limit lines,

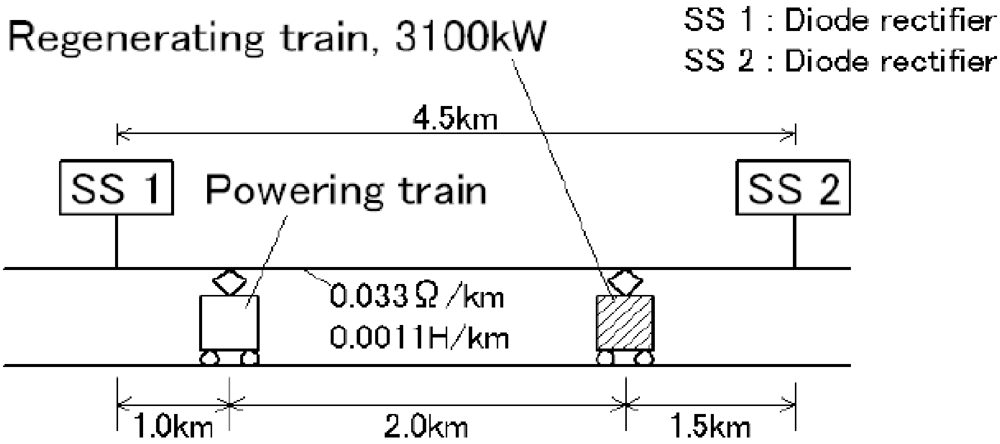


Fig. 7 Model for a preliminary case study.

where the braking current is continuously reduced to nearly zero, but the small regenerative braking operation is still kept, and the electric braking force can be immediately recovered, when the line-voltage becomes lower again.

The static and dynamic limitation lines are illustrated in Fig 8.

V. Calculated Results and Discussions

The following case study has been calculated by using the simulator described in sections II and III, in order to verify the advantage of then new current limiter proposed in section V.

[Case study]

i. Total line length is 26.5km.
ii. The running-curves of trains are subject to real ones.
iii. Single direction operation has been studied.
iv. Train head way is equal; 10 min.
v. Total travelling time of a train is 40min.
vi. The location of the substaions are: No1: 2.6km, No2: 6.7km, No3. 10.2km, No. 4: 191.km and No.5 24.8km from the original point.
vii. The V-I characteristics of the substations are given in Fig. 10.
viii. Scenario: actual train locations are given in Fig. 2.
ix. Trains 1 and 2 are coasting: they have neither powering nor braking currents.
x. Train 3 has been powering and taken load current of 1700A , but is stopping its powering, and
xi. Train 4 has just being braking and sending regenerated current of 1200A.

If the braking train 4 has no information on the type of the adjacent train 3, one must be so conservative to be able to react the worst case. In such case, the parameter setting for the current limitation cannot help being similar to conventional one: V_1=1670 and V_2=1850 V are assumed in case I and the calculated *V-I* operating loci of the regenerating train 4 is plotted in Fig 8. The train 3 in this case has been set as old resistance control type, whose powering current cuts off fast. Thanks to the conservative steady limit line of the current limiter, no voltage excess has been observed in Fig. 8

On the other hand, one can set more efficient limiter parameters V_1=1800 and V_2=1850 V and use out the regenerating mode, if the braking train 4 knows that the adjacent train 3 is a new inverter-fed type, whose powering current is being reduced in 100ms. This case II has been calculated and the resultant *V-I* loci in the train 4. The proposed efficient current limitation has worked well in spite of the reduced margin to V_{max}=1900 V, thanks to the additional information on the type of the powering train in this case. The calculation of total energy has indicated that this small modification of the regenerative braking behavior has resulted in more 10% energy saving of total system, which is substantial advantage of the modification.

VI. Experimental Verification

The squeezing control proposed in section IV was implemented into a test train and it was tested at Shinkeisei-Line in March and May in 2006. The authors have been informed that the modification of the algorithm of on-board squeezing controls has resulted in improvement of several percent of regenerated energy in a field study. Such dynamic simulation of transient behavior in a DC-electrification system is, therefore, useful in practice for redesign/relaxation of protection controls of regenerative braking trains for better usage of regeneration and total electrical energy.

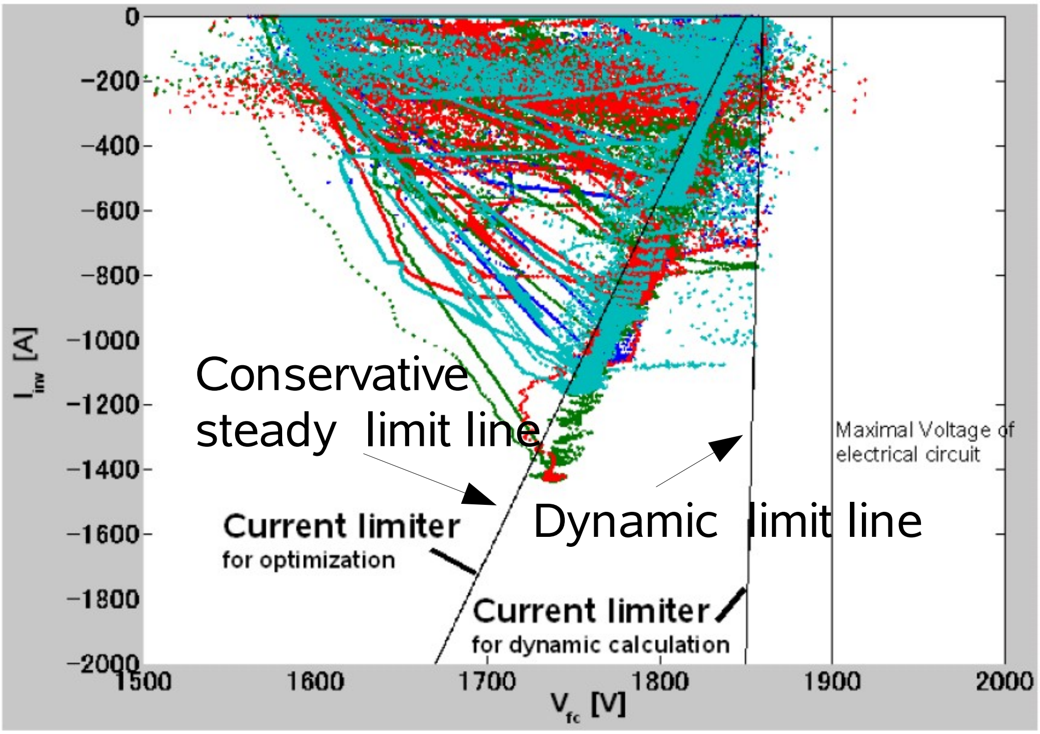


Fig. 8 Limit lines and calculated *V-I* loci when the train 4 is an old type.

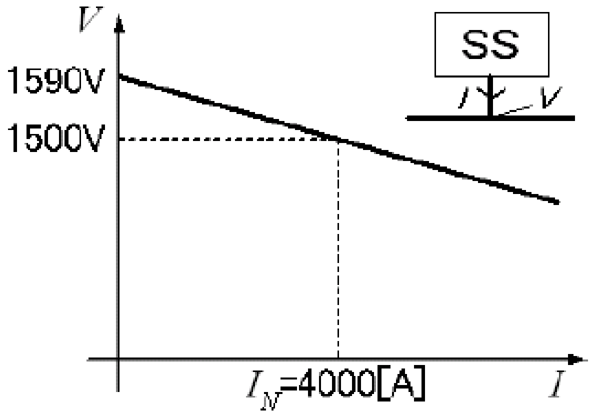


Fig. 9 V-I characteristics of a substation.

VII. Conclusions

The advantages and problems of recent DC-electrification have been briefly described in the first part of this paper. There was necessity of a strategy in order to make better use of regenerated energy. Transient calculation of the electrification circuit is inevitable for verifying a new protection criteria, since the peak voltages, to which one must be very careful, appears instantaneously just after fast reductions of electric loads of accelerating trains. The authors have shown a concrete method of such transient analysis of a DC-electrification circuit, which have nonlinearity of power stations and moving train loads by using a generic tool for numerical calculation MATLAB.

Present algorithm for a control for squeezing regenerative brakes was developed by assuming that most trains in a DC-electrification circuit are old types, whose accelerating current was reduced or cut off instantaneously. The squeezing of the regenerative current had to be, therefore, so conservative that no line voltage excesses might occur even in the worst case. In addition, when the regenerative current was once restricted, there was no recovery to a regenerating mode. Therefore, conventional regenerative braking systems could not make full use of their substantial advantages in energy-saving.

Recent DC-electrification systems have often other conditions: Many train-sets have been renewed to modern inverter-fed traction systems, whose reduction of load current is continuous and relatively slow, typically several hundred milliseconds, when the trains stop their acceleration. It is, therefore, inherently possible to set higher current-limiter values. In addition, the waiting mode has been introduced, in which the regenerative current is continuously reduced and held to zero while the line voltage is temporarily high, and the braking system is recovered to regenerative mode, when the line voltage comes lower again. This introduction of the waiting mode contributes to substantial increase of regenerated energy.

The effectiveness of the proposed squeezing control has been quantitatively verified through a transient voltage calculation of a DC-electrification circuit. It has been confirmed by a loci of operating points on a line-voltage- and braking-current- plain, that both effects of the safety and the energy-saving are simultaneously available. The idea has been also experimentally verified through a recent actual running tests.

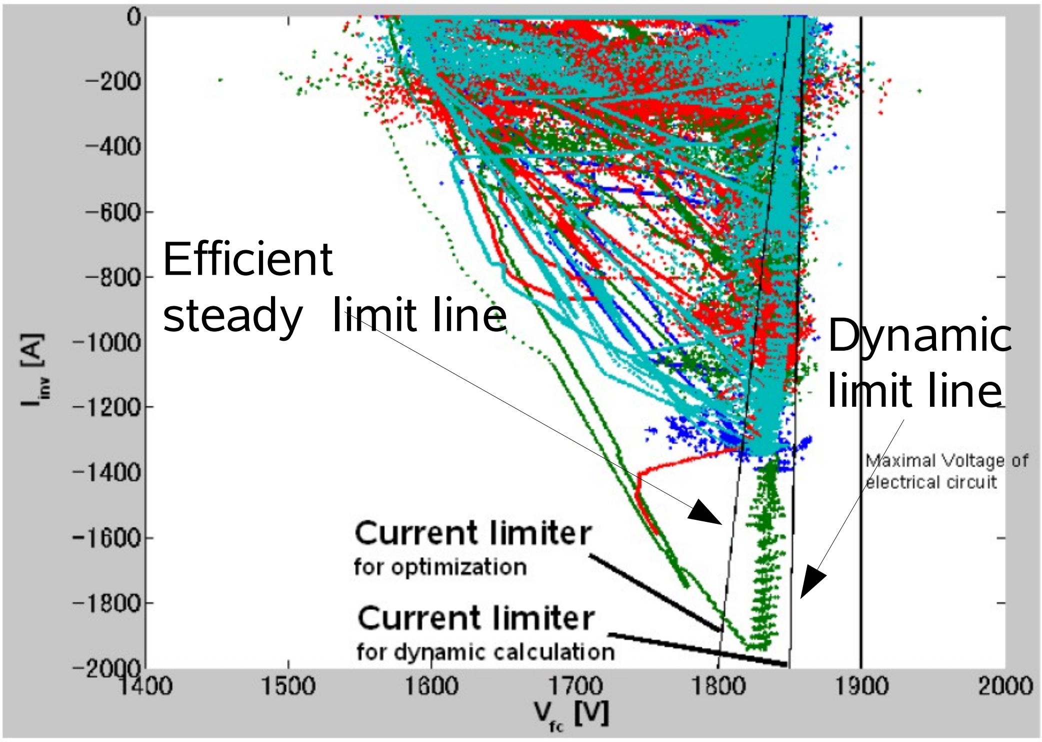


Fig. 10 Limit lines and calculated *V-I* loci when the train 4 is a new type.

This simulator will be also useful to the evaluation of effects of introducing wayside/on-board energy storage devices and regenerative functionality to substations.

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