Small Signal Stability Analysis of Wind Turbines

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Abstract. This paper analyzes the small signal stability of wind power systems, using Squirrel Cage Induction Generators and Doubly Fed Induction Generators which are today the most used rotating machines for manufacturers on wind farms.

It is presented the eigenvalue analysis of theses wind turbines near 2MW and an application in a wind farm using an open source toolbox.

Keywords:
Wind Power, Stability Analysis, Doubly Fed Induction Generator, Asynchronous generator.

1. Introduction

Nowadays, the fast growth of wind power on electricity grids, has been declared as an important issue on wind energy industry. Today a penetration of 20% in Europe is feasible.

As is widely known, basically wind turbines are manufactured for two conditions: Constant Speed or Variable Speed. In this way, the Constant Speed Wind Turbines (CSWT), are built with Squirrel Cage Induction Generators (SCIG) and the Variable Speed are built with Doubly Fed Induction Generators (DFIG) or synchronous machines.

This work researches the small signal stability of two kind of wind turbines used on conventional wind farms with eigenvalues analysis. That dynamic operation of wind turbines makes important to design, model and simulate their behavior prior to install them. By this way, one of the main studies realized for new wind farms are the stability studies that professionals, researchers and specialists are developing constantly due to the fast growth of the wind turbine industry and the way more wind farms are aggregated to a power systems. It is important to remark that this report will not be dedicated to power quality issues or the study and explanation of the physical or aerodynamic issues caused by the wind.

This paper presents the aspects of the modeling of constant speed wind farms and variable speed wind farms. Then, a comparative eigenvalue analysis of those wind turbines on a particular power system is done.

2. Stability Analysis

So far, basically two main small disturbance stability problems have been widely discussed and by that, are still clearly and widely accepted such as rotor angle stability and voltage stability [1]-[4].

Small signal stability is defined as the capability of a power system to return to a stable operating point or to the original steady, after the occurrence of a disturbance that leads to an incremental change in one or more of the state variables of the power system [1].

In this work, the small signal stability problems for wind power generation will be researched and how they impact on a power system.

All this work begins on the space equation and the output equation which give the necessary information.

$$\begin{aligned} \dot{x}(t) &= f(x,u,t) \\ y(t) &= g(x,u,t) \end{aligned} \qquad (1)$$

Where equation (1) has all state variables, u is the input variables, t the time and y the output function.

The linearization of (1) allows investigating the response to small variations. To do this, and considering that state functions contains some different variables on its polynomial equation, these equations are developed in

Taylor´s series expansion in which with higher orders of the derivatives omitted because of its minimum interaction to the response.

The linear result is a system presented in equation (2) [5]:

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \qquad (2)$$

Where A is the state matrix, B is the input matrix, C the output matrix and D coefficient's matrix. A, B,C and D are obtained from the Jacobian matrix, containing the partial derivatives of the functions in f and g respectively to the state variables x and the input variables u as:

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \quad B = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r} \\ \cdots & \cdots & \cdots \\ \frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r} \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial g_m}{\partial x_1} & \cdots & \frac{\partial g_m}{\partial x_n} \end{bmatrix} D = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_r} \\ \cdots & \cdots & \cdots \\ \frac{\partial g_m}{\partial u_1} & \cdots & \frac{\partial g_m}{\partial u_r} \end{bmatrix} \qquad (3)$$

These matrices can be transformed using Laplace to find the state equation linearized, in the frequency domain. Finally to obtain the eigenvalues it must be found the values of s that satisfy [5]:

$$\det(sI - A) = 0 \qquad (4)$$

The n-solutions of $\lambda = \lambda_1, \lambda_2, \ldots \lambda_n$ are the eigenvalues of A. These eigenvalues can be real or complex [2].

In this paper, PSAT software [6], (Fig.1), is used to analysis the eigenvalues. Roots positions and its values as they appear on this plot show if system is stable or not. As can be seen all real values are negatives which means system is stable under this conditions. The full eigenvalues report shows results in matrix and also participation factors are presented.

The electromechanical modes generated for small signal stability studies occur in the frequency range of 0.1 to 2 Hz. Interarea oscillations, are typically in the frequency range of 0.1 to 1 Hz. The interarea modes are usually complex and associated with groups of machines swinging to other groups across a transmission line.

The higher frequency electromechanical modes defined as local modes are in the order of 1 to 2 Hz, typically involve one or two generators swinging against the rest of the power system. [7]

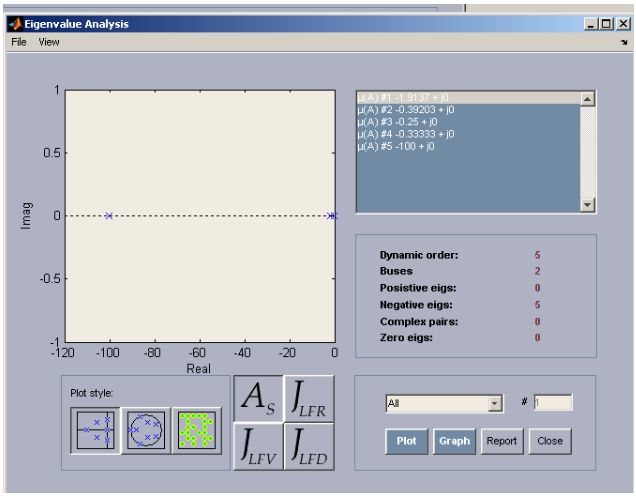

Fig. 1. Eigenvalues window of PSAT software.

The power system models in this project were all built using SIMULINK and the specialized Power Systems Analysis Toolbox, PSAT a software application developed for MATLAB, which performs both the numerical simulation and linearized eigenstructure analysis.

3. Stability Analysis of Wind turbines

A. Analysis of a wind turbine powered by a Squirrel Cage Induction Generator (SCIG)

In this simulation, a nominal wind speed of 10 m/s as manufacturer brochure says, is used. Air density considered is 1.225 Kg/m^3 under normal conditions, and wind model is Weibull.

Fig. 2 presents the PSAT graphic model done for constant speed wind turbine CSWT, with squirrel cage induction generator connected to a infinite bus.

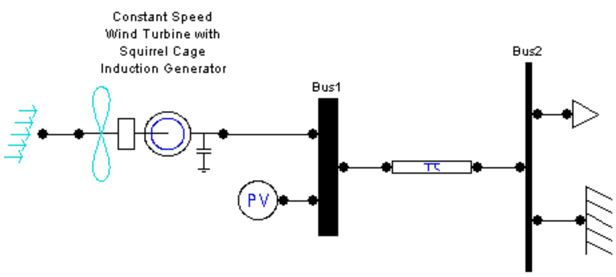

Fig. 2. PSAT model of constant speed wind turbine CSWT.

A simple click, Fig. 3, allows knowing graphically the eigenvalues result on S-domain. Then a report, Table I, presents more complete information. As can be seen all real values are negatives which means system is stable under his conditions. PV model is needed here to fix voltage magnitude and power injected at buses where they are connected.

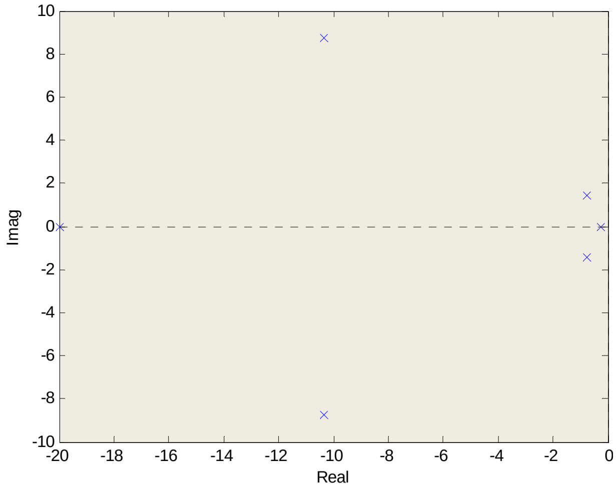

Fig. 3. Plot of all eigenvalues for CSWT analysis.

Other important information is the participation factor that indicates the relative contribution of each state variable to a certain mode. The elements in the right eigenvector belonging to a mode indicate the phase angle of the contribution of each of the state variables to that mode. High participation factors and phase angle differences in the order of 180° indicate (groups of coherent) generators oscillating against each other. The location of these generators in the system determines the oscillation type. A group of generators that oscillates coherently will be further referred to as a swing node.

TABLE I. State matrix eigenvalues.

Eig.	Most Associated States	Real part	Imag. Part	Freq.
#1	e1m_Cswt_1	-19.9829	0	0
#2	omega_m_Cswt_1, e1r_Cswt_1	-10.3635	8.7568	1.3937
#3	omega_m_Cswt_1, e1r_Cswt_1	-10.3635	-8.7568	1.3937
#4	gamma_Cswt_1, omega_wr_Cswt	-0.7606	1.4521	0.2311
#5	gamma_Cswt_1, omega_wr_Cswt	-0.76064	-1.4521	0.2311
#6	vw_Wind_1	-0.25	0	

Both pair of conjugate eigenvalues are complex numbers ($\lambda = \sigma \pm j\, w$), and each pair corresponds to an oscillatory mode, where the real part gives the damping and the imaginary gives the frequency of oscillation [2]. In this case these negative complex eigenvalues represents a damped oscillation. The Frequency column on table I is the oscillation frequency (Hz), where

$$f = \frac{w}{2\pi} \tag{5}$$

This represents damped frequency, while equation 6 gives the damping ratio. [2].

As results of this test case, frequencies of 0.2311 Hz represent interarea oscillations on important eigenvalues of large magnitude due to this complex conjugate mode.

The higher, also complex and conjugate modes 2 and 3, with frequencies of 1.3927 Hz, indicate one or two generators swinging against the rest of the power system, but in analytical aspects is quite difficult to know which of them.

In other way, damping ratios expressed by equation 6, [2], are presented on table III.

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + w^2}} \tag{6}$$

TABLE II. Damping ratios for SCIG.

σ	ω	Z
Real part	Imag. Part	
-19,9829	0	1
-10,3635	8,7568	0,76383369
-10,3635	-8,7568	0,76383369
-0,7606	1,4521	0,463995597
-0,7606	-1,4521	0,463995597
-0,25	0	1

Those magnitudes will be stabilised on $1/(2\pi\zeta)$ cycles of oscillation [2]. In this case, both complex conjugates eigenvalues ensure local stability being asymptotically stable. This values indicates how the amplitude decays.

TABLE III. Participation factors (Euclidean norm)

Eig	vw_Wind_1	Omega_wr_Cswt_1	omega_m_Cswt_1
#1	0	0	0.02816
#2	0	0.00036	0.47182
#3	0	0.00036	0.47182
#4	0	0.42654	0.07209
#5	0	0.42654	0.07209
#6	1	0	0
Eig	gamma_Cswt_1	e1r_Cswt_1	e1m_Cswt_1
#1	0.00079	0.11343	0.85761
#2	0.02887	0.47089	0.02806
#3	0.02887	0.47089	0.02806
#4	0.46711	0.03289	0.00137
#5	0.46711	0.03289	0.00137
#6	0	0	0

B. Analysis of a wind farm powered by a Doubly Fed Induction Generator

In Fig. 4, is shown a DFIG (2Mw) used to analyze the stability behavior with PSAT.

Data used for the DFIG is presented as follows. Windtubrine Vestas V66-2MW. (3 blades), with a nominal speed of 17m/s. This model uses a composite or a Weibull distribution for analysis. Some other data is Stator Resistance and Reactance are: [0.0105 0.10] (p.u) Rotor Resistance and Reactance are: [0.0130 0.08](p.u) All entire systems is working at 50 Hz, 690 Volts and 2MVA. Finally, the gearbox is between 1/100 and 1/120 for wtg near 2MW.

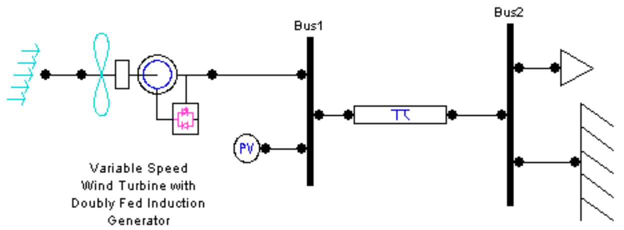

Fig. 4. Diagram of the 2MW DFIG.

Fig. 5 shows the eigenvalues result on S-domain and Table II, presents more complete information. One root (-100 + 0j), are far away from the rest, without affecting the system.

On Fig. 3 is presented the eigenvalues plot. It shows it has a great influence on this infinite bus stability analysis. In other way another state variables such as machine and wind speed influenced the stability but its low value says they are not a big deal for it.

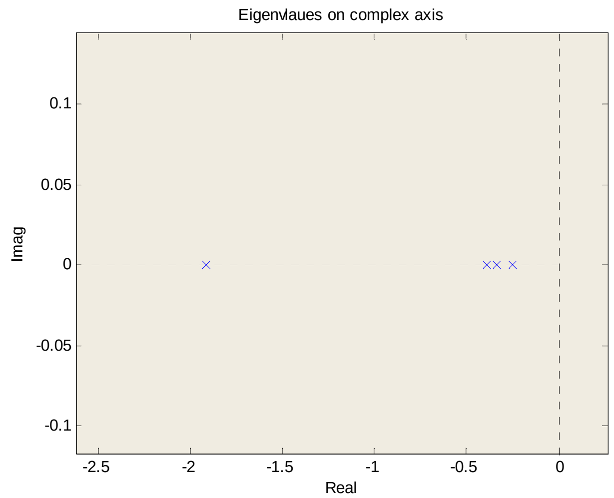

Fig. 5. Largest eigenvalues of DFIG.

A graphical analysis derived from Fig. 5, where all eigenvalues are under real negative part of the axis.

TABLE IV. State matrix eigenvalues.

Eig.	Most Associated States	Real part	Imag. Part	Freq.
#1	idr_Dfig_1	-1.9137	0	0
#2	omega_m_Dfig_1	-0.3920	0	0
#3	vw_Wind_1	-0.25	0	0
#4	theta_p_Dfig_1	-0.3333	0	0
#5	iqr_Dfig_1	-100	0	0

In of this test case, all frequency magnitudes represent a stable system. A small eigenvalue magnitude with its frequency of 0.0397 Hz, indicates a small oscillation in a interarea mode. This is the only one with imaginary magnitude. Damping ratios expressed by equation 6, are presented on table V.

TABLE V. Damping ratios for DFIG.

Real part σ	Imag. Part ω	Z (damping ratio)
-19.137	0	1
-0.3920	0	1
-0.25	0	1
-0.3333	0	1
-100	0	1

C. *Aggregation of Wind Farm with Squirrel Cage Induction Generator*

Due to the fast increasing wind power penetration the demands of grid operators and response of wind turbine generators manufactured, the aggregation of wind turbines in a grid is a very important matter to research. Research on wind energy aggregation is also important for the European Wind Energy Association EWEA, where previous results has showed that wind power plants contribute positively to system stability in the system. [8].

In previous sections, it has been modeled and simulates the Constant Wind Speed Squirrel Cage Induction Generator and Doubly Fed Induction Generator and their influence for power systems stability studies. Once the lonely model present stability connected to an infinite bus, some small networks with wind farms are considered.

A simple network modeled on PSAT 2.0 with three SCIG wind turbines for Constant Speed Wind Turbine (CSWT), interconnected with 3 load buses will be analyzed now as presented on Fig. 6. Some basic data is presented on Table VI for this network.

TABLE VI. Data model.

Frequency (Hz)	50
Base voltage (MVA)	2
Bus voltage (KV)	0.69
Power Generated (MVA)	2
wind speed (m/s)	17
Wind turbine power (MW)	2
wind turbine type	ECOT-80-2MW
Elevation (m)	70-80
Temperature (°C)	20
Air density (Kg/m^3)	1,190

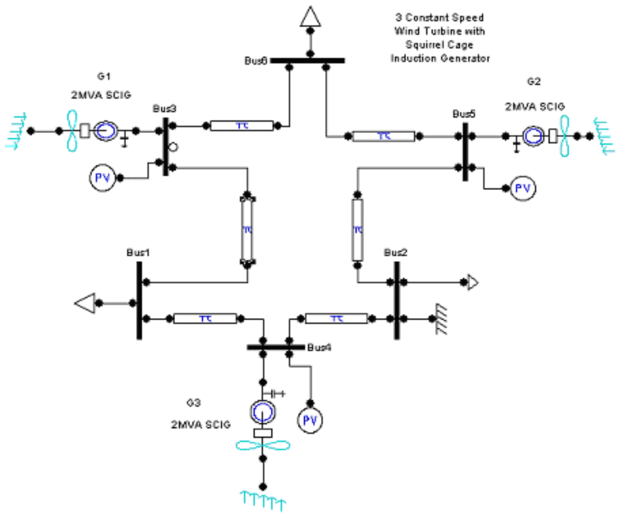

Fig. 6. Network with 6 buses and 3 wind turbines.

Once all small network has been modeled with SCIG´s, eigenvalues analysis is carried out by using PSAT. First result is the figure 7 where roots are placed on complex plane.

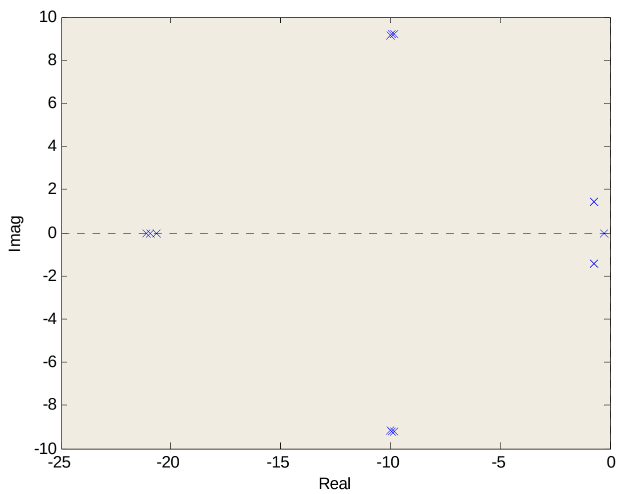

Fig. 7. Largest eigenvalues of DFIG.

The system is stable and the full report give it by PSAT is showed in Table VII.

This result shows that eigenvalues, 1,2, and 3 with the largest magnitudes and without imaginary component do not produce big influence on small signal analysis and they just contains real part which makes an stable behavior.

Eigenvalues 5 to 9, with real and imaginary part, produce stability on this power system. Its frequencies near 14 Hz, seems great but theoretically just produces oscillations on local mode, while eigenvalues 10 to 15, near 0,2 Hz produces oscillation of interarea mode as was told before.

TABLE VII. State matrix eigenvalues.

Eig.	Most Associated States	Real part	Imag. Part	Freq.(Hz)
# 1	e1m_Cswt_1	-20.6791	0	0
# 2	e1m_Cswt_3	-20.9529	0	0
# 3	e1m_Cswt_2	-21.0955	0	0
# 4	omega_m_Cswt_1, e1r_Cswt_1	-9.8298	9.2317	14.693
# 5	omega_m_Cswt_1, e1r_Cswt_1	-9.8298	-9.2317	14.693
# 6	omega_m_Cswt_3, e1r_Cswt_3	-10.0024	9.1518	14.566
# 7	omega_m_Cswt_3, e1r_Cswt_3	-10.0024	-9.1518	14.566
# 8	omega_m_Cswt_2, e1r_Cswt_2	-9.9308	9.2319	14.693
# 9	omega_m_Cswt_2, e1r_Cswt_2	-9.9308	-9.2319	14.693
#10	gamma_Cswt_1, omega_wr_Cswt	-0.72721	1.4528	0.23121
#11	gamma_Cswt_1, omega_wr_Cswt	-0.72721	-1.4528	0.23121
#12	gamma_Cswt_3, omega_wr_Cswt	-0.71714	1.4479	0.23044
#13	gamma_Cswt_3, omega_wr_Cswt	-0.71714	-1.4479	0.23044
#14	gamma_Cswt_2, omega_wr_Cswt	-0.71228	1.4492	0.23065
#15	gamma_Cswt_2, omega_wr_Cswt	-0.71228	-1.4492	0.23065
#16	vw_Wind_1	-0.25	0	0
#17	vw_Wind_2	-0.25	0	0
#18	vw_Wind_3	-0.25	0	0

D. Aggregation of Wind Farm with Doubly Fed Induction Generator

Date used for this simulation of DFIG is also the one presented on Table VI, for the small network with SCIG. The aim of this part is analyze the behavior of the same network if it uses DFIG.

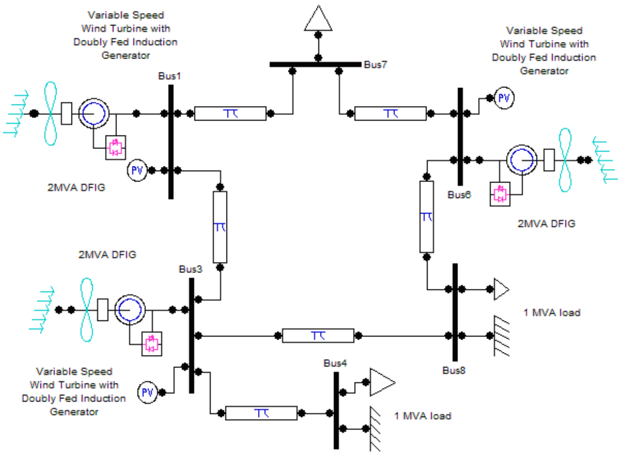

Fig.8. Small Network with 3 DFIG.

After run a power flow in 0.078 s,, eigenvalues 1, 2 10 and 13 on figure 9, appears with the largest magnitude under real negative part of real axis, but without affecting system stability.

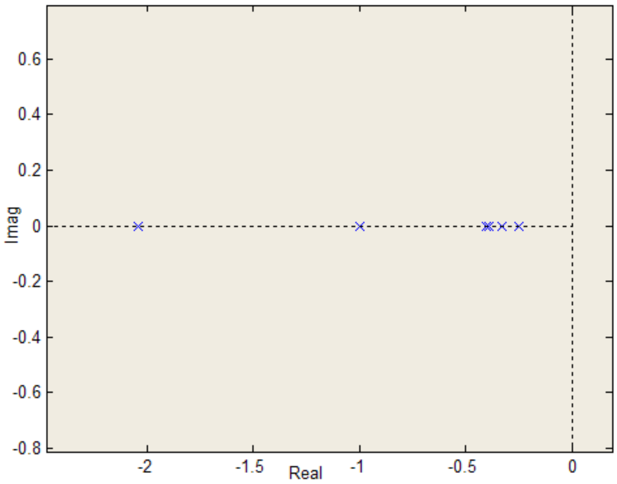

Fig.9. Eigenvalues of DFIG small network.

A full report with eigenvalues and participation factors is not presented due to lack of space in the paper.

4. Conclusions

As has been proved here, PSAT is a powerful power system toolbox, to analyze the small signal stability. It comes with procedures for static and dynamic wind models for power analysis, and a simulink-based network editor. Its main advantages are: model collection, easy handling, and a good graphic presentation of results. This robust method and its fast convergence, allows determining all system eigenvalues and indicates system stability

Small signal stability and power system oscillations shows that power systems contain many modes of oscillation due to a variety of interactions among all its components.

This analysis shows that the wind turbines have a great influence on the small signal power system stability. Frequencies determines that two possible oscillation modes are represented, interarea and local.

The use of electronics converter for the Doubly Fed Induction Generator, has showed an improved behavior for power system stability.

It was confirmed, that wind resource variability seems not to creates power system instabilities when it has Squirrel Cage or Doubly-Fed Induction generators aggregated on a small grid under certain conditions simulated here.

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