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COMBINED MODELS OF ELECTRIC SYSTEMS NORMAL MODES WITH THE ALLOWANCE FOR PECULIARAIES OF LONG TRANSMISSION LINES

The paper considers the method of formation of combined models of electric systems (ES) normal modes, that combine models of ES elements with concentrated parameters and presentation of long transmission lines in the form of passive two-ports. This enables to increase the adequacy of presentation of interinfluence processes in electric network of ES.

Key words: *electric systems, interinfluece of electric networks, combined modes of normal modes, long transmission lines, distributed parameters, passive two-ports.*

Introduction

As a result of rapid development of energy branch of national economy, modern electric systems (ES) acquire more complex technical and functional structure, that, in its turn, complicates the control of such systems. Transmission of electric energy in ES is characterized by the set of problems, stipulating increased level of technical losses of electric energy. Among these problems we should distinguish discrepancy between electric generation and consumption of ES to design parameters, as well as imperfection of available systems of on-line control [1]. One of the methods of present situation improvement is optimization of ES normal modes, taking into account interinfluence of main and distributive electric networks [2].

Preparation and expedient realization of optimal decisions, regarding the correction of ES normal modes parameters are possible only in case of involvement of automation facilities at all stages of control [1].

Determination of optimum states of ES in this case can be realized on the basis of various mathematical models of their normal modes, mainly based on the description of physical processes of electric energy transmission and distribution in ES [3]. For the description of mathematical models of ES normal modes used for formation of optimal control impacts, taking into account rigid time limitations, conventionally approaches, connected with establishment of a match between elements of eclectic networks in the form of equivalent circuits with concentrated parameters are used [3, 4]. In order to increase the adequacy of such circuits for long transmission lines correction factors are used [4, 5] as a result, accuracy of computer modeling, sufficient for planning of ES modes, formation of their reparation schemes, etc is achieved.

However, such approach does not allow to take into account completely the peculiarities of energy transmission over transmission lines of 330 kV and higher in particular, influence of their wave parameters on the process of power fluxes redistribution in the contour of electric networks. That is why, to reveal physical peculiarities of electric energy transmission necessary for increase of adequacy of ES normal modes control, especially, parallel operation of electric networks of various classes of voltage it is necessary to use more accurate mathematical models of controlled object, combining them with simplified ones, where it is possible.

Technical possibilities of computing facilities of automated systems of ES dispatching control and constantly growing volume of parameters being controlled of their mode, form preconditions for application of specified mathematic models [1], for the analysis of their states, registration of technological limitations relatively realization of their modes and their optimum control. That is why, the given paper contains the results of research, aimed at formation of combined models of ES normal modes, combining the advantages of models with concentrated parameters and models of long transmission lines in the form of two-ports – for more adequate representation of electric power transmission over such lines.

Peculiarities of long overhead transmission lines normal modes modeling and basis ratios of their parameters

As it is known, the process of energy transmission over a.c. lines is connected with the propagation of electromagnetic waves along the wires of the line. The analysis of operation modes of the lines of 300 km of length in practice does not require taking into account wave character of electric energy transmission processes, that is why it is expedient to apply equivalent circuits with concentrated parameters [5, 6].

In case of overhead transmission lines the length of which is comparable with the wavelength of operating voltage, it is necessary to take into account wave character of energy transmission process. Lines of such length must be represented as circuits with distributive parameters [6], for which special nonsimultaneity of state changes is a characteristic feature. Such property of long overhead transmission lines results in certain peculiarities of their interinfluence with overhead transmission lines of small length (up to 300 km), if they are connected for parallel operation.

Long overhead transmission lines are usually represented as lines with distributed parameters [5, 6], modes of which are described by the following relations (in hyperbolic form):

$$\begin{cases} \dot{U}_1 = ch(\gamma_0 l)\dot{U}_2 + \sqrt{3}\,\dot{Z}_c\, sh(\gamma_0 l)\,\dot{I}_2; \\ \dot{I}_1 = \dfrac{1}{\sqrt{3}\,\dot{Z}_c} sh(\gamma_0 l)\dot{U}_2 + ch(\gamma_0 l)\,\dot{I}_2, \end{cases} \tag{1}$$

where $\dot{U}_1$, $\dot{U}_2$ – are linear voltages, and $\dot{I}_1$, $\dot{I}_2$ – are phase currents at the beginning and at the end of transmission line; $\dot{Z}_c = \sqrt{\dfrac{r_0 + jx_0}{g_0 + jb_0}}$ – is wave resistance, and $\gamma_0 = \sqrt{(r_0 + jx_0)(g_0 + jb_0)}$ – is the coefficient of transmission line waves propagation; r_0, x_0 – are specific lateral resistances, and g_0, b_0 – are specific transversal conductances of transmission line; l – is the length of overhead transmission line.

Using constant two-ports $A = ch(\gamma_0 l)$, $B = \dot{Z}_c\, sh(\gamma_0 l)$, $C = \dot{Z}_c^{-1} sh(\gamma_0 l)$, $D = ch(\gamma_0 l)$ relation (1) will take the form:

$$\begin{cases} \dot{U}_1 = A\dot{U}_2 + \sqrt{3}B\,\dot{I}_2; \\ \dot{I}_1 = \dfrac{1}{\sqrt{3}} C\dot{U}_2 + D\,\dot{I}_2. \end{cases} \tag{2}$$

For lines of less than 300 km, taking into account that $ch(\gamma_0 l) \approx 1$, and $sh(\gamma_0 l) \approx \gamma_0 l$ (i.e. $A \approx 1$, $D \approx 1$, $B \approx \dot{Z}_c\,\gamma_0\, l = (r_0 + jx_0)l = \dot{Z}_b$, $C \approx \dot{Z}_c^{-1}\gamma_0\, l = (g_0 + jb_0)l = \dot{Y}_b$), equation (2) will take the form

$$\begin{cases} \dot{U}_1 \approx \dot{U}_2 + \sqrt{3}\dot{Z}_b\,\dot{I}_2; \\ \dot{I}_1 \approx \dfrac{1}{\sqrt{3}} \dot{Y}_b\,\dot{U}_2 + \dot{I}_2. \end{cases} \tag{3}$$

Comparing expressions (2) and (3) we see the similarity of relations of long transmission lines models parameters and equivalent circuits with concentrated parameters. This condition will be further used for formation of ES normal modes models in the form of equations systems by means of the method of node voltages and contour currents [4] in matrix and revealing of the essence of matrices, making part of these systems.

Formation of mathematical model of normal modes of electric system with long overhead transmission lines applying the method of node voltages

Programming facilities, used for determination of parameters of current and perspective modes of

ES in automated systems of dispetching control, frequently use algorithms, constructed on the solution of the systems of non-linear equations of ES normal modes, composed, using the method of node voltages and contour currents. These equations in matrix form are applied for the development of methods and algorithms, intended fro analysis of interinfluence of ES electric networks [2], evaluation of nonoptimality of ES normal modes and formation of control impacts or optimal control laws [7]. Thus, having obtained the descriptions of the above-mentioned mathematical modes, taking into account wave properties of long overhead transmission lines (at the expense of identification of matrix parameters), it becomes possible to develop basically new combined modes of ES normal modes and conditions of their optimality. The latter, slightly differing by form from the known, will be more adequate, since they take into account qualitatively new parameters and characteristics of the object under investigation.

The system of equations of steady mode of electric networks in matrix form can be presented as [4]:

$$\left[\mathbf{M}\,\mathbf{Z}_b^{-1}\dot{\mathbf{M}}^T + \mathbf{Y}_b\right]\dot{\mathbf{U}} = \dot{\mathbf{J}}\,, \tag{4}$$

where $\mathbf{M}$, $\mathbf{M}^{\mathrm{T}}$ – is matrix of branches connection of equivalent circuit of electric network in its nodes, correspondingly, direct and transposed [4]; $\mathbf{Z}_b, \mathbf{Y}_b$ – are diagonal matrices, correspondingly, of complex lateral resistances of equivalent circuits branches of electric networks and transversal conductances of theses branches, connected to nodes; $\dot{\mathbf{U}}$, $\dot{\mathbf{J}}$ – are, correspondingly, voltages in nodes and setting currents of equivalent circuits of electric networks.

For formation of mathematical model of stable mode of electric networks, taking into account long transmission lines, as passive two-ports, we use analogy between the expressions (2) and (3). Voltage drop in separate transmission line with concentrated and distributed parameters, correspondingly

$$\Delta\dot{U} = \dot{U}_1 - \dot{U}_2 = \sqrt{3}\dot{Z}_b\,\dot{I}_2\,;\ \Delta\dot{U} = \dot{U}_1 - A\,\dot{U}_2 = \sqrt{3}\,B\,\dot{I}_2\,. \tag{5}$$

To write down voltage drop in the set of transmission lines equivalent circuit of electric network, the transposed matrix of connections $\mathbf{M}^{\mathrm{T}}$ [8] is used: $\mathbf{M}^T\dot{\mathbf{U}} = \Delta\dot{\mathbf{U}}$. For equivalent circuit, describing electric network with long transmission lines it is necessary to take into account the lag of incident voltage waves that can be achieved by introduction of constant A. Proceeding from this fact, matrix of transmission line connections in nodes of electric network will be written

$$\dot{\mathbf{M}}_A^T = \mathbf{M}^{T+} + \mathbf{A}_{diag.}\mathbf{M}^{T-}\,, \tag{6}$$

where $\mathbf{M}^{T+}$, $\mathbf{M}^{T-}$ – are matrices, formed by replacement of negative and positive elements of transposed connections matrix $\mathbf{M}^{\mathrm{T}}$ by zeros; $\mathbf{A}_{diag.}$ – is diagonal matrix of constants of two-ports A for branches of equivalent circuit of electric network and the expression for vector of voltage drop:

$$\dot{\mathbf{M}}_A^T\dot{\mathbf{U}} = \Delta\dot{\mathbf{U}}\,. \tag{7}$$

Unlike $\mathbf{M}^{\mathrm{T}}$, matrix $\dot{\mathbf{M}}_A^T$ is complex.

For equivalent circuit with concentrated parameters voltage drop in branches vector can be expressed by means of phase currents $\dot{\mathbf{I}}_b$ in them as [8]: $\Delta\dot{\mathbf{U}} = \sqrt{3}\,\dot{\mathbf{Z}}_b\dot{\mathbf{I}}_b$. Taking into account (5), we can draw the analogy between diagonal matrices of the resistances of circuit $\dot{\mathbf{Z}}_b$ branches and constants of two-port $\mathbf{B}_{diag.}$. Then (5) in matrix form for the set of equivalent circuit branches of electric network:

$$\Delta\dot{\mathbf{U}} = \dot{\mathbf{M}}_A^T\dot{\mathbf{U}} = \sqrt{3}\,\mathbf{B}_{diag.}\dot{\mathbf{I}}^{end}{}_b\,, \tag{8}$$

where $\dot{\mathbf{I}}_b^{end}$ – is the vector of currents at the ends of equivalent circuits branches (according to their directions, set by matrix **M**). The expression (8) has physical sense of Ohm's law in matrix form for equivalent circuit of electric network with distributed parameters. In other matrix expressions for unambiguity vectors of currents $\dot{\mathbf{I}}_b^{end}$ will be used (if necessary, values of currents at the beginning of each branch can be calculated by the second equation from the system (2)).

Taking into account that according to (2) $\dot{I}_1 - A\dot{I}_2 = C\dot{U}_2 / \sqrt{3}$ (since $A = D$) and introducing the notion of connections matrix $\dot{\mathbf{M}}_A$, that is determined as:

$$\dot{\mathbf{M}}_A = \mathbf{M}^+ \mathbf{A}_{diag.} + \mathbf{M}^-, \qquad (9)$$

where $\mathbf{M}^+$, $\mathbf{M}^-$ – are matrices, formed by replacement of negative or positive elements of the first connections matrix **M** by zeros, correspondingly, the first Kirchhoff's law for equivalent circuit with distributed parameters, if lateral parameters are missing ($C_{i,j} = 0$) or taking them into account in the vector of setting currents, will be written as:

$$\dot{\mathbf{M}}_A \dot{\mathbf{I}}_b^{end} = \dot{\mathbf{J}}. \qquad (10)$$

If ($C_{i,j} \neq 0$), i.e., on condition, that equivalent circuit contains branches with lateral parameters, the first Kirchhoff's law may be written as:

$$\dot{\mathbf{M}}_A \dot{\mathbf{I}}_b^{end} - \mathbf{C}_\kappa \dot{\mathbf{U}} = \dot{\mathbf{J}}, \qquad (11)$$

where $\mathbf{C}_\kappa = \mathbf{M}^+ \mathbf{C}_{diag.} \mathbf{M}^{T-}$ – is a matrix of constants of two-port C in the branches of equivalent circuit. Thus, if lateral conductances are missing, the system of electric network equations by the method of node voltages [4, 8] may be written as

$$\dot{\mathbf{M}}_A \mathbf{B}_{diag.}^{-1} \dot{\mathbf{M}}_A^T \dot{\mathbf{U}} = \dot{\mathbf{J}}, \qquad (12)$$

where $\dot{\mathbf{M}}_A \mathbf{B}_{diag.}^{-1} \dot{\mathbf{M}}_A^T = \dot{\mathbf{Y}}$ – is a matrix of node conductances. If branches with lateral conductances are presented in equivalent circuit, then component $\mathbf{C}_\kappa \dot{\mathbf{U}}$ is introduced in node equations:

$$\left[\dot{\mathbf{M}}_A \mathbf{B}_{diag.}^{-1} \dot{\mathbf{M}}_A^T - \mathbf{C}_\kappa\right] \dot{\mathbf{U}} = \dot{\mathbf{J}}, \qquad (13)$$

where $\dot{\mathbf{M}}_A \mathbf{B}_{\partial diag.}^{-1} \dot{\mathbf{M}}_A^T - \mathbf{C}_\kappa = \dot{\mathbf{Y}}_c$ – is a matrix of node conductances taking into account lateral conductances of the transmission lines with concentrated and distributed parameters. The obtained matrix equation by its structure corresponds to the equation (4) that specifies the possibility of combination in one the descriptions of elements with concentrated (transformers, transmission lines of less tan 300 km, etc.) and distributed parameters.

Mathematical model of normal modes of electric system with long transmission lines by the method of contour currents

From the first equation of the system (2) we will write the expressions for voltages at the beginning and at the end of long transmission line.

$$\dot{U}_1 = A\dot{U}_2 + \sqrt{3}\,B\dot{I}_2;\ \dot{U}_2 = \frac{1}{A}\dot{U}_1 - \sqrt{3}\frac{B}{A}\dot{I}_2. \qquad (14)$$

With the account of (14), for contour, formed by the branches with distributed parameters (Fig. 1), expression, connecting the voltage of the basis angle with current loads of branches, will be written as:

$$\dot{U}_{Bas.} = \left(\left(\frac{1}{A_{Bas.1}}\dot{U}_{Bas.} - \sqrt{3}\frac{B_{Bas.1}}{A_{Bas.1}}\dot{I}_{Bas.1}^{end}\right)\frac{1}{A_{12}} - \sqrt{3}\frac{B_{12}}{A_{12}}\dot{I}_{12}^{end}\right)A_{Bas.2} + \sqrt{3}B_{Bas.2}\dot{I}_{Bas.2}^{end}. \qquad (15)$$

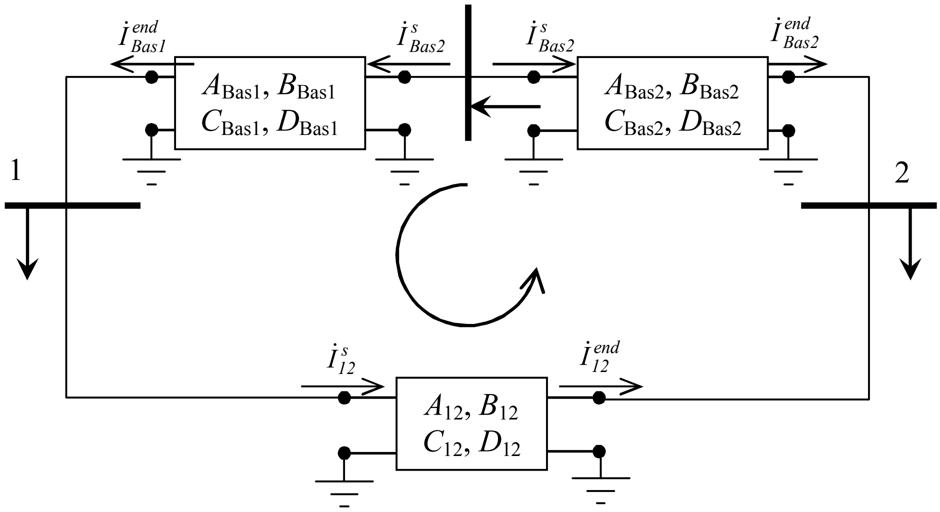

Fig. 1. The example of equivalent circuit of the contour, formed by long transmission line

From (15) $\dot U_{\text{Б}}$, we obtain:

$$\dot U_{Bas.}\left(1-\frac{1}{A_{\text{Б}1}}\frac{1}{A_{12}}A_{\text{Б}2}\right)=-\sqrt{3}\dot I^{end}{}_{Bas.1}B_{Bas.1}\left(\frac{1}{A_{\text{Б}1}}\frac{1}{A_{12}}A_{\text{Б}2}\right)-\sqrt{3}\dot I^{end}{}_{12}B_{12}\left(\frac{1}{A_{12}}A_{Bas.2}\right)+\sqrt{3}\dot I^{end}{}_{Bas.2}B_{Bas.2}$$

After simplification and generalization by random number of branches with distributed parameters in the contour, taking into account, that $B_{ij}\dot I^{end}{}_{ij}$ has the meaning of voltage drop in *i-j* branch:

$$\dot U_{Bas.}\left(1-\prod_{i\in\mathbf{S}}A_i^{\mu}\right)=-\sqrt{3}\sum_{j\in\mathbf{S}^+}\left[\dot I^{end}{}_jB_j\prod_{\substack{i\in\mathbf{S}\\ i\geq j}}A_i^{\mu}\right]+\sqrt{3}\sum_{j\in\mathbf{S}^-}\left[\dot I^{end}{}_jB_j\prod_{\substack{i\in\mathbf{S}\\ i>j}}A_i^{\mu}\right], \qquad (16)$$

where $\mathbf{S}$, $\mathbf{S}^+$, $\mathbf{S}^-$ – are, correspondingly, sets of branches, composing the contour, composing and coinciding by direction with the direction of contour by-pass composing and non-coinciding by direction with direction of contour by-pass; μ – is sign function: $\mu = -1$ for branches, that belong to the set $\mathbf{S}^+$, $\mu = 1$ for branches, that belong to the set $\mathbf{S}^-$. In physical sense (16) describes contour e.m.f., formed due to non-uniformity of wave propagation coefficients γ_0 for different transmissions lines ($A_{ij} \neq$ const) in the contour.

For generalized description of the second Kirchhoff's law we will introduce the notion of the second connections matrix of equivalent circuit with long transmissions lines – $\dot{\mathbf{N}}_A$. Location of zero elements of the given matrix corresponds to the second matrix of connections $\mathbf{N}$ is defined by the expression [8]. Each non-zero element of matrix $\dot{\mathbf{N}}_A$ is defined by the expression:

$$\dot N_{Aij}=\begin{cases}N_{ij}\prod\limits_{\substack{k\in\mathbf{S}_i\\ k\geq n_j}}A_k^{\mu}, if\ N_{ij}>0;\\ N_{ij}\prod\limits_{\substack{k\in\mathbf{S}_i\\ k>n_j}}A_k^{\mu}, if\ N_{ij}<0,\end{cases} \qquad (17)$$

where n_j – is the number of *j*-th branch in by-pass direction of *i*-the contour, starting from conventional node of contour beginning (for the system of basis contours – basis node); $\mathbf{S}_i$ – is the set of branches of *i*-th contour.

Unlike $\mathbf{N}$, matrix $\dot{\mathbf{N}}_A$ is complex for general case of transmission line with distributed parameters presentation. For transmission line without losses ($r_0 = 0,\ g_0 = 0$) γ_0 may be replaced by α_0, as a result matrix $\dot{\mathbf{N}}_A$ passes in real plane. For short transmission lines as $A_{ij} \approx 1$, matrix of connections $\dot{\mathbf{N}}_A$ is transformed into the second matrix of connections **N**.

Using the introduced symbols, the second Kirchhoff's law for equivalent circuit of electric system with distributed parameters, taking into account

$$\dot{\mathbf{E}}_{\kappa} = \dot{\mathbf{U}}_{Bas.}\dot{\mathbf{E}}_{cont.*} = -\sqrt{3}\dot{\mathbf{N}}_A \mathbf{B}_{diag.}\dot{\mathbf{I}}_b^{end}, \tag{18}$$

where $\dot{\mathbf{E}}_{cont.*}$ – is matrix-vector of contour e.m.f., presented in relative units, each element of the matrix is defined by the expression $\dot{E}_{cont.*ij} = 1 - \prod_{i \in \mathbf{S}} A_i^{\mu}$.

Influence of distributed parameters of long transmission lines on the adequacy of computer modeling of ES normal modes

The developed mathematical models served as the basis of algorithmic realization of calculation of steady state models of electric systems of programming complex "VTRATY" (LOSSES). As a result of such improvements it became possible to perform comparative analysis of computing modeling result of ES steady state mode under such conditions:

1) all the elements of ES are presented in equivalent circuits by the branches with concentrated parameters;

2) long transmission line are presented in equivalent circuits of ES by branches, concentrated parameters of which are specified by means of correction factors [5] (programming complex "Graphscanner is used");

3) long transmission lines are presented in equivalent circuits of ES by passive two-ports.

As the object of modeling the scheme of electric networks 110-750 kV of South-West Electric Energy system was used, the system comprises 32 nodes, 38 branches (5 of which are transmission lines 750 kV, 14 – transmission lines of 330 kV), 10 coupling transformers. The results of power losses modeling for characteristic mode of ES in above-described conditions are presented in Table 1.

Table 1

Loses of power in electric networks, 750 – 110 kV of South-West Electric Energy System

Conditions of payment	Arrivals P, MWt	Sale P, MWt	Total loses P, MWt	Losses in transmission lines 750-330 kV, ΔP, MWt	Losses in transmission lines 220-35 kV, ΔP, MWt	Losses in transformers, MWt
Concentrated parameters of all transmission lines (1)	7063,1	6962,5	100,6	62,1	17,1	21,4
Parameters correction of long transmission lines (2)	7064,3	6962,5	101,8 (+1%)	63,1 (+2%)	17,3 (+1%)	21,4
Distributed parameters of long transmission lines (3)	7065,8	6962,4	**103,4 (+3%)**	**63,3 (+2%)**	**18,7 (+9%)**	21,4

As it is seen from Table, nonaccount of peculiarities of electric energy transfer over long transmission lines leads to errors of power losses determination in electric networks. As due to wave processes occurring in long transmission lines redistribution of power fluxes takes place in ES, that is not taken into account in equivalent circuits with concentrated parameters, then the error of losses determination is given for electric networks of lower classes of voltage. And if the error of total losses determination (1-3%) in practical tasks can be neglected, the deviation of calculated values for electric networks of lower classes of voltage (up to 9%) must be taken into account, especially in problems of optimization of electric networks interinfluence. The results of calculations show that application of correction factors for correction of equivalent circuits of long transmission lines allows to define more exactly calculated values of losses in electric networks, but it does not give the possibility to take into account the phenomenon of power fluxes redistribution in ES due to the difference of wave propagation factors in transmission lines. That is why, value of losses in electric networks of lower classes of voltages practically is not corrected.

Conclusions

1.The problem of efficiency increase of electric energy transmission in transmission lines is connected with the necessity of constant monitoring of electric system modes, that nowadays, due to non-complete observability of ES is impossible without usage of computer modeling facilities. The adequacy of mathematic models, used as the basis of programming systems dispatching control is the determining factor for the quality of systems operation.

2. Research, carried out, gave the possibility to obtain complex mathematical models to steady state modes of electric systems, enabling to combine ES elements, that are presented by equivalent circuits with distributed and concentrated parameters without additional assumptions. Thus, the obtained models are more efficient as compared with convectional ones, since they allow to take into account peculiarities of energy transfer over long transmission lines without considerable complication.

3. As a result of modeling of inteaction between e.m.f. in contours, formed by long transmission lines and voltage drop in them, it was established that due to non-uniformity of established that due to non-uniformity of propagation factors of transmission lines waves, balancing e.m.f. can emerge in the contour fluxes. The latter lead to redistribution of power fluxes., that must be taken into account in the process of formation and adaptation of control impacts for optimization of ES normal modes.

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