Optimal Control of Automatic Generation with Automatic Voltage Regulator Using Particle Swarm Optimization

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Abstract A simultaneous study of load frequency control and automatic voltage regulation is considered. The single-area and two-area power systems have been considered with a combined model of AGC and AVR for analysis of frequency and voltage deviation. The primary aspect of the design is to keep real power control as to preserve frequency of the system in a prescribed limit. Reactive power control is used to keep the voltage magnitude of synchronous generator at a tolerable limit. The transients produced in dynamic responses are controlled using intelligent and soft-computing technique. The fuzzy logic controller and particle swarm optimization based PID controllers are considered. The steady state error and settling time of the dynamic responses are observed and found to be reduced very effectively. The frequency and terminal voltage results of a single-area power system with proposed PSO-PID controller is compared to the responses of system with controllers presented in literature and found to be more effective. The comparison of fuzzy logic controller with PSO-PID is done by observing the nature of two-area responses. The result obtained by soft computing algorithm and intelligent controller is analyzed on the basis of settling-time, undershoot and ISE Error.

Keywords Automatic Voltage Regulation (AVR), Automatic Load Frequency Control (ALFC), Particle Swarm Optimization (PSO), Fuzzy Logic Control (FLC), Proportional Plus Integral Plus Derivative (PID) Controller, Integral Square Error

1 Introduction

For supplying good and Reliable power to consumer, control of generation is must [1]. If load is change in one area it will badly affect the whole interconnected area, so some control technique is needed to overcome such situation.

By ALFC the deviation in frequency and Tie-line power responses which are generated due to disturbance in power

system are minimized [2]. A change in the Frequency directly depends on rate of generation [3]. where as a change in the excitation is related to voltage magnitude [4]. Combined study of AGC and AVR is done together in this proposed work [5]. Excitation of the alternator is control for maintaining the reactive power balance. The change in voltage at alternator terminals are sensed by AVR for brining the voltage at its rated value by adjusting the alternator [6]. At generating station the application of proportional-integral-derivative (PID) controller is in demand. Therefore proper tuning of such controllers is necessary. The optimal tuning of PID gains (K_p , K_i and K_d) is required for obtaining best results from tuned controller [7].

The settling time and overshoot of dynamic responses are reduced by using Tuned PID controller. The parameter adopted for problem formation is settling time, ISE error and oscillations [8]. In conventional PID controller the parameters are set by hit and trial approach, which is time consuming. To reduce the complexity in tuning PID parameters, Evolutionary computation techniques are used to solve a wide range of practical problems including calculation of PID gains and optimization it [9].

The response time of integral controller is more and it not able to remove transients from dynamic responses. Therefore for obtaining good and fast responses intelligent controller is needed [10]. The proposed Fuzzy logic control is also used for getting better dynamic responses. Proposed PSO PID results are compared with FLC [11].

Chandrasekhar and Jayapal [12], presented work on AGC and AVR combined model. PI and PID and Fuzzy controller are implemented for two area systems. Fuzzy controller offers better performance then PI and PID. Fuzzy controller corrects the area control error of AGC and Excitation of AVR [13].

Mulalidharan and Anbarasi [14], proposed work for controlling Dynamic responses of AGC and AVR. Bacterial foraging optimization Algorithm (BFOA) is used. Results of BFOA tuned PID controller is compared with Z-N tuned PID. Proposed algorithm gives better result [15].

Dabur et al [16], analysis the AGC of interconnected thermal systems with combination of automatic voltage regulation (AVR), design implementation and operation of fuzzy controller is shown.

Shyama et al [17], proposed controller which is used for tuning LFC and AVR to maintain system responses at nominal value. Fuzzy gain scheduled proportional-integral controller gives better result than conventional controller [18].

Mukherjee et al [19], proposed work for AGC and AVR. PSO is used for tuning PID. Nagendra and Krishanayalu [20], presented work for multi - area interconnected power system. The plant responses by considering GRC in examined for every area. Fuzzy and tuned PID is compared.

In this paper for tuning the PID controller PSO algorithm is used. The tuned PID controller is implemented for minimizing deviation in frequency and Tie-line power responses.

2 Automatic voltage regulator

As the coupling between the load frequency control (LFC) and automatic voltage regulation (AVR) system is weak. So they can be studied separately. In this paper the effect of both are considered together. The real power depends on synchronizing power coefficient p_s and change in the power angle $\Delta\delta$. When voltage is consider together then the new expression is formed which is shown in below Eqn. 1.

$$\Delta p_e = p_s \Delta\delta + k_2 E' \quad (1)$$

Where k_2 , the change is in electrical power for a small change in stator emf, the Eqn. 2 shows the small effect of rotor angle upon the generator voltage

$$\Delta p_e = k_5 \Delta\delta + k_6 E' \quad (2)$$

Where k_5 , represents change in terminal voltage for a small change in rotor angle at constant stator emf and k_6 represents change in terminal voltage for a small change in the stator emf at constant rotor angle. For stable system p_s is positive. The constants k_2, k_4, k_6 are taken positive and k_5 is taken negative. The process for modelling of an AVR model is carried out below.

2.1 Amplifier model

The gain of the amplifier is denoted by k_A , its gain value is from 10 to 400. Time constant for Amplifier is very small its range lies 0.02 to 0.1 sec. transfer function for amplifier model is

$$\frac{V_R(s)}{V_e(s)} = \frac{K_A}{1 + T_A s} \quad (3)$$

2.2 Exciter model

The gain k_E and time constant T_E of exciter is represented in transfer-function form given as

$$\frac{V_F(s)}{V_R(s)} = \frac{K_E}{1 + T_E s} \quad (4)$$

2.3 Generator model

Range of Gain k_G is between 0.7 to 1 and T_G lies between 1 to 2 seconds.

$$\frac{V_t(s)}{V_F(s)} = \frac{K_G}{1 + T_G s} \quad (5)$$

2.4 Sensor model

Sensor sensed voltage through a potential transformer the T_R time constant of sensor is assuming a range from 0.01 to 0.06.

$$\frac{V_S(s)}{V_t(s)} = \frac{K_R}{1 + T_R s} \quad (6)$$

By using the above Eqn. 3 - Eqn. 6, the schematic diagram is made which shown in Fig. 1. From the above block diagram

Figure 1. Block diagram of automatic voltage Regulator

in Fig. 1, we can write open loop transfer function which is given as: The relation between generator terminal voltages $V_t(s)$ to the reference voltage $V_{ref}(s)$ is given in Eqn. 8.

3 Problem Formulation

In this paper, study of AGC and AVR is taken together. Two areas interconnected with tie-line are considered for analyzing the behavior of frequency and voltage deviation. The control signal u_1, u_3 are given to governor in AGC and u_2, u_4 are control signal given to amplifier in AVR model. By implementing FLC and PSO the frequency deviation ($\Delta f_1, \Delta f_2$) and voltage deviation ($\Delta v_1, \Delta v_2$) are controlled. The disturbance of 0.2 p.u is given in both area of automatic generation control connected with tie-line. The step load of 1 p.u is taken in AVR model. When controller is not their steady state error can is there in frequency and voltage response. Block diagram for combine study of AGC and AVR is given in Fig. 2.

3.1 Objective function

Load frequency of power system to control the deviation of frequency and Tie-line power. The problem is considered for single, two and three-area system as an optimization problem for setting the parameters of PID controller. The parameters of PID controller (K_p, K_i and K_d) are considered without specifying the lower and upper bounds. The objective function for optimization is considered as in Eqn. 9.

$$ISE = \int_0^{Tsim} |\Delta f_1(t) - \Delta f_2(t)|^2 dt \quad (9)$$

$$K G(s)H(s) = \frac{K_A K_E K_G K_R}{(1 + T_A s)(1 + T_E s)(1 + T_G s)(1 + T_R s)} \quad (7)$$

$$\frac{v_t(s)}{v_{ref}(s)} = \frac{K_A K_E K_R K_G (1 + T_R s)}{(1 + T_A s)(1 + T_E s)(1 + T_G s)(1 + T_R s) + K_A K_E K_G K_R} \quad (8)$$

Figure 2. Block diagram of combined AGC and AVR

4 Fuzzy Logic Controller

FLC is a very useful method of reasoning when mathematical models are not available and large numbers of input data are present [11]. Fuzzy logic controller is based on fuzzy logic concept [21]. It provides an algorithm by which Expert knowledge based linguistic control starter is converted to automatic control strategy [22]. imprecise but very descriptive language is used by FLC to deal with input data similar to a human operator. Fuzzy logics approach mimics the behavior of an person to make decisions must faster [23]. FLC is more useful in solving complex and non-linear control prob-

lems for which a conventional controllers takes more time and also less efficient [24]. Fuzzy logic controller has three main components it is fuzzification, knowledge base and defuzzification.

Fuzzification: Fuzzification is a process in which crisps quantity is converted into the linguistic variables. Knowledge base: it consists of data base and linguistic control rule base [25, 26].

The data base provides necessary definitions which are used to define linguistic control rules and fuzzy data, manipulation in a FLC [27, 28].

The rule base characterizes the control goals and control

policy of the domain experts by means of set of linguistic control rules [29, 30].

Defuzzification involves turning a set of membership values into a single output value. The block diagram of fuzzy controller used for AGC and AVR is shown in Fig. 3 [31, 32].

Figure 3. Block diagram of fuzzy logic controller for load frequency control

5 Particle swarm optimization

The particle swarm optimization (PSO) method is derived by absorbing the behavior of animal like bird flocking, fish schooling population [33]. For solving an optimization problem PSO use concept of social interaction of animals [34]. This algorithm was developed by James Kennedy in 1995.

Both local search methods and global search methods are combined in PSO system for balancing Exploration and Exploitation. Swarms fly for obtaining a new position. It is done by comparing its own fitness with neighbor fitness. If its near particle have better fitness then with a certain velocity it occupy that position. Swarm keeps its own expression and its neighbor expression in mind at time of searching best fitness value.

Two terms mainly used in algorithm

- Local Best: each particle has proper information about its immediate neighbor by using certain swarm technique.
- Global Best: the particle is attracted towards the best solution found by any particle member in the group of swarms. It means each particle is interconnected with other particles with some topology and can access towards the best fitness.

The basic idea on which PSO algorithm work is that each particle is searching for the best solution and each swarm is moving so it has velocity, every particle keeps knowledge about its position where it has best result so far.

The PSO search technique is shown in vector form in Fig. 4. The position of individual particle updated by using Eqn. 10 and velocity is calculated by Eqn. 11.

$$z_m^{n+1} = z_m^n + v_m^{n+1} \quad (10)$$

$$v_m^{n+1} = v_m^n + c_1 r_1 (p_m^n - z_m^n) + c_2 r_2 (g_m^n - z_m^n) \quad (11)$$

The variable above is defined as, z_m^n is initial searching point,

Figure 4. Particle swarm searching technique

z_m^{n+1} modified point searched, v_m^n initial velocity, v_m^{n+1} modified velocity, v_m^{pbest} velocity based on individual particle position, v_m^{gbest} velocity based on global best. The acceleration constant is given as c_1 , c_2 ; the random value between 0 and 1 is given as r_1 , r_2 . The constants c_1 and c_2 represent the weighting of the acceleration terms that allow each particle to reach at its best position.

A balance between global and local explorations is met by Suitable selection of inertia weight ω . which reduces the no of iteration value to obtain optimal solution.

$$\omega = \omega_{\max} - iter \times \frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \quad (12)$$

The $iter_{\max}$ represents maximum number of iteration and represent current number of iterations.

The design steps of PSO based PID controller for LFC of a power generating system is

- Swarm particle are initiated by a random position
- Fitness of each particle is evaluated
- For every individual particle, Fitness value of particle is compared with its neighbor fitness. if its fitness is better than its p_{best} value then remain at current position. If not then neighbor position is occupied by particle with a velocity v_m^{n+1} .
- Now find the global fitness of particle in group of swarm.
- Velocity and position of particle is Update by using equation 10 and 11.
- Repeat the steps 2 to 5 until the desired goal is achieved. It means iteration are stopped when good fitness value is found.

The particle swarm optimization (PSO) is shown in Algorithm 1.

6 Result and discussion

In this article, single-area and two-area power system models with AGC and AVR are considered for analysis, the behavior of frequency and voltage with varying load conditions. Two different PID controllers are connected in AGC

Algorithm 1 Particle swarm optimization algorithm for tuning parameters of proportional-integral-derivative controller

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1: procedure OBJECTIVE FUNCTION  $F(X)$  AS IN EQN. 10,
    $X = (X_1, X_2, \dots, X_d)^T$  (minimization of objective function;
   where  $X_d$  is the number of free Coefficients of PID controller
   as 6 in numbers for single-area and 12 for two-area power system)
2: Initialization of the parameters, Size of the swarm i.e. no of
   birds ( $n$ ) set to 10; Maximum number of birds steps set to 50;
   dimension of the problem is set to 6 in case of single-area system
   and 12 in case of two-area system; the PSO parameters  $C_1$ 
   and  $C_2$  are selected as 1.2 and 0.12 with moment of inertia  $\omega$  as
   0.9, the maximum iteration count is set to  $Itr_{max}$  as 50.
3: The fitness function is defined using  $F = Error * Error$  as
   in Eqn. 9 with parameters  $X(1) = k_{p1}$ ,  $X(2) = k_{i1}$ ,  $X(3) =$ 
 $k_{d1}$ ,  $X(4) = k_{p2}$ ,  $X(5) = k_{i2}$ ,  $X(6) = k_{d2}$ .
4: Initializing velocities and position, "position = 10*(rand(dim,
   n)-0.5); velocity = 0.3*randn(dim, n)"
5: calculation of initial position of swarms
6:   for  $i = 1 : n$ ,  $fitness(i) = F_{obj}(position(:, i))$  do
7:     end for
8:  $[fitness_{gb}, g] = \min(fitness)$ ;
9:
10:   for  $i = 1 : n$ ,  $position_{gb}(:, i) = position(:, g)$  do
11:     end for
12: The main-loop operation is set using while loop and started using
   iter = 0.
13:   while ( $iter < Itr_{max}$ ) do
14: the iteration count is forwarded as iter = iter + 1;
15: the fitness function is calculated for the set values of bird steps
   using
16:
17:   for  $i = 1 : n$ ,  $current_{fitness}(i) = F_{obj}(current_{position}(:, i))$  do;
18:     end for
19: the minimum value of the fitness function and position of is
   selected; the position of swarms is updated using Eqn. 10 and
   the velocity is updated using Eqn. 11. The weight value is
   updated using Eqn. 12.
20:   end while
21: post process results( $f_{min}$ , best_position) and visualization
22: end procedure

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and AVR loop of an area of power system. Therefore, six free coefficients of two PID controllers in single-area and 12 free coefficients for 4 PID controllers in case of two-area system are the target of optimization. A load disturbance of 0.2 p.u. is given in two-area system of LFC connected with tie-line. Robustness of interconnected system is seen. A step input of 1 p.u is applied as v_{ref} in AVR model. When there is no controller, there is a steady state error which can be seen in below figures of frequency and voltage response of isolated and multi-area power system.

6.1 Single-area power system

Proposed work is carried out for analyzing the dynamic responses (frequency and voltage) using fuzzy logic control (FLC) and particle swarm optimization (PSO) techniques.

The frequency and terminal voltage responses obtained by fuzzy logic controller for a single area system having combined model of AGC and AVR is shown in Fig. 5 and Fig. 6. The comparison of proposed controller with recent published

Table 1. Comparison of PSO based PID parameters for single-area system with controllers in literature [37, 14, 38]

Controllers	Loop	K_p	K_i	K_d
Proposed (PSO-PID)	AGC	10.5181	17.7225	3.5581
	AVR	3.3892	1.0137	3.5808
Thakur [37]	AGC	0.8300	0.5400	0.1400
	AVR	4.2155	4.5999	0.5789
Anbarasi [14]	AGC	3.1850	4.6700	0.6556
	AVR	0.7886	0.6086	0.3357
Sadaat [38]	AGC	1.0000	0.2800	0.2500
	AVR	1.0000	0.2800	0.2500

paper PID is carried out. The optimal values of PSO based PID for single-area and two-area systems are included in Table 1 and Table 2, respectively. By analysis, it is found that proposed controller results are better than classical controller. Both classical and intelligent controller reduces the steady state error to zero but the settling time and ISE error of proposed controller are very small as compared to conventional PID controllers. The integral of squared error (ISE) is well defined in [35, 23, 32, 36]. Comparison of Intelligent controller with PID controller on the basis of settling-time, under-shoot and ISE error is in Table 3 and Table 4.

Some of the observations are enlisted as following:

- Frequency response of single-area system with proposed fuzzy logic controller settles at 16 seconds while it settles at 18, 22 and 30 seconds with controllers presented in Thakur [37], Anbarasi [14] and Sadaat [38], respectively as in Table 3..
- The value of ISE error of frequency response is 0.00111 while that of with controllers in in Thakur [37], Anbarasi [14] and Sadaat [38] is 0.00168, 0.04120 and 0.00685, respectively.
- The terminal voltage response with proposed fuzzy controller settles at 6 seconds while that of with Thakur [37], Anbarasi [14] and Sadaat [38], settles in 14, 10 and 16 seconds, respectively as in Table 4.
- The ISE error of terminal voltage response with proposed fuzzy controller, Thakur [37], Anbarasi [14] and Sadaat [38] is 48.52, 50.92, 49.74 and 48.65, respectively.
- The settling time with proposed PSO-PID for frequency response is 8 seconds (as in Table 5) and the settling time for voltage response is 10 seconds (as in Table 6). The response is appreciable improved as compared to the responses with controllers in literature [37, 14, 38]. Similarly, the ISE error with proposed PSO-PID is highly reduced as compared to the controllers in [37, 14, 38].

PSO tuned PID controller is also applied for isolated system having combined model for controlling frequency and voltage deviation of the system. The system response with optimally tuned PID controller PID results are compared to response with PID controllers presented in recent published paper used for LFC and AVR. The PSO-PID results are better. Comparison of dynamic responses is shown in Fig. 7

Table 2. The parameters of the PID controller using PSO algorithm for two-area system with controllers in literature [37, 14, 38]

Loop	Area	K_p	K_i	K_d
AGC	Area-1	6.7292	9.0540	6.3230
	Area-2	5.2940	4.5847	3.8312
AVR	Area-1	4.1512	16.3485	3.0177
	Area-2	2.1296	4.7747	1.2329

Table 3. Frequency response of single-area power system with fuzzy logic controller and controllers in literature [37, 14, 38]

Controllers	Settling-time	Under-shoot	ISE Error
Proposed (Fuzzy)	16	-0.0250	0.00111
Thakur [37]	18	-0.0400	0.00168
Anbarasi [14]	22	-0.0410	0.04120
Sadaat [38]	30	-0.0181	0.00685

Figure 5. Frequency response for a single area power system obtained by Fuzzy logic controller [37, 14, 38]

and Fig. 8. Frequency and voltage responses obtained by PSO tuned PID and compared with conventional controller on basis of settling-time, undershoot and integral square error (ISE) is given in Table 5 and Table 6.

6.2 Two-area power system

The fuzzy logic controller and PSO tuned PID controller is implemented for a two area power system having combined model of ALFC and AVR.

The frequency responses obtained by Fuzzy and PSO tuned PID controller is shown in Fig. 9 and Fig. 10. The Tuned PID results are supreme as compared to fuzzy logic controller. Tie-line power response is given in Fig. 13.

Table 4. Terminal voltage response of single-area power system with fuzzy logic controller and controllers in literature [37, 14, 38]

Controllers	Settling-time	Under-shoot	ISE Error
Proposed (Fuzzy)	6	-	48.52
Thakur [37]	14	0.4	50.92
Anbarasi [14]	10	-	49.74
Sadaat [38]	16	0.93	48.65

Figure 6. Terminal voltage response for a single area power system obtained by Fuzzy logic controller [37, 14, 38]**Table 5.** Frequency response of single-area power system with proposed PID-PSO controller and controllers in literature [37, 14, 38]

Controllers	Settling-time	Under-shoot	ISE Error
Proposed (PSO-PID)	8	-8.1×10^{-3}	0.0001
Thakur [37]	18	-0.04	0.00168
Anbarasi [14]	22	-8.85×10^{-3}	0.0412
Sadaat [38]	30	-0.0181	0.00685

Figure 7. Frequency response for a single area power system obtained by PSO tuned PID controller [13, 22, 23]

The terminal voltage responses are shown in Fig. 11 and Fig. 12 for AVR. It is absorbed that settling - time of terminal voltage simulated by PSO is quite fast as compared to FLC

Table 6. Terminal voltage response of single-area power system with proposed PID-PSO controller and controllers in literature [37, 14, 38]

Controllers	Settling-time	Under-shoot	ISE Error
Proposed (PSO-PID)	10	0.7	29.93
Thakur [37]	14	0.4	50.92
Anbarasi [14]	10	-	49.74
Sadaat [38]	16	0.93	48.65

Figure 8. Terminal voltage response for a single area power system obtained by PSO tuned PID controller [13, 22, 23]

voltage response. Both controllers are succeeding in reducing steady state error to zero. Comparative analysis of both proposed controller on basis of settling time, under-shoot and ISE error for frequency and Tie-line power is given in Table 7. For terminal voltage comparison is given in Table 8. Data used for ALFC for isolated system is similar to area-1 data given in Appendix - A and for AVR model data is given in Appendix - B.

Figure 9. Frequency response for area-1 of two-area power system

Some important observations from the responses of the system with fuzzy logic controller and with PSO-PID controller are as following:

- The settling time observed for frequency response with proposed PSO-PID controller is 13 seconds for area-1 and 18 seconds for area-2; which is much lesser as compared to fuzzy response as 27 seconds and 25 seconds, respectively (Table 7).
- The terminal voltage response for area-1 and area-2 with PSO-PID controller is 20 and 14 seconds, while that of with fuzzy controller is 34 and 32 seconds, respectively. Therefore, it is easy to say that the response with

Figure 10. Frequency response for area-2 of two-area power system

Figure 11. Terminal voltage response for area-1 of two-area power system

Figure 12. Terminal voltage response for area-2 of two-area power system

proposed PSO-PID is greatly enhanced as compared to fuzzy controller.

Figure 13. Tie-Line power response for two-area power system

Table 7. Frequency response analysis for interconnected power system

Mode	Controllers	Settling-time	Under-shoot	ISE Error
Δf_1	PSO-PID	13	- 0.0108	0.0012
	FLC	27	- 0.038	0.0021
Δf_2	PSO-PID	18	- 0.0058	0.0018
	FLC	25	- 0.03	0.0013
ΔT_p	PSO-PID	32	- 0.003	0.00214
	FLC	45	- 0.03	0.0014

7 Conclusion

In this paper, single-area and two-area power system models are considered with AGC and AVR loops. The two different controllers, (i) fuzzy logic controller and (ii) particle swarm optimization based PID controllers; are designed for both of the above power systems.

It have been presented that the response with fuzzy logic controller is better in terms of reduced settling time and minimum value of ISE error as compared to the response with controllers in [37, 14, 38]. However, the response of system with proposed PSO-PID controller is better to the fuzzy controller and controllers in [37, 14, 38].

In case of two-area power system, the PSO-PID based response is proven to be better in terms of reduced settling time and minimum ISE error as compared to fuzzy controller.

Appendix - A

The data for inter-connected system:

- Governor speed regulation: $R_1 = 0.051$, $R_2 = 0.065$

Table 8. Terminal voltage response analysis for interconnected power system

Mode	Controllers	Settling-time	ISE Error
Δv_{t1}	PSO-PID	20	83.11
	FLC	34	97.83
Δv_{t2}	PSO-PID	14	86.33
	FLC	32	97.35

- Frequency bias factors: $D_1 = 0.62$, $D_2 = 0.91$
- Inertia constant: $H_1 = 5$, $H_2 = 4$
- Governor time constant: $T_{g1} = 0.2$, $T_{g2} = 0.3$
- Turbine time constant: $T_{t1} = 0.5$, $T_{t2} = 0.6$
- Load disturbance: $\Delta p_{d1} = 0.2$, $\Delta p_{d2} = 0.2$

Appendix - B

The data used for AVR is given as:

Amplifier gain $K_A = 9$, its time constant $T_A = 0.1$, Exciter gain $K_E = 1$, Time-constant $T_E = 0.1$, Generator-gain $K_G = 1.0$ and its time constant $T_G = 1.0$, Sensor gain $K_R = 1$ and its time constant $T_R = 0.05$.

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