OPTIMAL ACTIVE AND REACTIVE POWER DISPATCH AND EXCITATION SYSTEM CONTROLLER DESIGN USING GENETIC ALGORITHM

التوزيع الأمثل للقدرة الفعالة و القدرة الغير فعالة و تصميم محكم لنظام الاثارة للمولد باستخدام خوارزم جينى

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ملخص:

مشكلة التشغيل الاقتصادي للشبكة تنقسم إلى جزئين. الجزء الأول يتعامل مع توزيع القدرة الفعالة الكلية بين المولدات. الجزء الثاني يتعامل مع توزيع القدرة الغير فعالة في الشبكة. هذه المشكلة هي مشكلة متعددة الأهداف. في هذا البحث يتم عرض حل أمثل لهذه المشكلة بجزأيها باستخدام خوار زم جيني. يتم تطبيق تلك الطريقة في الحل على نظام اختبار IEEE 14-bus. يتم أيضا في هذا البحث تصميم محكم أمثل لنظام الاثارة للمولد باستخدام خوار زم جيني.

Abstract: Power system economical operation consists of two aspects: active power regulation and reactive power dispatch. This multiobjective optimization problem is solved in this paper as two subproblems: P- and Q-problems. The solution is applied to an IEEE 14-bus system using Genetic Algorithm (GA). Additionally, an exciter system lead-lag controller and feedback compensator parameters are also optimally selected using GA.

Keywords: active power dispatch, reactive power dispatch, genetic algorithm, excitation system, feedback and feedforward control.

Symbols:

C_t : Total fuel cost.
C_i : Fuel cost of generating unit i.
n_g : number of generating units.
α_i , β_i, γ_i : coefficients of heat rate curves.
P_i : active generated power of unit i.
P_D : power demand
P_L : power loss.
$P_{i(min)}$, $P_{i(max)}$: min. and max. generated active power limits for unit i.
Q_{gi} : reactive power generated of unit i.
$Q_{gi(min)}$, $Q_{gi(max)}$: min. and max. generated reactive power limits for unit i.
V_D load bus voltage.
$V_{D(min)}$, $V_{D(max)}$: min. and max. limits of load bus voltage.
V : bus voltage in pu.
δ : phase angle in degrees.
P_{load} , P_{gen} : load and generated active power, respectively, in MW.
Q_{load} , Q_{gen} : load and generated reactive power, respectively, in MVAR
VCPI: Voltage Collapse Proximity Indicator.

1. INTRODUCTION

Power system economical operation consists of two aspects: active power regulation and reactive power dispatch. This forms a multiobjective global optimization problem of a large-scale industrial system. This problem is considered as two separate problems: P- and Q-problem. The P-problem is to regulate active power outputs of generators to minimize fuel costs. The Q-problem is to control voltages of PV (generator) buses and tap-settings of under load tap changing transformers besides using some VAR compensating elements to minimize network power loss. Solving these problems is subjected to a number of constraints such as limits on bus voltages, reactive and active power of power resources and number of controllable variables, etc [1].

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Controlling the generator excitation voltage through the automatic voltage regulation (AVR) system could control the voltage magnitudes at the PV buses. That is why it is important to design high performance excitation controllers to guarantee a good and fast response of the excitation system.

In this paper, the problem of power economical operation is solved in two stages using GA. The first stage deals with the P-problem and the second one deals with the Q-problem. A standard IEEE 14-bus system has been employed to carry out the simulation study. The GA performs very well in such a system for both active and reactive power dispatch and gives satisfactory results within a reasonable search time. Compared with the original IEEE 14-bus system described in [2], the proposed method gave much better results considering the network power loss and constraints violations. Finally, a GA search is made to determine the parameters of a lead-lag controller and a feedback compensator in the excitation system. The selected parameters offered a very good, stable and fast response of the excitation system.

2. GENETIC ALGORITHM

Genetic algorithms are inspired by the mechanism of natural selection, a biological process in which stronger individuals are likely be the winners in a competitive environment. They presume that the potential solution of problem is an individual and can be represented by a set of parameters. These parameters are regarded as the genes of a chromosome and can be structured by a string of values in binary form. A positive value, generally known as fitness value, is used to reflect the degree of "goodness" of the chromosome for solving the problem [3].

The algorithm starts from an initial population generated randomly. Using the genetic operations considering the fitness of a solution, which corresponds to the objective function for the problem generates a new generation is generated. The fitnesses of solutions are improved through iterations of generations. When the algorithm converges, a group of solutions with better fitnesses is generated, and the optimal solution is obtained [4,5].

Some of the main components of GAs are:

1. Coding: representing the problem at hand by strings.
2. Initialization: initializing the strings.
3. Fitness Evaluation: determining how fit is a string.
4. Selection: deciding who mates.
5. Crossover: exchanging information between two mates.
6. Mutation: introducing random information.

1. *Coding:*
   Each individual in the population consists of a number of parameters equal to the number of weak buses. Each parameter is binary coded to form the chromosome. The value of each parameter expresses the size of VAR source placed at the selected bus.
2. *Initialization:*
   Fair coin tosses are used to initialize all binary coded strings forming the unrated population
3. *Fitness Evaluation:*
   All strings are evaluated with the same fitness function. The fitness function incorporates the objective function, i.e., the total cost of the proposed capacitor placement scheme with the cost of real power loss and cost penalties if a string violates any of the constraints. In this way a rated population is formed and GA proceeds such that the fitness function is maximized and, consequently, the objective function is minimized.
4. *Selection:*
   The roulette-wheel selection scheme is used. Each slot on the wheel is paired with an individual in the population. The size of each slot is proportional to the corresponding individual fitness. In such a scheme, a fitter string receives a higher number of offspring and thus has a higher chance of surviving in the subsequent generation
5. *Crossover:*
   Given a crossover probability, simple crossover is performed to exchange information between strings. In the proposed algorithm single-point crossover is performed.
6. *Mutation:*
   Given a mutation probability, random alteration of genes in a string may occur For a binary coded string, a mutation represents a simple bit change.
7. *Convergence / Termination of the GA:*
   When the maximum allowable number of generations for the GA is reached the best solution found so far is returned.

Fig. 1 shows a complete cycle representing one generation of the search: [6]

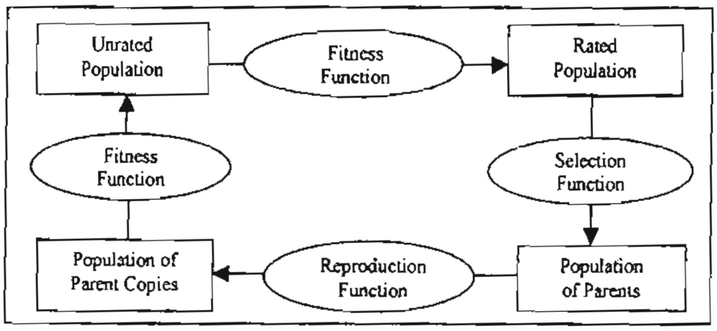


Fig. 1: General procedure for all evolutionary computations.

3. PROBLEM FORMULATION

a. P-Problem:

One type of bus in the power flow was the voltage-controlled bus, where the real power generation and voltage magnitude were specified The power flow solution provides the voltage phase angle and the reactive power generation. In practical power system, the power plants are not located at the same distance from the center of loads and their fuel costs are different. Also, under normal operating conditions, the generation capacity is more than the total load demand and losses Thus, there are many options for scheduling generation Production costing models are widely used in the electric power industry to forecast the cost of producing electricity. These forecast are used as inputs in financial planning, fuel management, and operational planning. The production cost over a given time interval is a random variable because it is dependent on several uncertain quantities such as the availability of generating units, load and fuel prices [7]. The power output of any generator should not exceed its rating nor should it be below that necessary stable operation. Thus, the generators are restricted to lie within minimum and maximum limits However, in a large interconnected network where power is transmitted over long distances with low load density data, transmission losses are a major factor and affect the optimum dispatch of generation. The economic dispatching problem is to minimize the overall generating cost C_i, which is a function of plant output [8]

$$C_t=\Sigma C_i=\Sigma(\alpha_i+\beta_i P_i+\gamma_i P_i^2)$$

Subjected to the constraint that the generation should equal total demands plus losses,

$$\Sigma P_i = P_D + P_L$$

Satisfying the inequality constraints, expressed as follows,

$$P_{i(min)} \le P_i \le P_{i(max)} \quad i=1,..,n_g$$

b. Q-Problem:

In an interconnected power system, the objective is to find the real and reactive power scheduling of each power plant in a way as to minimize the operating cost. This means that the generators real and reactive power are allowed to vary within certain limits so as to meet a particular load demand with minimum fuel cost [7] Reactive power dispatch is an optimization method to determine the reactive power required whose results allow some objective to be achieved. The control variables will be the terminal voltages of generators. The dependent variables are the reactive power of generators Q_g and the voltage of loads V_D.

The objective is to minimize the transmission real power losses which in turn minimizes the fuel cost of generators where the generated power includes both the power demand and power loss [9].

The objective function will be,

$$\text{Min } f_P = \text{Ploss}$$

Subjected to the following inequality constraints,

$$Q_{gi(min)} \le Q_{gi} \le Q_{gi(max)} \quad i=1,..,n_g$$

$$V_{D(min)} \le V_D \le V_{D(max)}$$

4. TEST RESULTS

The IEEE 14-bus system under study has four voltage controlled buses (bus 2, 3, 6 and 8). Table 1 contains the generators data.
The allowable limits for generator terminal voltage are E_g= 1.0 – 1.1 pu and the allowable limits of load bus voltage V_D = 0.95 – 1.05 pu.

a. First Stage (P-Problem):

The parameters chosen for the test were as follows:
Population size = 50
Max. generation = 50
Crossover probability = 0.9
Mutation probability = 0.001

The number of parameters is 5, expressing the number of generators including the generator at the slack bus.

b. Second Stage (Q-Problem):

The parameters chosen for the test were as follows:
Population size = 20
Max. generation = 20
Crossover probability = 0.9
Mutation probability = 0.001

The number of parameters are 4, expressing the voltages of the PV buses.
Table 2 shows a comparison of the results before and after active and reactive power dispatch. Fig. 2 shows the power loss in the system before and after power dispatch.

Table 1: Generators Data

No.	P_{min}	P_{max}	Q_{min}	Q_{max}	α	β	γ
1*	54.25	155	--	--	143.0288	10.7154	0.00473
2	15.2	76	-40	50	81.1364	13.3272	0.00876
3	15.2	76	0	40	81.1364	13.3272	0.00876
4	4	20	-6	24	118.9083	37.9637	0.01561
5	4	20	-6	24	118.9083	37.9637	0.01561

Table 2: Results Comparison

	Before dispatch	After dispatch
Min. load voltage	0.923	0.929
Max. load voltage	1.036	1.045
No. of V_D violations	4	1
No. of Q_g violations	4	2

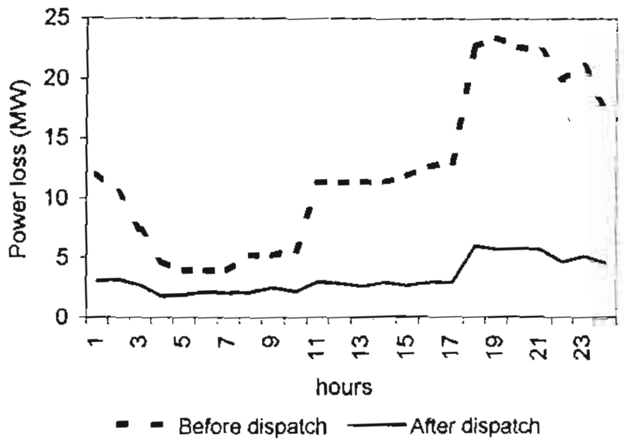


Fig. 2: Power loss through 24 hours

5. EXCITATION SYSTEM CONTROLLER DESIGN

Power system stability involves voltage stability in which a constant voltage can be restored and maintained even when changes in load occur. It also involves power stability in which the power perturbation that arises between generators that are operating in parallel is quickly suppressed and a constant power can be maintained It is necessary to sufficiently guarantee both types of stability, taking the most severe operating conditions into consideration.

The approaches to improve power system stability include methods of improving the main circuits by increasing the system voltage, construction of additional power transmission lines, installation of series capacitors, installation of SVC (static VAR compensator) and so on and the method of generator exciter control.

Although the main circuit improvement approach is a fundamental measure, the scale of reconstruction is very large. The control approach, on the other hand, makes it possible to extract the maximum capability of the generator by improving the control algorithm, which has a very large economical effect [10].

The basic function of an excitation system is to provide direct current to the synchronous machine field winding. In addition, the excitation system performs control and protective functions essential to the satisfactory performance of the power system by controlling the field voltage and there by the field current. Excitation systems comprised of elements with significant time delays have poor inherent dynamic performance This is particularly true of dc and ac type excitation systems Unless a very low steady-state regulator gain is used, the excitation control (through feedback of generator stator voltage) is unstable when the generator is on open circuit. Therefore, excitation control system stabilization, comprising either series or feedback compensation, is used to improve the dynamic performance of the control system [11]. A series lead-lag compensator is introduced in the AVR system to deal with the time delay (sluggishness) of the system. The transfer function of such a compensator will be as follows.

$G_c(s) = (1+sT_c) / (1+sT_b)$

To damp the oscillations and overshoot of the system dynamic response a feedback compensation is used. The most commonly used form of compensation is a derivative feedback having the following transfer function·

$G_F(s) = sK_f / (1+sT_f)$

Fig. 3 shows the overall excitation system and generator with the two compensator described

It is required now to determine the parameters of both compensators to satisfy a certain objective function.

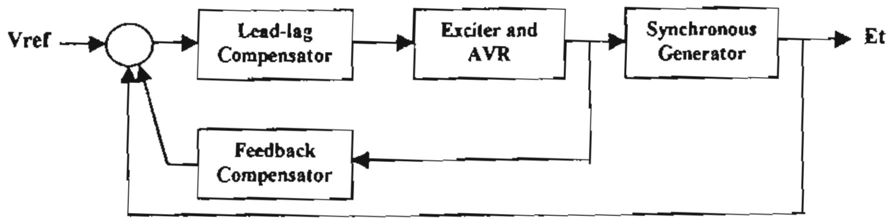


Fig. 3 : The overall excitation system and generator

6. CASE STUDY

The excitation system used for this application is the IEEE AC1A type described in [9]. The test parameters were as follows:

Population size = 140
Max. generation = 100
Crossover probability = 0.9
Mutation probability = 0.001

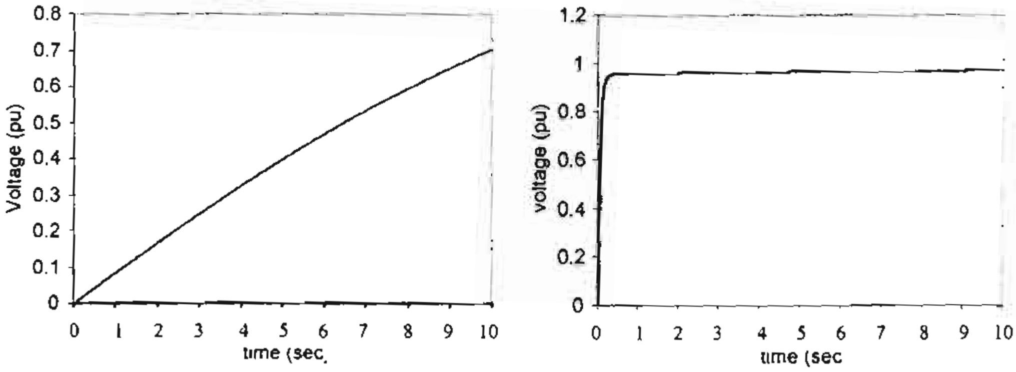
The objective was to minimize the error sum.

Obj. func = Σerror

The results were as follows:

$T_c = 116.41$ $T_b = 0.33$
$K_f = 0.0002$ $T_f = 9.96$

Fig. 4 shows the system step response before and after compensation.



a. before compensation b. after compensation

Fig. 4: Step Response of Excitation System

7. CONCLOSION

The optimal economical operation of power system is a global optimization problem of noncontinuous nonlinear function arising from large-scale industrial power systems. The conventional optimization algorithms have been applied with many mathematical assumptions, but not powerful enough to deal with this problem. The proposed genetic algorithm developed especially to be coupled with power flow computation has been evaluated on IEEE 14-bus network. The GA method is able to undertake global search with a fast convergence rate and a feature of robust computation. From simulation results, a great saving of active power and less violations has been obtained using GA. Also, a good transient and steady-state response excitation system has been accomplished by introducing feedback and feedforward compensators designed using GA.

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$$\mu_{\mathrm{Hp}}(R_p) = f(R_p\,;\, 1/s_1\,,\, 2\times s_1,\, 1) \tag{4}$$
$$\mu_{\mathrm{Lm}}(R_m) = f(R_m\,;\, 1/s_2\,,\, 2\times s_2,\, 0) \tag{5}$$
$$\mu_{\mathrm{Mm}}(R_m) = f(R_m\,;\, 1/(1.5\times s_2),\, 0,\, P_0/2) \tag{6}$$
$$\mu_{\mathrm{Hm}}(R_m) = f(R_m\,;\, 1/s_2\,,\, 2\times s_2,\, P_0) \tag{7}$$

$$\mu_{\mathrm{Lb}}(B) = f(B\,;\, 1/2\,,\, 4,\, 0) \tag{8}$$
$$\mu_{\mathrm{Mb}}(B) = f(B\,;\, 1/3\,,\, 0,\, 5) \tag{9}$$
$$\mu_{\mathrm{Hb}}(B) = f(B\,;\, 1/2\,,\, 4,\, 10) \tag{10}$$

$$\mu_{\mathrm{Ld}}(D) = f(D\,;\, 1/800\,,\, 1600,\, 0) \tag{11}$$
$$\mu_{\mathrm{Md}}(D) = f(D\,;\, 1/1200\,,\, 0,\, 2000) \tag{12}$$
$$\mu_{\mathrm{Hd}}(D) = f(D\,;\, 1/800\,,\, 1600,\, 4000) \tag{13}$$

$$\mu_{C_1}(R_c) = f(R_c\,;\, 1/s_3\,,\, 2\times s_3,\, M_0) \tag{14}$$
$$\mu_{C_2}(R_c) = f(R_c\,;\, 1/s_3\,,\, s_3,\, 0.25\times(P_0 - M_0) + M_0) \tag{15}$$
$$\mu_{C_3}(R_c) = f(R_c;\, 1/s_3\,,\, s_3,\, 0.5\times(P_0 - M_0) + M_0) \tag{16}$$
$$\mu_{C_4}(R_c) = f(R_c\,;\, 1/s_3\,,\, s_3,\, 0.75\times(P_0 - M_0) + M_0) \tag{17}$$
$$\mu_{C_5}(R_c) = f(R_c;\, 1/s_3\,,\, 2\times s_3,\, P_0) \tag{18}$$

where $s_1 = (1 - M_0)/5$, $s_2 = P_0/5$, and $s_3 = (P_0 - M_0)/9$.

The rule structure for the fuzzy capacity allocator is described in Table I.

TABLE I
Rule Structure for The Fuzzy Capacity Allocator

R_p	R_m	B	D	R_c	R_p	R_m	B	D	R_c	R_p	R_m	B	D	R_c
L	L	L	L	C_1	M	L	L	L	C_1	H	L	L	L	C_2
L	L	L	M	C_1	M	L	L	M	C_1	H	L	L	M	C_2
L	L	L	H	C_1	M	L	L	H	C_2	H	L	L	H	C_3
L	L	M	L	C_1	M	L	M	L	C_2	H	L	M	L	C_2
L	L	M	M	C_1	M	L	M	M	C_2	H	L	M	M	C_3
L	L	M	H	C_2	M	L	M	H	C_3	H	L	M	H	C_4
L	L	H	L	C_2	M	L	H	L	C_2	H	L	H	L	C_3
L	L	H	M	C_2	M	L	H	M	C_3	H	L	H	M	C_4
L	L	H	H	C_3	M	L	H	H	C_4	H	L	H	H	C_5
L	M	L	L	C_1	M	M	L	L	C_2	H	M	L	L	C_2
L	M	L	M	C_1	M	M	L	M	C_2	H	M	L	M	C_3
L	M	L	H	C_2	M	M	L	H	C_3	H	M	L	H	C_4
L	M	M	L	C_2	M	M	M	L	C_2	H	M	M	L	C_3
L	M	M	M	C_2	M	M	M	M	C_3	H	M	M	M	C_4
L	M	M	H	C_3	M	M	M	H	C_4	H	M	M	H	C_4
L	M	H	L	C_2	M	M	H	L	C_3	H	M	H	L	C_4
L	M	H	M	C_3	M	M	H	M	C_4	H	M	H	M	C_5
L	M	H	H	C_4	M	M	H	H	C_4	H	M	H	H	C_5
L	H	L	L	C_1	M	H	L	L	C_2	H	H	L	L	C_3
L	H	L	M	C_2	M	H	L	M	C_3	H	H	L	M	C_4
L	H	L	H	C_3	M	H	L	H	C_4	H	H	L	H	C_4
L	H	M	L	C_2	M	H	M	L	C_3	H	H	M	L	C_4
L	H	M	M	C_3	M	H	M	M	C_4	H	H	M	M	C_5
L	H	M	H	C_4	M	H	M	H	C_4	H	H	M	H	C_5
L	H	H	L	C_3	M	H	H	L	C_4	H	H	H	L	C_5
L	H	H	M	C_4	M	H	H	M	C_5	H	H	H	M	C_5
L	H	H	H	C_4	M	H	H	H	C_5	H	H	H	H	C_5

Larsen product inference method is assumed. In this method, the product membership value of each rule consequent is used. The rules are connected together using the *OR* connective before an appropriate control action is taken. The fuzzy capacity allocator assumes the Center of Area (CoA) deffuzzification method since it takes into account the union of all the contributions of the fired rules.

4. Fuzzy Admission Controller

The fuzzy admission controller decides to accept or reject a new call request based on not only the allocated capacity that was obtained from the previous stage but also the feedback performance measures represented by the evaluated cell loss probability (S_e), the queue length (q), and the queue length change rate (Δq) that describe the local dynamics of the difference between the arrival rate and the service rate.

After evaluating the ratio R_c in the fuzzy capacity allocator, the required capacity for a new cell (C_r) is obtained and subtracted from the total capacity (C_t) to show that if it is sufficient or not. On the other hand, when a call ends its service after connection or if it is rejected, its C_r is added to C_t. In addition, the cell loss for the class of the requested call is obtained from the performance evaluator and compared with the cell loss requirements defined in the QoS requirements during the call setup for that class. If the evaluated cell loss (S_e) is less than the required cell loss (S_r), then the procedure guarantees a satisfactory QoS.

The fuzzy input linguistic variables are C_t, S_e, q, Δq and the output linguistic variable is the decision O_d. The term sets for C_t, S_e, q, Δq are defined as T(C_t) = {Sufficient (S), Insufficient (IS)}, T(S_e) = {Less (L), More (M)}, T(q) = {Empty (E), Full (F)}, and T(Δq) = {Decrease (D), Increase (I)}; respectively. On the other hand, The term set for the output decision O_d is defined as T(O_d) = {Accept (A), Reject (R)}.

The universe of discourse of q ranges between 0 and the maximum buffer size K. The maximum possible negative and positive queue length change rate would be $-K_l$ and $+K_l$ where $K_l = ¼ \times K$. The range from $-K_l/2$ to $+K_l/2$ is a safety range provided to tolerate the dynamic behavior of Δq. In this sense, the universe of discourse of C_t ranges between $-C_l$ and $+C_l$ where $C_l = ½ \times C_t$. Because of the exponential wide range of cell loss probability (from 10^{-10} to 10^{0}), it is difficult to describe the universe of discourse. Hence, log(S_e) will be used and then the universe of discourse ranges from $-S_l$ to $+S_l$ where S_l =-5. The membership functions for T(C_t), T(S_e), T(q), and T(Δq) are defined as

$$\mu_{S}(C_t) = f(C_t ; 1/C_l , 1/2\times C_l , C_l) \tag{19}$$
$$\mu_{NS}(C_t) = f(C_t ; 1/C_l , 1/2\times C_l , -C_l) \tag{20}$$

$$\mu_{L}(S_e) = f(S_e ; 1/S_l , 1/2\times S_l , -S_l) \tag{21}$$
$$\mu_{M}(S_e) = f(S_e ; 1/S_l , 1/2\times S_l , S_l) \tag{22}$$

$$\mu_{E}(q) = f(q , 3/K , 2/3\times K , 0) \tag{23}$$
$$\mu_{F}(q) = f(q ; 3/K , 2/3\times K , K) \tag{24}$$

$$\mu_{D}(\Delta q) = f(\Delta q ; 1/K_l , 1/2\times K_l , -K_l) \tag{25}$$
$$\mu_{I}(\Delta q) = f(\Delta q ; 1/K_l , 1/2\times K_l , K_l) \tag{26}$$

On the other hand, the membership function of the output linguistic variable O_d is assumed to be a singleton function.

Table II describes the rule structure for the fuzzy admission controller.

TABLE II
Rule Structure for The Fuzzy Admission Controller

q	Δq	S_e	C_t	O_d	q	Δq	S_e	C_t	O_d	q	Δq	S_e	C_t	O_d
E	D	L	S	A	E	I	M	S	A	F	D	M	IS	R
E	D	L	IS	R	E	I	M	IS	R	F	I	L	S	R
E	D	M	S	A	F	D	L	S	A	F	I	L	IS	R
E	D	M	IS	R	F	D	L	IS	R	F	I	M	S	R
E	I	L	S	A	F	D	M	S	A	F	I	M	IS	R
E	I	L	IS	R										

The fuzzy admission controller assumes Larsen product inference method for the inference engine and Center of Area (CoA) defuzzification method for the defuzzifier.

5. Fuzzy QoS Controller

The fuzzy QoS controller classifies the services into three priority classes (I, II, and III) based on delay and loss priority jointly. In addition, the allocated capacity at the call time-scale is considered. The three different classes are subsequently subdivided into seven subclasses. Class I includes three Subclasses: IL assigns cells that have high sensitivity to loss (i.e., low loss constraints), ID for cells that have high sensitivity to delay, and IC for cells that have high sensitivity to both loss and delay. Similarly Class II includes three Subclasses IIL, IID, and IIC. While Class III is not divided since it has the lowest priority. The fuzzy QoS controller has three input linguistic variables: loss (S_r) and delay (d) constraints and required capacity (C_r).

The terms "Low", "Medium", and "High" are used to describe the loss-priority and thus, the term set for the loss-priority is defined as T(S_r) = {Low (Ls), Medium (Ms), High (Hs)}. In the same way, the delay-priority and the required capacity are defined as T(d) = {Low (Ld), Medium (Md), High (Hd)} and T(C_r) = {Low (Lc), Medium (Mc), High (Hc)}; respectively. On the other hand, The term set for the output class O_c is defined as T(O_c) = { IC, IL, ID, IIC, IIL, IID, III}.

As mentioned before, log(S_r) will be used and then the universe of discourse ranges from -10 to 0. The universe of discourse of d and C_r range from 0 to 1000 and from 0 to C_t ; respectively. The membership functions for T(log (S_r)), T(d) and T(C_r) are defined as follows

$$\mu_{Ls}(\log(S_r)) = f(\log(S_r);\ 1/2.5,\ 2,\ 0) \tag{27}$$
$$\mu_{Ms}(\log(S_r)) = f(\log(S_r);\ 1/2.5,\ 0,\ -5) \tag{28}$$
$$\mu_{Hs}(\log(S_r)) = f(\log(S_r);\ 1/2.5,\ 2,-10) \tag{29}$$

$$\mu_{Ld}(d) = f(d;\ 1/250,\ 200,\ 1000) \tag{30}$$
$$\mu_{Md}(d) = f(d;\ 1/250,\ 0,\ 500) \tag{31}$$
$$\mu_{Hd}(d) = f(d;\ 1/250,\ 200,\ 0) \tag{32}$$

$$\mu_{Lc}(C_r) = f(C_r;\ 1/(0.25\times C_t),\ 0.2\times C_t,\ 0) \tag{33}$$

$$\mu_{Mc}(C_r) = f(C_r; 1/(0.25\times C_t), 0, \tfrac{1}{2}\times C_t) \quad (34)$$
$$\mu_{Hc}(C_r) = f(C_r; 1/(0.25\times C_t), 0.2\times C_t, C_t) \quad (35)$$

It is assumed that the membership function of the output linguistic variable O_c is a singleton function.

The rule structure for the fuzzy QoS controller is describes in Table III.

TABLE III
Rule Structure for The Fuzzy QoS Controller

S_r	D	C_r	O_c	S_r	d	C_r	O_c	S_r	d	C_r	O_c
Ls	Ld	Lc	IIC	Ms	Ld	Lc	IIC	Hs	Ld	Lc	IL
Ls	Ld	Mc	III	Ms	Ld	Mc	III	Hs	Ld	Mc	IIL
Ls	Ld	Hc	III	Ms	Ld	Hc	III	Hs	Ld	Hc	IIL
Ls	Md	Lc	IIC	Ms	Md	Lc	IC	Hs	Md	Lc	IL
Ls	Md	Mc	III	Ms	Md	Mc	IIC	Hs	Md	Mc	IL
Ls	Md	Hc	III	Ms	Md	Hc	III	Hs	Md	Hc	IIL
Ls	Hd	Lc	ID	Ms	Hd	Lc	ID	Hs	Hd	Lc	IC
Ls	Hd	Mc	IID	Ms	Hd	Mc	ID	Hs	Hd	Mc	IC
Ls	Hd	Hc	IID	Ms	Hd	Hc	IID	Hs	Hd	Hc	IIC

Larsen product inference method is assumed. Depending on the problem at hand, the defuzzification method is chosen The Center of Maxima (CoM) deffuzzification method is chosen since it is appropriate for classification [21].

6. Fuzzy Buffer Manager

In the fuzzy buffer manager, the multi-threshold type is considered in order to implement multiple priority classes. That is for each priority class there is a threshold, and if the number of cells in the main buffer exceeds that threshold, the cells of that class are blocked. The fuzzy buffer manager determines the two threshold values T_1 and T_2 based on the cell arrival rates of the three classes that were defined in the fuzzy QoS controller. It is assumed that, each arriving cell is a cell of Class I (i.e., a high-priority cell) with probability R_I, a cell of Class II (i.e., a medium-priority cell) with probability R_{II}, or a cell of Class III (i.e., a low-priority cell) with probability $(1- R_I - R_{II})$ Thus, the arrival rates of the cells of the three classes are $\lambda_I = R_I\,\lambda$, $\lambda_{II} = R_{II}\,\lambda$, and $\lambda_{III} = (1- R_I - R_{II})\,\lambda$ where λ is the total load.

The fuzzy buffer manager uses R_I and R_{II} as the input linguistic variables and T_1 and T_2 as the output linguistic variables. The terms "Very Low", "Low", "Medium", "High", and "Very High" are used to describe both R_I and R_{II}. Thus, the term set for R_I is defined as T(R_I) = {Very Low (VL_1), Low (L_1), Medium (M_1), High (H_1), Very High (VH_1)}. Similarly, the term set for R_{II} is defined as T(R_{II}) = {Very Low (VL_2), Low (L_2), Medium (M_2), High (H_2), Very High (VH_2)}. On the other hand, the term sets "Very Small", "Small", "Medium", "Big", and "Very Big" are used to describe both T_1 and T_2 Thus the term set for T_1 is defined as T(T_1) = {Very Small (VS_1), Small (S_1), Medium (M_1), Big (B_1), Very Big (VB_1)}, and the term set for T_2 is defined as T(T_2) = {Very Small (VS_2), Small (S_2), Medium (M_2), Big (B_2), Very Big (VB_2)}

The membership functions of input and output linguistic variables are assumed to be triangular membership functions. The universe of discourse of the two probabilities R_I

and R_{II} are as usual ranges between 0 and 1. Assuming the buffer size is 100, the universe of discourse of T_I ranges between 0 to 90, and the universe of discourse of T_2 ranges between 10 to 100. These guarantee the portion of the buffer from 0 to 10 to be equipped by each of the three classes and from 90 to 100 for Class I only. The membership functions for T(R_I), T(R_{II}), T(T_I), and T(T_2) are defined as follows.

$$\mu_{VL_1}(R_I) = f(R_I;\ 1/0.25,\ 0,\ 0) \quad (36)$$
$$\mu_{L_1}(R_I) = f(R_I;\ 1/0.25,\ 0,\ 0.25) \quad (37)$$
$$\mu_{M_1}(R_I) = f(R_I;\ 1/0.25,\ 0,\ 0.5) \quad (38)$$
$$\mu_{H_1}(R_I) = f(R_I;\ 1/0.25,\ 0,\ 0.75) \quad (39)$$
$$\mu_{VH_1}(R_I) = f(R_I;\ 1/0.25,\ 0,\ 1.0) \quad (40)$$

$$\mu_{VL_2}(R_{II}) = f(R_{II};\ 1/0.25,\ 0,\ 0) \quad (41)$$
$$\mu_{L_2}(R_{II}) = f(R_{II};\ 1/0.25,\ 0,\ 0.25) \quad (42)$$
$$\mu_{M_2}(R_{II}) = f(R_{II};\ 1/0.25,\ 0,\ 0.5) \quad (43)$$
$$\mu_{H_2}(R_{II}) = f(R_{II};\ 1/0.25,\ 0,\ 0.75) \quad (44)$$
$$\mu_{VH_2}(R_{II}) = f(R_{II};\ 1/0.25,\ 0,\ 1.0) \quad (45)$$

$$\mu_{VS_1}(T_I) = f(T_I;\ 1/22.5,\ 0,\ 0) \quad (46)$$
$$\mu_{S_1}(T_I) = f(T_I;\ 1/22.5,\ 0,\ 22.5) \quad (47)$$
$$\mu_{M_1}(T_I) = f(T_I;\ 1/22.5,\ 0,\ 45) \quad (48)$$
$$\mu_{B_1}(T_I) = f(T_I;\ 1/22.5,\ 0,\ 67.5) \quad (49)$$
$$\mu_{VB_1}(T_I) = f(T_I;\ 1/22.5,\ 0,\ 90) \quad (50)$$

$$\mu_{VS_2}(T_2) = f(T_2;\ 1/22.5,\ 0,\ 10) \quad (51)$$
$$\mu_{S_2}(T_2) = f(T_2;\ 1/22.5,\ 0,\ 32.5) \quad (52)$$
$$\mu_{M_2}(T_2) = f(T_2;\ 1/22.5,\ 0,\ 55) \quad (53)$$
$$\mu_{B_2}(T_2) = f(T_2;\ 1/22.5,\ 0,\ 77.5) \quad (54)$$
$$\mu_{VB_2}(T_2) = f(T_2;\ 1/22.5,\ 0,\ 100) \quad (55)$$

Tables IV and V describe the rule structure for control of the two thresholds T_I and T_2; respectively. As can be seen in Tables IV and V, of the 25 possible rules, only 15 appear in the knowledge base of the fuzzy buffer manager. The remaining ten are not included as they would never be activated. For example, if R_I is VH_1 that means R_I is in the range between 0.75 and 1, which also means that R_{II} can not exceed 0.25, i.e., R_{II} can not be in L_2, M_2, H_2, or VH_2.

TABLE IV
Rule Structure for Control of T_I

R_I / R_{II}	VL_1	L_1	M_1	H_1	VH_1
VL_2	VB_1	B_1	M_1	S_1	VS_1
L_2	B_1	M_1	S_1	VS_1	
M_2	M_1	S_1	VS_1		
H_2	S_1	VS_1			
VH_2	VS_1				

TABLE V
Rule Structure for Control of T_2

R_I / R_{II}	VL_1	L_1	M_1	H_1	VH_1
VL_2	VB_2	B_2	M_2	S_2	VS_2
L_2	VB_2	B_2	M_2	S_2	
M_2	VB_2	B_2	M_2		
H_2	VB_2	B_2			
VH_2	VB_2				

The fuzzy buffer manager assumes Larsen product inference method for the inference engine and Center of Area (CoA) defuzzification method for the defuzzifier.

7. Simulation Results

Several results that present the behavior of the proposed FTCC are introduced. It is assumed that each input queue is modeled by *M/D/1* queueing model. The size of each input queue (K) is equal to 100 cells, whereas the two thresholds T_1 and T_2 are dynamic. The total link capacity (C_t) is 1 Gbps The number of multiplexed input sources is 32. Cells are served on the FCFS rule. The simulation is performed on a system running 10^6 slot times.

In each time slot, cells are discarded according to the two-threshold discarding policy. In order to guarantee fixed small delay for high delay sensitivity cells (Subclasses ID and IID), it is assumed that they are dropped if they are not serviced during two time slots. In addition, since Subclasses IC and IIC have higher delay sensitivity than Subclasses IL and IIL; respectively, it is assumed that they are dropped after four time slots. Otherwise, the cells remain in the buffer until transmitted in a following time slot.

The cell arrival processes of all service traffic in the simulations were as follows. The data sources are characterized by Poisson arrivals that are generated by generating the (independent, identical) exponentially distributed interarrival times. The cell generation process for a voice is assumed to be *ON/OFF* or *bursty* sources where the number of cells per burst has a geometric distribution with a mean of $E[x]$=5 cells, the duration of the idle phase has an exponential distribution with a mean of $E[s]$=0.14772 s, and the intercell time during a burst is t_c=0.016 s [9]. The *Video sources* are simulated using first order Autoregressive Markov Model. This model is simulate by the following difference equation:

$$\lambda(n) = a \ \ \lambda(n-1) + b \ \ w(n) \tag{56}$$

where, $\lambda(n)$ represents the source bit rate during the n^{th} frame, and $w(n)$ is a Gaussian random process having mean η and variance 1 As shown in [22], by matching the model with the corresponding real time source, the average value $\bar{\lambda}$ is then 0 52 bit/pixel. This gives the parameters in the autoregressive model of equation (56) as: a = 0.878, b = 0.11, and η = 0.58. Using this autoregressive model, video traffic is generated assuming that there are 30 frames/second and the picture is 500×500 pixels, then the maximum size of a frame is 250 000 pixels.

Since the data cells have medium loss sensitivity and low delay sensitivity, it is assumed for the arrival process of a data source that the log of loss constraints ranges between $10^{-6.5}$ and $10^{-3.5}$ and the delay constraints ranges between 700 and 1000 For the arrival process of a voice source, since the voice calls have low loss sensitivity and high delay sensitivity, it is assumed that the log of loss constraints ranges from 10^{-3} to 10^{0} and the delay constraints ranges between 0 and 300. For video sources, the video traffic has high loss sensitivity and medium delay sensitivity. Thus, it is assumed that the log of loss constraints ranges between 10^{-10} and 10^{-7} and the delay constraints ranges between 350 and 650.