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

التوزيع الأمثل للقدرة الفعلية والقدرة الفاصلة وتصميم متحكم لنظام الإثارة للمولد

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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:

\[ C_i \] : Total fuel cost.
\[ C_{i}^{k} \] : Fuel cost of generating unit \( i \).
\[ n_{i} \] : number of generating units.
\[ \alpha_{i} , \beta_{i} , \eta_{i} \] : coefficients of heat rate curves.
\[ P_{i} \] : active generated power of unit \( i \).
\[ P_{d} \] : power demand.
\[ P_{L} \] : power loss.
\[ P_{min} , P_{max} \] : min. and max. generated active power limits for unit \( i \).
\[ Q_{i} \] : reactive power generated of unit \( i \).
\[ Q_{min} , Q_{max} \] : min. and max. generated reactive power limits for unit \( i \).
\[ V_{P} \] : load bus voltage.
\[ V_{min} , V_{max} \] : min. and max. limits of load bus voltage.
\[ V_{i} \] : bus voltage in pu.
\[ \delta \] : phase angle in degrees.
\[ P_{load} , P_{load} \] : load and generated active power, respectively, in MW.
\[ Q_{load} , Q_{load} \] : 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 fittest 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.
5. Crossover: exchanging information between two mates.

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 even fitnesses 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.
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 systems, 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 forecasts 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 to enable stable operation. Thus, the generators are restricted to lie within minimum and maximum limits. However, in large interconnected networks 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, which is a function of plant output [8]

\[ C = \sum C_i = (1 + \alpha_i + \beta_i) (P_i + \gamma_i P_i^2) \]

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

\[ \sum P_i = P_L + P_L' \]

Satisfying the inequality constraints, expressed as follows,

\[ P_{(\min)} \leq P_i \leq P_{(\max)} \quad i = 1, \ldots, n \]

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 \( Q_e \) and the voltage of loads \( V_0 \).

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,

\[ \text{Min } \sum C_i = \frac{Q_e}{2} \]

Subjected to the following inequality constraints,

\[ Q_{(\min)} \leq Q_e \leq Q_{(\max)} \quad i = 1, \ldots, n \]

\[ V_{(\min)} \leq V_0 \leq V_{(\max)} \]
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 $E_g = 0.9 - 1.1 \, \text{pu}$ and the allowable limits of load bus voltage $V_D = 0.95 - 1.05 \, \text{pu}$.

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

<table>
<thead>
<tr>
<th>No.</th>
<th>$P_{min}$</th>
<th>$P_{max}$</th>
<th>$Q_{min}$</th>
<th>$Q_{max}$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
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<td>1</td>
<td>54.25</td>
<td>155</td>
<td>--</td>
<td>--</td>
<td>143.1288</td>
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<td>76</td>
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<td>50</td>
<td>31.1364</td>
<td>13.3272</td>
<td>0.00876</td>
</tr>
<tr>
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<td>15.2</td>
<td>76</td>
<td>0</td>
<td>40</td>
<td>31.1364</td>
<td>13.3272</td>
<td>0.00876</td>
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<td>4</td>
<td>4</td>
<td>20</td>
<td>-6</td>
<td>24</td>
<td>118.9083</td>
<td>37.9637</td>
<td>0.01561</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>20</td>
<td>-6</td>
<td>24</td>
<td>118.9083</td>
<td>37.9637</td>
<td>0.01561</td>
</tr>
</tbody>
</table>

Table 2: Results Comparison

<table>
<thead>
<tr>
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<th>Before dispatch</th>
<th>After dispatch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. load voltage</td>
<td>0.923</td>
<td>0.929</td>
</tr>
<tr>
<td>No. of $V_p$ violations</td>
<td>1.036</td>
<td>1.045</td>
</tr>
<tr>
<td>No. of $V_q$ violations</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
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 into account 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 hence 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:

\[
G_c(s) = \frac{(1 + sT_1)}{(1 + sT_2)}
\]

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:

\[
G_f(s) = sK_f (1 + sT_d)
\]

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.
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:

\[ \text{Obj. func.} = \sum \text{error} \]

The results were as follows:

- \( T_e = 116.41 \)  \( T_h = 0.33 \)
- \( K_f = 0.0002 \)  \( T_r = 9.96 \)

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

![Step Response of Excitation System](image)

a. before compensation  
b. after compensation

7. CONCLUSION

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.
8. REFERENCES

\[
\begin{align*}
\mu_{H_{rp}}(R_p) &= f\left( R_p ; 1/5, 2\times s_2, 1 \right) \\
\mu_{L_{am}}(R_m) &= f\left( R_m ; 1/82, 2\times s_2, 0 \right) \\
\mu_{M_{am}}(R_m) &= f\left( R_m ; 1/(1.5\times s_2), 0, P_0/2 \right) \\
\mu_{H_{am}}(R_m) &= f\left( R_m ; 1/s_2, 2\times s_2, P_0 \right) \\
\mu_{L_{b}}(B) &= f\left( B ; 1/2, 4, 0 \right) \\
\mu_{M_{b}}(B) &= f\left( B ; 1/3, 0, 5 \right) \\
\mu_{H_{b}}(B) &= f\left( B ; 1/2, 4, 10 \right) \\
\mu_{L_{d}}(D) &= f\left( D ; 1/800, 1600, 0 \right) \\
\mu_{M_{d}}(D) &= f\left( D ; 1/1200, 0, 2000 \right) \\
\mu_{H_{d}}(D) &= f\left( D ; 1/800, 1600, 4000 \right) \\
\mu_{C_{1}}(R_c) &= f\left( R_c ; 1/ s_3, 2\times s_3, M_0 \right) \\
\mu_{C_{2}}(R_c) &= f\left( R_c ; 1/ s_3, s_3, 0.25\times(P_0 - M_0) + M_0 \right) \\
\mu_{C_{3}}(R_c) &= f\left( R_c ; 1/ s_3, s_3, 0.5\times(P_0 - M_0) + M_0 \right) \\
\mu_{C_{4}}(R_c) &= f\left( R_c ; 1/ s_3, s_3, 0.75\times(P_0 - M_0) + M_0 \right) \\
\mu_{C_{5}}(R_c) &= f\left( R_c ; 1/ s_3, 2\times s_3, P_0 \right)
\end{align*}
\]

where \( s_1 = (1 - M_0) \div S \), \( s_2 = P_0 \div S \), and \( s_3 = (P_0 - M_0) \div 9 \).

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

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>Rule Structure for The Fuzzy Capacity Allocator</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_p )</td>
<td>( R_m )</td>
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</tbody>
</table>
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) defuzzification 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 ($S_c$), the queue length ($q_r$), and the queue length change rate ($\Delta q_r$) 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 ($C_c$) 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 cell ends its service after connection or if it is rejected, its $C_c$ 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 ($S_c$) is less than the required cell loss ($S_c^*$), then the procedure guarantees a satisfactory QoS.

The fuzzy input linguistic variables are $C_t$, $S_c$, $q_r$, $\Delta q_r$ and the output linguistic variable is the decision $D_q$. The term sets for $C_t$, $S_c$, $q_r$, $\Delta q_r$ are defined as $T(C_t) = \{\text{Sufficient (S), Insufficient (IS)}\}$, $T(S_c) = \{\text{Less (L), More (M)}\}$, $T(q_r) = \{\text{Empty (E), Full (F)}\}$, and $T(\Delta q_r) = \{\text{Decrease (D), Increase (I)}\}$, respectively. On the other hand, the term set for the output decision $D_q$ is defined as $T(D_q) = \{\text{Accept (A), Rej ect (R)}\}$.

The universe of discourse of $q_r$ ranges between 0 and the maximum buffer size $K$. The maximum possible negative and positive queue length change rate would be $-K$ and $+K$, where $K = \frac{1}{2} \times C_t$. The range from $-K/2$ to $+K/2$ is a safety range provided to tolerate the dynamic behavior of $\Delta q_r$. In this sense, the universe of discourse of $C_t$ ranges between $-C_t$ and $+C_t$, where $C_t = \frac{1}{2} \times C_t$. Because of the exponential wide range of cell loss probability (from $10^{-10}$ to $10^1$), it is difficult to describe the universe of discourse. Hence, log($S_c$) will be used and then the universe of discourse ranges from $-S_c$ to $-S_c$ where $S_c = S_c$. The membership functions for $T(C_t)$, $T(S_c)$, $T(q_r)$, and $T(\Delta q_r)$ are defined as

\begin{align*}
\mu_{S_t}(C_t) &= f(C_t; C_c, 1/2 \times C_t, C_t) \quad (19) \\
\mu_{S_{IS}}(C_t) &= f(C_t; 1/2 \times C_t, C_t, -C_t) \quad (20) \\
\mu_{L}(S_c) &= f(S_c; S_c, 1/2 \times S_c, S_c) \quad (21) \\
\mu_{IS}(S_c) &= f(S_c; 1/2 \times S_c, S_c, -S_c) \quad (22) \\
\mu_{L}(q_r) &= f(q_r; 3K/2, 2S_c \times K, 0) \quad (23) \\
\mu_{IS}(q_r) &= f(q_r; 3K/2, 0, 2S_c \times K) \quad (24) \\
\mu_{D}(\Delta q_r) &= f(\Delta q_r; 1K, 1/2 \times K, -K) \quad (25) \\
\mu_{IS}(\Delta q_r) &= f(\Delta q_r; 1/2 \times K, -K, K) \quad (26)
\end{align*}
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>
<thead>
<tr>
<th>$\Delta q$</th>
<th>$S_a$</th>
<th>$C_t$</th>
<th>$O_d$</th>
<th>$\Delta q$</th>
<th>$S_a$</th>
<th>$C_t$</th>
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<tbody>
<tr>
<td>E</td>
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<td>M</td>
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</table>

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 III, 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 ($S_a$) and delay ($d$) constraints and required capacity ($C_t$).

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 $T(S_a) = \{\text{Low (Ls)}, \text{Medium (Ms)}, \text{High (Hs)}\}$. In the same way, the delay-priority and the required capacity are defined as $T(d) = \{\text{Low (Ld)}, \text{Medium (Md)}, \text{High (Hd)}\}$ and $T(C_t) = \{\text{Low (Lc)}, \text{Medium (Mc)}, \text{High (Hc)}\}$, respectively. On the other hand, The term set for the output class $O_d$ is defined as $T(O_d) = \{\text{IC, IL, ID, IIC, IIID, IIID, III}\}$.

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

\[
\begin{align*}
\mu_{\text{Ls}} (\log(S_a)) &= f(\log(S_a); 1/2, 5, 2, 0) \\
\mu_{\text{Ms}} (\log(S_a)) &= f(\log(S_a); 1/2, 5, 0, -5) \\
\mu_{\text{Hs}} (\log(S_a)) &= f(\log(S_a); 1/2, 2, -10) \\
\mu_{\text{Ld}} (d) &= f(d; 1/250, 200, 1000) \\
\mu_{\text{Md}} (d) &= f(d; 1/250, 0, 500) \\
\mu_{\text{Hd}} (d) &= f(d; 1/250, 200, 0) \\
\mu_{\text{Lc}} (C_t) &= f(C_t; 1/0.25 \times C_t, 0.2 \times C_t, 0)
\end{align*}
\]
\[
\mu_{mc}(C_i) = f(C_i, 1/(0.25 \times C_i), 0, 0.25 \times C_i)
\]
\[
\mu_{mc}(C_i) = f(C_i, 1/(0.25 \times C_i), 0.2 \times C_i, C_i)
\]

It is assumed that the membership function of the output linguistic variable \(Q \in \) is a singleton function.

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

<table>
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<tr>
<th>(S_c)</th>
<th>(D)</th>
<th>(C)</th>
<th>(O_c)</th>
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<td>IID</td>
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<td>HD</td>
<td>HE</td>
<td>IIC</td>
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</table>

Larsen product inference method is assumed. Depending on the problem at hand, the defuzzification method is chosen. The Center of Maxima (CoM) defuzzification 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 \(\lambda\) 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 \(T(R_I) = \{\text{Very Low (VL)}, \text{Low (L)}, \text{Medium (M)}, \text{High (H)}, \text{Very High (VH)}\}\). Similarly, the term set for \(R_{II}\) is defined as \(T(R_{II}) = \{\text{Very Low (VL)}, \text{Low (L)}, \text{Medium (M)}, \text{High (H)}, \text{Very High (VH)}\}\). 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 \(T(T_1) = \{\text{Very Small (VS)}, \text{Small (S)}, \text{Medium (M)}, \text{Big (B)}, \text{Very Big (VB)}\}\), and the term set for \(T_2\) is defined as \(T(T_2) = \{\text{Very Small (VS)}, \text{Small (S)}, \text{Medium (M)}, \text{Big (B)}, \text{Very Big (VB)}\}\).

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 \( R_H \) are as usual ranges between 0 and 1. Assuming the buffer size is 100, the universe of discourse of \( T_1 \) 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 1 only. The membership functions for \( T(R_H) \), \( T(R_H) \), \( T(T_1) \), and \( T(T_2) \) are defined as follows.

\[
\begin{align*}
\mu_{VL_1}(R_H) &= f(R_H; 1/0.25, 0, 0) \\
\mu_{L_1}(R_H) &= f(R_H; 1/0.25, 0, 0.25) \\
\mu_{M_1}(R_H) &= f(R_H; 1/0.25, 0, 0.5) \\
\mu_{H_1}(R_H) &= f(R_H; 1/0.25, 0, 0.75) \\
\mu_{VL_2}(R_H) &= f(R_H; 1/0.25, 0, 1.0) \\
\mu_{L_2}(R_H) &= f(R_H; 1/0.25, 0, 0) \\
\mu_{M_2}(R_H) &= f(R_H; 1/0.25, 0, 0.25) \\
\mu_{M_3}(R_H) &= f(R_H; 1/0.25, 0, 0.5) \\
\mu_{H_2}(R_H) &= f(R_H; 1/0.25, 0, 0.75) \\
\mu_{VL_3}(R_H) &= f(R_H; 1/0.25, 0, 1.0) \\
\mu_{L_3}(T_1) &= f(T_1; 1/22.5, 0, 0) \\
\mu_{M_4}(T_1) &= f(T_1; 1/22.5, 0, 22.5) \\
\mu_{M_5}(T_1) &= f(T_1; 1/22.5, 0, 45) \\
\mu_{H_1}(T_1) &= f(T_1; 1/22.5, 0, 67.5) \\
\mu_{VL_1}(T_1) &= f(T_1; 1/22.5, 0, 90) \\
\mu_{VL_2}(T_2) &= f(T_2; 1/22.5, 0, 10) \\
\mu_{L_2}(T_2) &= f(T_2; 1/22.5, 0, 32.5) \\
\mu_{M_3}(T_2) &= f(T_2; 1/22.5, 0, 55) \\
\mu_{H_2}(T_2) &= f(T_2; 1/22.5, 0, 77.5) \\
\mu_{VL_3}(T_2) &= f(T_2; 1/22.5, 0, 100)
\end{align*}
\]

Tables IV and V describe the rule structure for control of the two thresholds \( T_1 \) 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 \( R_H \) is \( VH_1 \) that means \( R_H \) is in the range between 0.75 and 1, which also means that \( R_H \) can not exceed 0.25, i.e., \( R_H \) can not be in \( L_3 \), \( M_2 \), \( H_3 \), or \( VH_2 \).

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>Rule Structure for Control of ( T_1 )</th>
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<tr>
<td>( R_H )</td>
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<tr>
<td>( VL_2 )</td>
<td>( VB_1 )</td>
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<tr>
<td>( L_2 )</td>
<td>( B_1 )</td>
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<tr>
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<td>( VS_1 )</td>
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</table>

<table>
<thead>
<tr>
<th>TABLE V</th>
<th>Rule Structure for Control of ( T_2 )</th>
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</thead>
<tbody>
<tr>
<td>( R_H )</td>
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<tr>
<td>( VL_2 )</td>
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<tr>
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<td>( VB_1 )</td>
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<td>( VB_1 )</td>
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<tr>
<td>( VH_2 )</td>
<td>( VB_2 )</td>
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</table>
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 ($C$) 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 I and IID), it is assumed that they are dropped if they are not serviced during two time slots. In addition, since Subclasses IC and IID have higher delay sensitivity than Subclasses II and III, 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 $E[x]=0.14772$ s, and the intercell time during a burst is $\lambda_i=0.016$ s [9]. The Video sources are simulated using first order Autoregressive Markov Model. This model is simulate by the following difference equation:

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

where, $\lambda(n)$ represents the source bit rate during the $n^{th}$ frame, and $w(n)$ is a Gaussian random process having mean $\eta$ and variance 1. As shown in [22], by matching the model with the corresponding real time source, the average value $\lambda$ 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 $\eta = 0.58$. Using this autoregressive model, video traffic is generated assuming that there are 30 frames/second and the picture is $500 \times 500$ 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 $10^{-0.5}$ and $10^{-3.7}$ 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.