

Parameter Identification of Steam Turbine Speed Governing System Using an Improved Gravitational Search Algorithm

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Abstract. Since most of the traditional parameter identification methods used in the steam turbine speed governing system (STSGS) have the shortages of great work load, poor fitness and long period by hand, a novel improved gravitational search algorithm (VGSA) method, whose gravitational parameter can be dynamically adjusted according to the current fitness and search space will keep being more and more narrow during the iteration process, is proposed in this paper based on an improved gravitational search algorithm (IGSA). The performance of this new method was identified through the comparisons of the steam turbine speed governing system identification results with IGSA using the measured data from a 600MW and a 300MW thermal power unit. The results show that the new method VGSA has the features of higher precision and higher speed during the identification process, and it brings a new scheme for steam turbine speed governing system identification.

1. Introduction

As one of the most important parts, the steam turbine speed governing system (STSGS) is very important in the safe and economical operation of the whole thermal power plant, through the speed and load adjusting. The requirements of good accuracy and rapidity of the steam turbine speed governing system are needed with the increasing capacity of the units, which lead to the speed governing system becoming increasingly complicated. Due to the complexity of system and the characteristic variation of equipment installation and debugging, it is difficult to build an integrated and accurate model indicating the dynamic features of a system through mechanism modeling method, since that, building system dynamic model using parameter identification method plays key roles. As a result, identification modeling is an effective way to monitor the operational states, predict the performance of governing system and analyze trouble after establishing integrated and accurate speed governing system through parameter identification method.

Some achievements have been made in parameter identification scheme, such as Least Square method (LS)[1-2], Correlation Analysis (CA)[3], Genetic Algorithm (GA)[4-6], Neural Network Algorithm (NNA)[7], Particle Swarm Optimization (PSO)[8], Differential Evolution Algorithm (DE)[9] and other new algorithms[10], have been practically used in engineering. However, most of these methods cannot be sued in a specific engineering application without lots of human intervention. In addition, considerations as to the deviations between the design parameters and operational parameters due to field assembly and uncertainty factors, and the irregularity of field test data affected by various factors compared with general theory data, an efficient identification algorithm with the features of rapidity, accuracy and robustness is needed in engineering applications.



Regarding what has been mentioned above, some novel identification algorithms have been developed in recent years. Gravitational Search Algorithm (GSA)[11], as a newly heuristic optimization method, has a good optimization effect comparing with GA, PSO and CFO (Central Force Optimization) when applied to 23 standard benchmark functions in reference [11], which confirms its high convergence rate and efficient searching ability. However, GSA trips into local optima easily because of its strong convergence speed. For this reason, researchers make lots of improvements based on standard GSA. Opposition-based Gravitational Search Algorithm (OGSA)[12], is an improved GSA, which is introduced “opposition operation” according to the ranges of parameters in order to raise the convergence rate effectively and improve the exploration and exploitation abilities, so the scale of agents is doubled. Better agents will be selected from the newly added agents as the next generation. But it is an unrealistic method for identification parameter to use OGSA since large amount of field test data must be used to evaluate the fitness of an agents and the evaluation process is a time-consuming process. Another improved Gravitational Search Algorithm (IGSA) is proposed in reference [13], which combines the “memory characteristic” of PSO and is applied to the parameter identification of hydraulic. Compared with standard GSA, PSO and GA, IGSA is shown the best performance with high accuracy and stability and demonstrated its optimal ability. From the results of parameter identification using IGSA, we know that a lot of iterations are needed until convergence and the engineering application of the method is uncertainty because parameters are identified with IGSA using theory data.

For the problems in parameter identification of steam turbine speed governing system currently, this paper proposed a variable gravitational search algorithm (VGSA) based on IGSA after further analysing GSA. The performance of this new method was demonstrated through the comparisons of the steam turbine speed governing system identification results with IGSA using the measured data from a 600MW and a 300MW thermal power unit.

2. Identification Algorithm

GSA [11] is a novel heuristic optimization method inspired by the motion of particles in space under gravity governed by the Newton’s law of motion. Under gravity, particles with bigger mass move slower than particles with smaller mass. Analogously, agents with better fitness move slower than agents with worse fitness and all the agents move to the agent with best fitness in the end. So the optimization based on GSA is achieved.

Assumed a system with N particles (agents), the position X_i of the i th particle is:

$$X_i = (x_i^1, x_i^2, \dots, x_i^d, \dots, x_i^{dimension}) \quad (1)$$

where x_i^d is the position of i th particle in d th dimension, and $dimension$ is the maximum dimensionality.

The mass fraction of i th particle at time t is $M_i(t)$, which can be calculated according to equation (2) and (3).

$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \quad (2)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)} \quad (3)$$

where $m_i(t)$ is the mass of i th particle at time t and $fit_i(t)$ is the fitness of i th particle at time t . $best(t)$ and $worst(t)$ are the best fitness and the worst fitness of all particles at time t , respectively.

According to the law of gravity, the force $F_{ij}^d(t)$ acting on i th particle in d th dimension exerted by the j th particle at time t can be defined as follows.

$$F_{ij}^d(t) = G(t) \frac{M_{pi}(t) \times M_{aj}(t)}{R_{ij}(t) + e} (x_j^d(t) - x_i^d(t)) \quad (4)$$

where e is a small constant in case of denominator being zero and $R_{ij}(t)$ is the Euclidian distance between particle i and particle j which is defined as equation (5).

$$R_{ij}(t) = \sqrt{\sum_{d=1}^{dimension} (x_j^d(t) - x_i^d(t))^2} \quad (5)$$

The value of the gravitational constant function can be calculated as equation (6).

$$G(t) = G_0 \cdot \exp\left(-\beta \cdot \frac{t}{max_t}\right) \quad (6)$$

where β is a constant, G_0 is the initial value of the gravitational constant, t is the current iteration, max_t is the maximum iteration.

The total force that other particles act on i th particle in d th dimension can be described as equation (7).

$$F_i^d(t) = \sum_{j=1, j \neq i}^N rand_j F_{ij}^d(t) \quad (7)$$

where $rand_j$ is a random number in the interval $[0, 1]$.

The acceleration of i th particle in d th dimension is given as follows.

$$a_i^d(t) = \frac{F_i^d(t)}{M_i(t)} \quad (8)$$

Finally, the velocity and position of i th particle in d th dimension are defined as equation (9) and (10), respectively.

$$v_i^d(t+1) = rand_i \times v_i^d(t) + a_i^d(t) \quad (9)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (10)$$

where $rand_i$ is a random variable in the range $[0, 1]$.

The fitness function of i th particle at time t is defined as follows. In this paper, the smaller the fitness value, the better.

$$fit_i(t) = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_{out,i} - Y_{out,i})^2} \quad (11)$$

where $y_{out,i}$ and $Y_{out,i}$ are field test output and simulation modeling output respectively.

Considering the global optimum and local optimum, an improved GSA combining the “memory characteristic” of PSO is proposed in reference [13]. Therefore, the velocity and position of i th particle should be updated as equation (12) and (13).

$$v_i^d(t+1) = rand_1 \cdot v_i^d(t) + a_i^d(t) + c_1 \cdot rand_2 (x_{gi}^d - x_i^d(t)) + c_2 \cdot rand_3 \cdot (p_i^d - x_i^d(t)) \quad (12)$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \quad (13)$$

where $rand_1$, $rand_2$ and $rand_3$ are three random numbers in the interval $[0,1]$, c_1 and c_2 are positive constants, p_i^d and x_{gi}^d represent the best position of the i th particle and the best position among all the particles up to the current iteration.

After further analyzing the optimization process of GSA, we know that besides the mass and position can affect the motion of particles, gravitational constant G is another independent important factor. Since particles may trip into local optimum due to the low velocity after a series of iterations and be far from the global optimum, they should move with higher velocity. For this reason, VGSA, whose gravitational constant function can be dynamically adjusted according to the current fitness, is proposed based on IGSA. By adjusting the value of gravitational constant function, the force acting on

particles increase, which lead to the velocities of the particles become higher so they can move out of the local optimum. In order to detect the particle's distance away from the optimal particle's position in present iteration, the current average fitness among all the particles is introduced. If the fitness of i th particle is better than the average fitness, the gravitational constant function is calculated according equation (6), otherwise the gravitational constant function is calculated according to the initial gravitational constant value. So the gravitational constant function can be described as follows.

$$G = \begin{cases} G_0 \cdot \exp(-\beta \frac{t}{max_t}) & \text{if } fit_i(t) < average_fit \\ G_0 & \text{if } fit_i(t) \geq average_fit \end{cases} \quad (14)$$

where the current average fitness among all the particles is defined[14] as equation (15).

$$average_fit = \frac{1}{N} \sum_{i=1}^N fit_i(t) \quad (15)$$

where G_0 is the initial gravitational constant, $fit_i(t)$ is the fitness of i th particle at time t , N is the population of particles.

Furthermore, the search space of VGSA will become more and more narrow during iteration process according to equation (16) and (17) after drawing on the idea in reference [15].

$$x_{min}^d(t+1) = \max(\gamma_1 \cdot x_{min}^d(t), x_g^d(t) - rand_1(\gamma_2 \cdot x_{max}^d(t) - \gamma_1 \cdot x_{min}^d(t))) \quad (16)$$

$$x_{max}^d(t+1) = \min(\gamma_2 \cdot x_{max}^d(t), x_g^d(t) + rand_2(\gamma_2 \cdot x_{max}^d(t) - \gamma_1 \cdot x_{min}^d(t))) \quad (17)$$

where $x_{min}^d(t+1)$ and $x_{max}^d(t+1)$ are the lower boundary and higher boundary, respectively, x_g^d represents the best previous position among all particles, γ_1 and γ_2 are a number slightly less than 1 and a number slightly greater than 1 respectively, $rand_1$ and $rand_2$ are two uniform variables in the interval $[0,1]$.

3. Model of STSGS and Identification Process

The steam turbine speed governing system is a complex nonlinear system which consists of four major subsystems shown in Figure 1. Where T_C is the close time constant of governing valve, T_o is the open time constant of governing valve, T_{CH} is the time constant of main inlet volumes and steam chest, T_{RH} is the time constant of reheater, T_{CO} is the time constant of crossover piping and LP inlet volumes, F_{HP} , F_{IP} , F_{LP} are the fractions of total turbine power generated by HP, IP, LP sections, respectively. They are rotational speed measuring and frequency differences amplification system model, power control or CCS control system model, executive mechanism system model and steam turbine model respectively. The rotational speed of the steam turbine generator will not change in steady running until the balance of steady operation is off when external factors affect it. Then load change rate will be obtained by frequency differences amplification system according to the frequency differences between the actual rotary speed and the given rotary speed measured. Given the load change command, power control or CCS control system will adjust the corresponding controller to output the valve change command. The executive mechanism system will adjust the inlet valve position accordance of the valve change command till reaching the new equilibrium state.

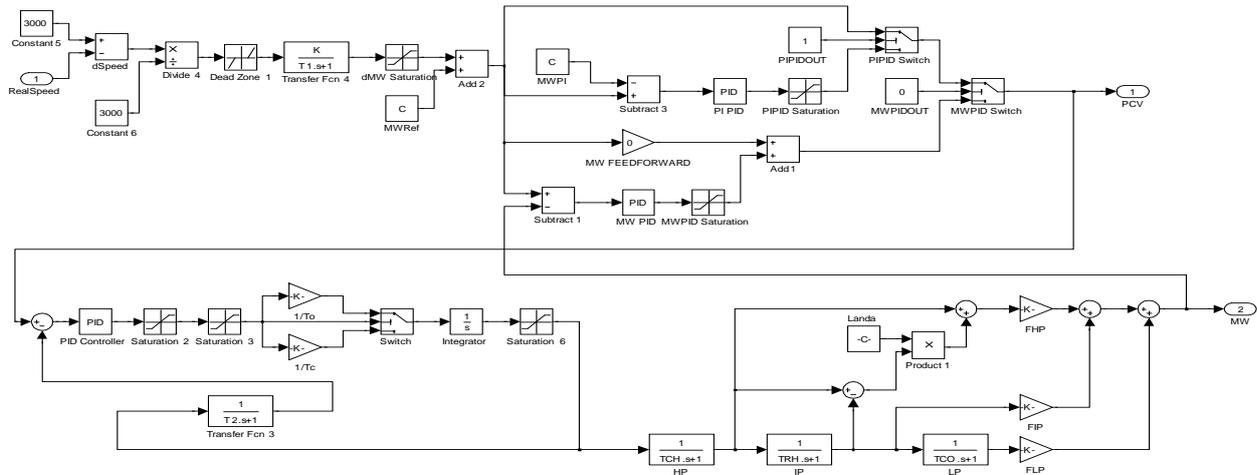


Figure 1. The steam turbine governing system model under power control mode.

According to what has been mentioned above, there are 7 parameters in steam turbine speed governing system model will be identified one time in this paper, including feed-forward coefficient and PID correction in power control system model, time constant of main inlet volumes and steam chest T_{HP} , time constant of reheater T_{RH} , time constant of crossover piping and LP inlet volumes T_{CO} .

During the identification process, the open or close time constant of governing valves should be identified before the 7 parameters in steam turbine speed governing system model are identified one time using VGSA. Flowchart of parameter identification based on VGSA is illustrated in Figure 2.

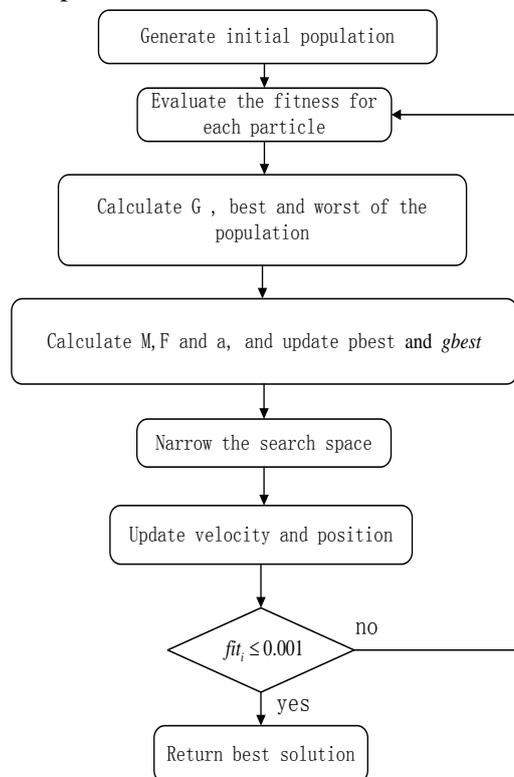


Figure 2. Flowchart of parameter identification based on VGSA.

4. Identification Test

In order to test the performance of VGSA in parameter identification of steam turbine speed governing system, feed-forward coefficient and PID correction in power control system model, time constant of main inlet volumes and steam chest T_{HP} , time constant of reheater T_{RH} , time constant of crossover piping and LP inlet volumes T_{co} are identified through the comparisons of identification results with IGSA using the measured data from a 600MW and a 300MW thermal power units.

For the 600 MW thermal power unit, the sampling period of field test data is 0.002s, the initial interval of feed-forward is [0, 1] and the initial range of the other 6 parameters is [0, 20]. Regarding the 300 MW thermal power unit, the sampling period of field test data is also 0.002s, the initial value ranges of feed-forward and PID correction are [0, 1] and the initial value scopes of other parameters are set as [0, 20]. In experiments, the control parameters of IGSA are set as: population size is 50, iteration number is 50, $c_1 = c_2 = 0.5$, $G_0 = 30$, $\beta = 10$. For VGSA, the parameters are set as: population size is 50, iteration number is 50, $c_1 = c_2 = 0.5$, $G_0 = 30$, $\beta = 10$, $\gamma_1 = 0.9$, $\gamma_2 = 1.1$.

4.1. Parameter Identification of a 600 MW unit

In order to obtain the dynamic characteristics of power of a 600 MW thermal power unit, step disturbance of rotation speed experiment has been made. Under power control mode, step disturbance signal was input after the turbine generator steady runs at a 3010r/min, and actual rotation speed decreased to 3000r/min. What we should do is collecting the output data of dynamic characteristics of power. After the power output standard disposal, IGSA and VGSA are used respectively to identify the 7 parameters of the steam turbine speed governing system based on the model. The parameter identification process and the convergence of the two algorithms are illustrated in Figure 3 and Figure 4 respectively.

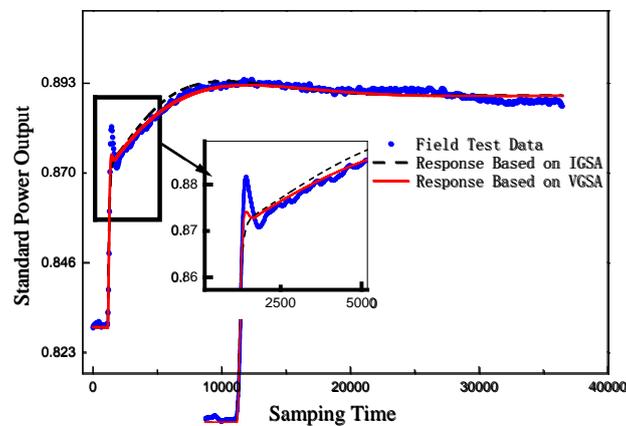


Figure 3. Comparison of a 600MW power unit identified results using the two algorithms respectively.

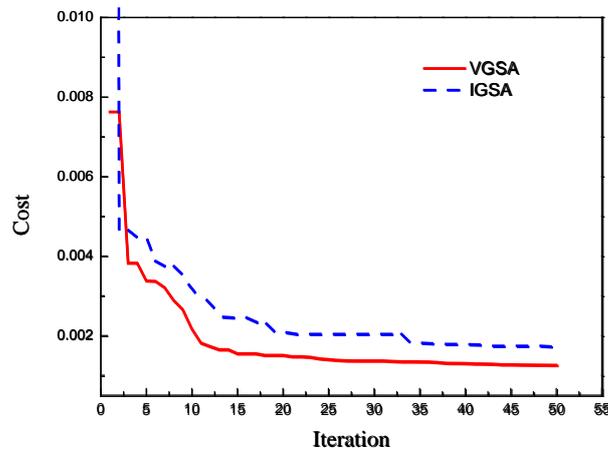


Figure 4. Comparison of iteration process using the two algorithms respectively.

Figure 3 shows the real response and simulation responses of taking the identified parameters obtained by IGSA and VGSA. Both simulation responses using IGSA and VGSA respectively are almost in coincidence with the real response in Figure. 3. In fact, the real response curve affected by feed-forward in original system has the trend of step rise, a sharp decline then gradually rising in the early stage. However, the simulation results using IGSA doesn't reflect the affection of feed-forward in real system. On the contrary, the simulation response of taking identified parameters by VGSA reflects the trend of real response to some extent and provides a better real variation of power. In Figure 4, both algorithms have good convergence rate in early iteration, but the convergence rate of IGSA is slower in latter iteration and IGSA more likely traps into local optimum than VGSA. At 20th iteration, the cost of IGSA is 0.00211 and the cost of VGSA is 0.00151. From then on, the error of VGSA is smaller than IGSA, which shows that VGSA has the performance of high optimizing precision and rapid convergence rate. Further analyzing VGSA, since the dynamically adjusting gravitational constant function according to the fitness of particle, particle easily moves out of local optimum. At the same time, the search space of parameter become more and more narrow during iteration process, the optimizing efficiency is better. The identification results of a 600 MW thermal unit are listed in Table 1.

Table 1. The identification results of a 600MW power unit.

	IGSA	VGSA
T_{HP} (s)	0.156	0.300
T_{RH} (s)	5.000	15.547
T_{CO} (s)	7.512	6.476
P	1.983	3.123
I	0.257	0.567
K_g	0.900	0.452
D	0.330	0.003
Cost	0.0017	0.00126

Table 1 shows the identification results and accuracy by the 2 methods. After 50 iterations, both algorithms achieve high accuracy while VGSA performs better comparing with IGSA and its cost is 0.00126, which shows a very precision in engineering application.

4.2. Parameter Identification of a 300 MW unit

Before parameter identification of a 300 MW thermal unit, step disturbance of rotary speed test should do also. In order to obtain the power output under control mode, the actual rotary speed varies from 3000r/min to 3010r/min after step disturbance signal coming. Then the parameter identification

process of steam turbine speed governing system is as follows: after the field test data standard processed, the corresponding parameters are identified one time based on IGSA and VGSA respectively according to the standard disposed data. The actual power output and the simulation responses using the two algorithms respectively are shown in Figure 5 and the convergence processes of the two methods are illustrated in Figure 6.

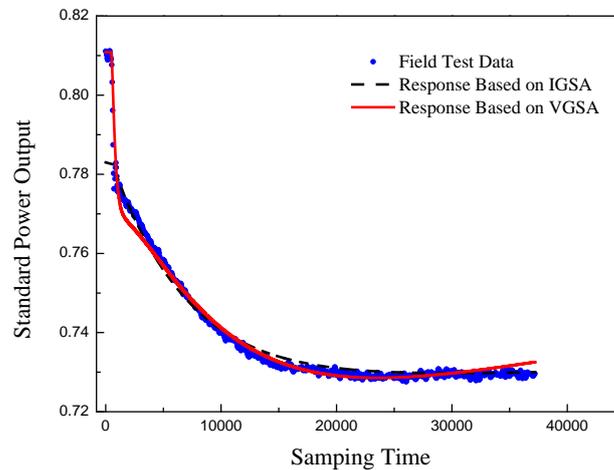


Figure 5. Comparison of a 300MW power unit identified results using the two algorithms respectively.

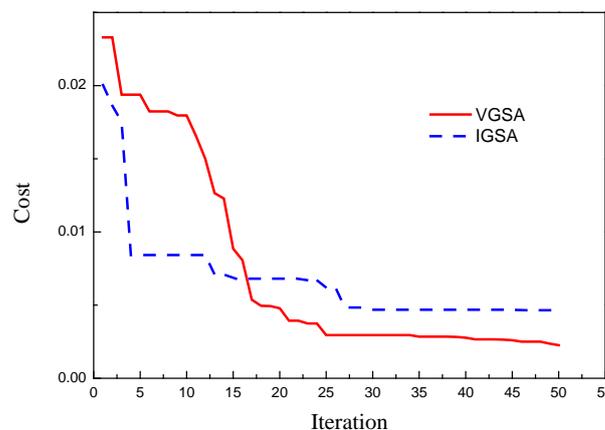


Figure 6. Comparison of iteration process using the two algorithms respectively.

Figure 5 shows the power declining process. The response of taking identified parameters obtained by IGSA is consistent with the real response after the decline of power. However, the initial value of power (about 0.783) by IGSA before step changing is different from the real initial value of power (about 0.81). On the other hand, not only does the response obtained by VGSA match perfect with the real response after the power down process, but also its initial power value (about 0.81) is very close to the real initial power value (about 0.81). In Figure 6, the accuracy obtained by VGSA is higher than that obtained by IGSA after 15 iterations. The performance of VGSA is more excellent than IGSA in identification efficiency and optimizing effect. The identification results of the 300 MW thermal unit are listed in table 2.

Table 2. The identification results of a 300MW power unit.

	IGSA	VGSA
T_{HP} (s)	5.526	0.405
T_{RH} (s)	12.641	16.437

T_{co} (s)	1.290	4.570
P	0.0754	0.00714
I	0.00241	0.00151
K_6	0.903	1.455
D	0.703	0.0595
Cost	0.00465	0.00226

It shows that the cost (0.00465) obtained by IGSA is greater than that (0.00226) obtained by VGSA after 50 iterations in Table 2. So the using adaptability of VGSA is better than IGSA and the identification results are more reliable and accurate, which provides perfect simulation of the power variation.

It has been confirmed that regardless of the rise or fall of power, VGSA performs better with good adaptability and high accuracy comparing with IGSA in the 2 identification cases.

5. Conclusions

In this paper, a novel heuristic optimization method (VGSA) is introduced and improved after further analyzed. VGSA is an improved algorithm with a dynamically adjusted gravitational constant function and more and more narrow search space during iterations. Meanwhile, the method has been applied to identify the parameter identification of steam turbine speed governing system using measured data from 2 thermal power units. The identification results show that VGSA has engineering application significance with the performance of high accuracy, high efficiency and general adaptability. So VGSA is an effective new method with engineering application prospects.

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