# Captive Power Management using Op-Amp based Fuzzy Controller

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*Abstract* – **There have been some studies reported in recent literature for power management of islanded power plants, ad hoc network etc., but most studies are confined to computer simulations only. The use of captive power is on the rise across the globe and most of the practical power plants are run sub-optimally by operators (albeit experienced ones). This calls for low-cost dedicated automatic controllers for the efficient management of captive power. This paper reports a novel practical implementation of a dedicated real-time Fuzzy Logic Controller (FLC) using low cost Operational Amplifiers (Op-Amps) based circuitry for the management of 125 kW of captive power available from a Diesel Generator Set (D. G. Set). A college campus has been chosen as the site for this implementation since it represents requirements typically suited for captive power use.**

## I. Introduction

Captive power refers to electric power generation from a unit set up by an organization for its exclusive consumption. A number of organizations are now increasingly relying on their own generation rather than on grid supply primarily for the reasons of inadequate grid supply as well as its poor quality and reliability.

Traditionally, the operation and management of D. G. sets in captive power plants is done manually. Experienced though, the plant operators are prone to all the pitfalls of manual control, and typically their inadequate decisions may not only lead to inefficient use of available captive power but also create dissatisfaction among its users. To obviate such shortcomings, it is natural to conceive Zadeh's suggested concept of Fuzzy Logic System in [6]-[9], [11] for such applications, which is capable of taking adequate decisions for the efficient management of captive power, as per the rule base suggested by expert opinions of the experienced D. G. Set operators.

This paper reports a practical implementation of real-time FLC based on Op-Amp circuitry [10], for the management of 125kW captive power available from D. G. Set, for a college campus. During power cuts the Campus is left with D. G. Set power of 125 kW to backup. For the undisturbed functioning of college and efficient use of remaining power, this FLC plays the role of automatic load shedding for specific area(s) in case of overload; otherwise there is no requirement of power cut(s).

The load shedding is done taking into account the time and the load at that point of time, sensed using clock and current transformer circuitry respectively. Analog FLC using Op-Amps is designed to make decisions to make efficient and appropriate use of captive power depending upon load requirement of various sections of the college and time at that instance for the smooth functioning of college.

## II. Captive Power Management Scenario

The importance of captive power can hardly be over emphasized. It is estimated that about 30% of the total energy requirement of the Indian industry is currently met through in-house power plants [5]. The estimates of captive power capacity in India alone are of the order of 20,000 MW. The state-wise captive capacity in 1998 is given in Table I. Based on the fuel type used for captive power generation about 45% of power generated is from steam, 40% from Diesel and 15% from Gas.

Captive power obtained from such natural fuel sources, if not managed and consumed efficiently is just wastage of our natural resources. Once in-house captive power plant is 'on', it will consume same amount of fuel regardless of usage of output power.

TABLE I.
COMPARISON OF INSTALLED & CAPTIVE CAPACITY STATE-WISE

| State | Installed Capacity (MW) | Captive Capacity (MW) |
|---|---|---|
| Andhra Pradesh | 8204 | 1220 |
| Assam | 1078 | - |
| Bihar | 4656 | 614 |
| Delhi | 1436 | - |
| Gujarat | 8376 | 1505 |
| Haryana | 882 | 335 |
| Himachal Pradesh | 3570 | 32 |
| Jammu & Kashmir | 1536 | 3 |
| Karnataka | 3462 | 1045 |
| Kerala | 1766 | 151 |
| Madhya Pradesh | 7173 | 1333 |
| Maharashtra | 11072 | 570 |
| Meghalaya | 239 | - |
| Orissa | 3243 | 1544 |
| Punjab | 2620 | 311 |
| Rajasthan | 2176 | 528 |
| Tamil Nadu | 8271 | 1107 |
| Uttar Pradesh | 12473 | 1240 |
| West Bengal | 6515 | 786 |
| Total | 89167 | 12322 |

***Source: Power Line Research***

Various authors have studied different schemes for islanding in industrial plants with captive power generation. Design considerations in islanding and load shedding schemes have been described in [1] along with a discussion of reliability aspects, and major benefits that accrue from interfacing power plants with SCADA.

Power management is a very important aspect of ad-hoc networks. With power management, the capacity, the throughput and battery lifetime could be increased, and latency could be reduced. But all of these advantages may be hindered depending on the power management employed and depending on the network configuration. The issues and advantages involved in the design of power control and management schemes are discussed in [2], along with a novel approach to power management by utilizing modern control theory to achieve the low-level power control. By simulations, it is shown in the cited paper that their new approach provides a more accurate and faster power control, than traditional power control.

In [12] Mendel explored how fuzzy set theory and fuzzy logic are helpful in handling the numeric data and linguistic knowledge simultaneously. He suggested the design approach to handle engineering problems through fuzzy logic.

In [4], design automation is discussed for making FPGA as programmed dedicated Fuzzy Logic Controller. One can generate program in VHDL to program an FPGA chip in accordance Fuzzy Logic and the system requirements and then use them at the appropriate place. Since such chips are working on circuitry which accepts and delivers only digital signals, so one has to convert real life analog signals into digital signals. There are now FPGA chips available in the market which have inbuilt Analog to Digital and Digital to Analog Converters but at the same time cost also increases.

None of the above mentioned works has contributed in direction of practical implementation of low cost FLC for the management of commonly available medium scale captive power systems such as D. G. set. This paper emphasizes the practical implementation of a low cost FLC based on analog circuitry for management of D. G. set captive power, with implications of lowering the cost of operation and the increased probability of satisfaction among its users.

## III. Network Layout for Power Distribution

### *A. Campus Layout*

The FLC designed here is meant for managing the captive power of 125kW of D. G. Set for a residential college campus. The site chosen for this case study & implementation is BRCM College of Engineering & Technology, Bahal, Bhiwani (Haryana), India. The layout of local power distribution sub-station is shown in Fig. 1.

The D. G. Set is located near the power distribution station, where mains supply is available from a transformer of 630 kVA rating and then distributed among various areas of the campus viz academic area, staff residential area, hostels, office air conditioners, sewage treatment plant tube-well etc. Separate distribution lines are laid down for these different parts of the college from the distribution point to the destination through 3Ø manual changeover of rating 415Volts and 320A to changeover mains to D. G. Set and vice versa.

### *B. Control Panel*

The college has a local power sub-station for the distribution of available power from either grid or D. G. Set among various sections of the college campus shown in the Fig. 1. It incorporates a control panel consisting of one main manual changeover for grid & captive and many others gear boxes for various sections.

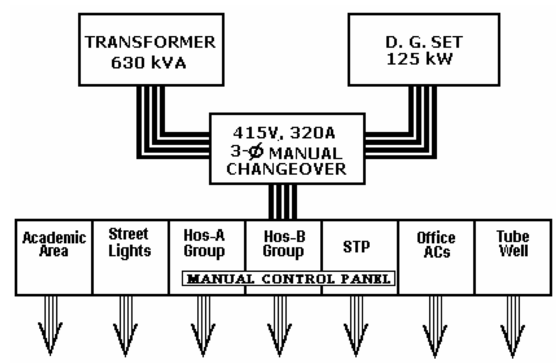


Figure 1. Layout of Power Distribution Control Room

The outputs of the control panel feed various sections of the college like Academic Area, Street Lights, Hostel Group-A, Hostel Group-B, Sewage Treatment Plant, Office ACs & Tube Well and traditionally operated manually. Operators have to take decisions to manage 125kW captive power among various areas, as best as he can, by cutting some area(s) in case of overload. A dedicated FLC based on Op-Amp circuitry is designed to make Manual Control Panel automated, intelligent and more efficient in power management.

## IV. Implementation of FLC using Op-Amp

Block diagram of FLC designed for the captive power management is shown in the Fig. 2. As per the requirement *TIME* is fuzzified by 'Fuzzifier-A', into three trapezoidal fuzzy sets, shown in the Fig. 3(a), using three different tunable circuits shown in the Fig. 5 and similarly *LOAD* is fuzzified by 'Fuzzifier-B' into five triangular fuzzy sets as shown in the Fig 3(b). Then rule base, con-

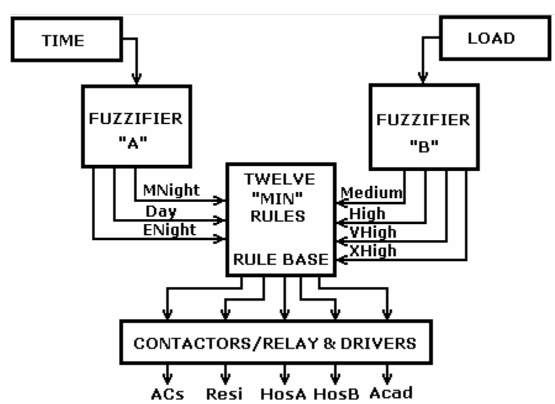


Figure 2. Block diagram of FLC for Automated Control Panel

sisted of twelve *MIN* operator circuits (shown in Fig. 6), takes them as fuzzy inputs and after aggregation using five MAX operators (shown in Fig. 7) gives five different commands as *Off Area* specifying area(s) to be cut.

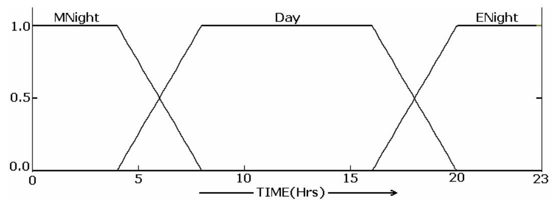

Figure 3(a) Fuzzily specified *TIME*

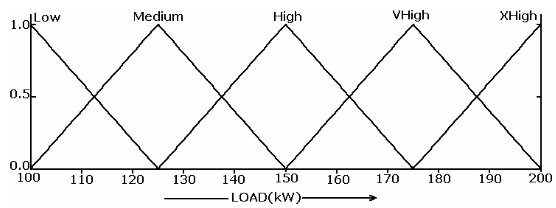

Figure 3(b) Fuzzily specified *LOAD*

Further if any output is having net membership value crosses the 50% of maximum possible, then corresponding relay will be trigger to cut-off respective area.

If microprocessor, micro-controller, PLC or FPGA chip etc, which accept or deliver digital signals only, are used for designing any FLC, then additional processes of Analog-to-Digital (A/D) conversion at the input and Digital-to-Analog (D/A) conversion at the output have to performed. This not only increases the hardware requirement but also increases the processing time that leads to a slower FLC and higher cost.

In this paper, all suggested modules are based on analog circuitry so that the task of A/D and D/A conversion can be avoided. Outputs in such circuitry can be checked after small propagation delay due to discrete components which further can be reduced if designed and fabricated in the form of analog ASIC (Application Specific Integrated Circuit).

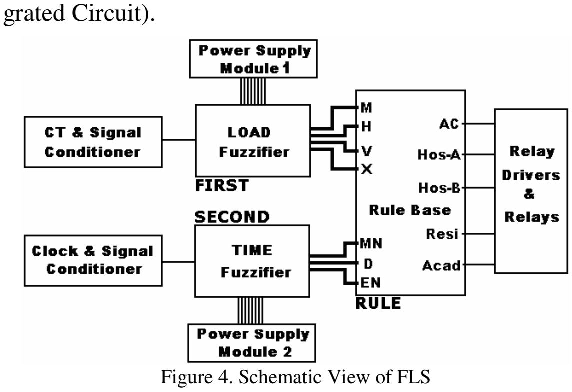

Figure 4. Schematic View of FLS

Schematic diagram of FLC is shown in the Fig. 4 consisting of two Fuzzifier modules, one rule base and two reference power supply modules.

*A. Fuzzifier Circuit*

The circuits for these membership functions are designed using operational amplifiers (Op-Amps). One general purpose circuit is shown below in the Fig.5. This circuit can be tuned for any of the above mentioned four possible shapes.

In this circuit, the Op-Amp U1A and U1B, in combination, constitute Z-shaped (Negative Slope) transfer curve, while Op-Amp U1C is responsible for the S-shape (Positive Slope) transfer curve and the last Op-Amp of the IC LM124 is nothing but a buffer. The input is common between both the parts while REF1 & REF2 refer to voltages specifying the start of slopes. In between, an AND gate combines both the parts and Double Clipper circuit is designed for the better shape of the curves. Resistors R3 & R4 are ganged together, while R12 & R13 are ganged together and used to tune the slopes of S and Z curves.

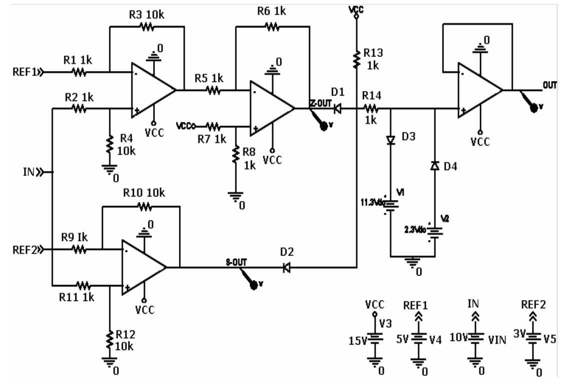

Figure 5. Tunable basic circuit for Triangular, Trapezoidal, S or Z-shaped membership function

Simulated results of the circuit tunable for various shapes of fuzzy sets are shown in Fig. 6. REF1 responsible for the start of slope of Z-shaped curve and REF2 for S-Shaped curve are 5 Volts and 3 Volts respectively. Slopes of both the curves are made equal and opposite simply by making R3=R4=R10=R12=10 kΩ.

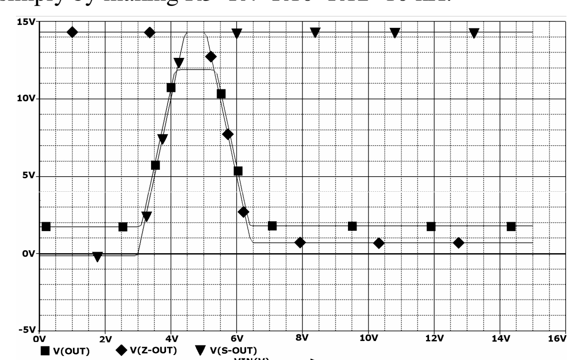

Figure 6. Simulated results for tunable circuit of Fig.5.

*B. Rule Base*

The *Sugeno-type* of inference system is preferred here giving command *Off Area* to cut one or more areas from five possibilities viz. *ACs* (Office ACs), *HosA* (Group-A of Hostels), *HosB* (Group-B of Hostels), *Resi* (Staff Residential Area) and *Acad* (Academic Blocks), based on the conditions of load and the time of the day. These conditions are tabulated in Table-II in the form of rule base matrix consisting of twelve minimum but adequate rules, based on the expert opinions of the D. G. set operators. The peak loads of various sections, namely *ACs*, *HosA*, *HosB*, *Acad* and *Resi* are 40kW, 40kW, 40kW, 80kW, 70kW respectively.

As it is obvious, if *LOAD* is *Low* no area should face power cut independently of the *TIME*. So, during designing of rule base *Low* fuzzy set is not included for making any decision. It can be observed here that, as per the requirement, multiple areas can face power cuts, which would happen when load far exceeds the captive power.

TABLE II.
RULE MATRIX

| | | TIME | | |
|---|---|---|---|---|
| | | **MNight** | **Day** | **ENight** |
| **LOAD** | **Medium** | ACs | HosA, | ACs |
| | **High** | ACs, Acad | ACs, HosA | ACs, HosB |
| | **VHigh** | ACs, Acad | ACs, HosA, HosB | ACs, HosA, HosB |
| | **XHigh** | ACs, Acad, Resi | ACs, HosA, HosB, Resi | ACs, HosA, HosB, Resi |

Antecedents of rules are combined using *MIN* operators for giving command, to cut-off some area(s), as *Off Area.* Triggering of relays / contactors at the output is done, if net aggregated (*MAX*) outputs from similar consequents cross the 50% of maximum membership value.

### C. Fuzzy Operators

The analog circuit for *AND* operation is designed using Diode-Resister logic as shown in the Fig. 7. Diode D3 and Op-Amp serve the purposes of buffering and removal of additional 0.7 Volts to deliver exactly the minimum possible at the output terminal 'z'.

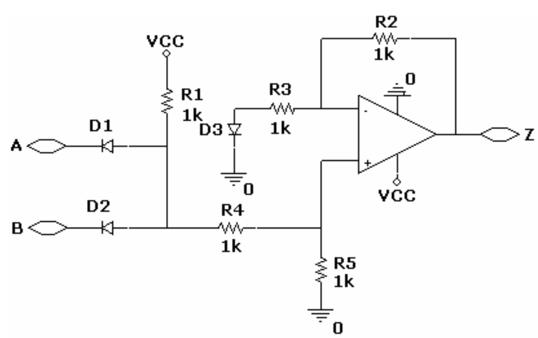


Figure 7. Fuzzy AND/MIN operator circuit

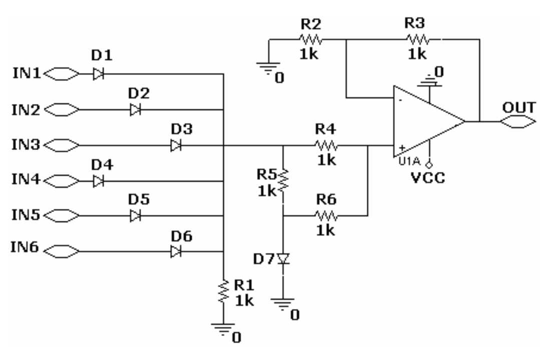


Figure 8. Fuzzy OR/MAX operator circuit

This Circuit that can do the function of *MAX* operation is shown in the Fig. 8. Diode D7 and Op-Amp serve the purpose of buffering and adding of 0.7 Volt, lost across diodes during Diode-Resistor OR operation.

Similar outputs of multiple rules are aggregated using *MAX* operator to give one output, maximum of all similar ones. Seeing the significant importance of the decision, that is the net membership value of output fuzzy set if crosses the 50% of its maximum then corresponding area relay will be triggered, to undergo power cut otherwise not. This function of checking the membership level is done simply changing the base resistor value of the transistor used for switching corresponding relay.

### D. Parameter Sensors

The input parameters, *TIME* and *LOAD* are sensed and converted into voltage signals by incorporating a Clock and a Current Transformer (CT) along with signal conditioning circuits respectively. The Universe of Discourses (UODs) of both input parameters, that is, the range of variations of outputs of sensing circuits are normalized into range of 1-11 Volts (net 10 Volts) to meet circuit requirements. Membership values are also normalized onto a range of 2-12 Volts (again a net of 10 Volts) instead of 0-1 because FLC circuits incorporate many PN diodes at various places in the circuits which lead to either addition or subtraction of 0.7 Volts. To eliminate these problems double clipper circuits have been used in Fuzzifier circuits and which further leads to such normalization requirements.

## V. RESULTS & CONCLUSIONS

### A. MATLAB Simulated Results

Before simulation on PSPICE and physical fabrication, the complete fuzzy response was simulated on the MATLAB platform [14]. There is a problem in MATLAB *Fuzzy Toolbox*, that multiple outputs cannot be specified for a single rule, as desired. So all these twelve rules are broken into twenty eight rules, each specifying single output, and then simulated for results. Results of simulation are shown in Fig. 8. Various possible outputs are numbered here as 1: *Resi*, 2: *Acad*, 3: *ACs*, 4: *HosB* and 5: *HosA*, for the convenience.

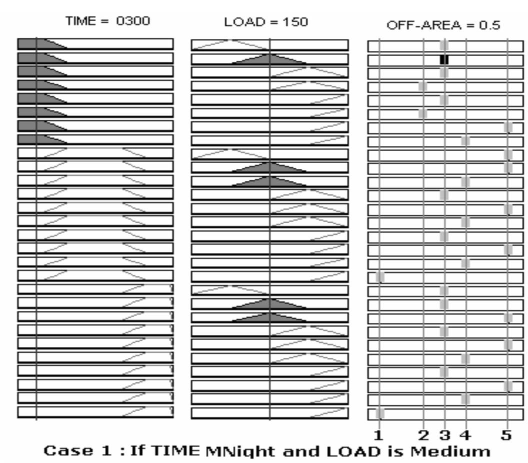


Figure 9(a). Fired rules for sample cases 1

If input *TIME* is *MNight* (0300 Hrs) & *LOAD* is *Medium* (150kW), then only one, output is having net output membership value more than the 50% of maximum, that is 3: *ACs* and hence only that area none other than *Office ACs* need to be switched off.

Now let consider the case of *Low LOAD*, as expected, if *LOAD* is *Low* (105kW), no area should be switched off, irrespective of the *TIME.* This is shown in Figure 8(b) as Case 2 that none of the output fuzzy set can obtain the membership value more than half the maximum and hence no decision to cut any area.

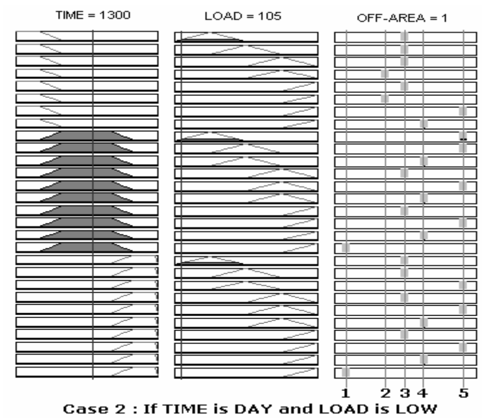

Figure 9(b). Fired rules for sample cases 2

Similarly, if *TIME* is *Day* (1300 Hrs) and *LOAD* is *XHigh* (196kW) then all areas are required to be switched

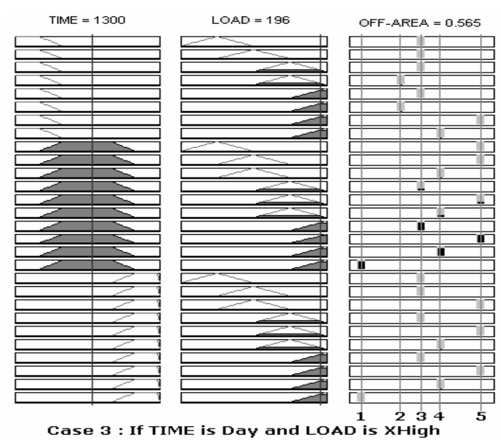

Figure 9(c). Fired rules for sample cases 3

off except 2: *Acad* shown in Case 3. In this case it can be observed that importance of the academic area during day time is much more than any other part of the college for

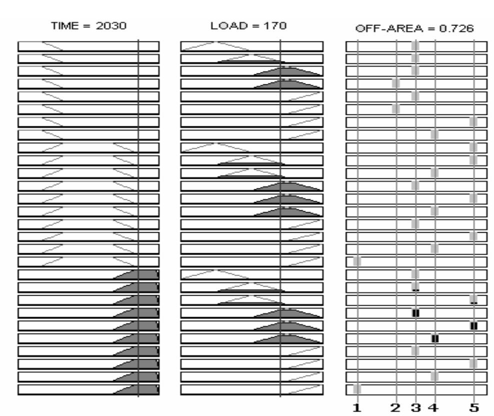

Figure 9(d). Fired rules for sample cases 4

its smooth functioning and hence similar decision is the output also of suggested FLC.

In the last simulated result, Case 4, *TIME* is *ENight* (2030 Hrs) and *LOAD* is *VHigh* (170KW) which recommends that residential and academics area should not face power cut but 3: *ACs*, 4: *HosB*, 5: *HosA* should be cut off.

### *B. PSPICE Simulated Results*

Input quantities *TIME* and *LOAD* as discussed earlier are normalized into the range of 1-11 Volts (net 10 Volts) for the reason of meeting the circuit requirements. For the sake of simulations on PSPICE [14] inputs are applied in the form of direct voltage signals of the range 1-11 Volts instead of sensor and signal conditioning circuit outputs. The simulated transfer curves generated as output of the 'DC Sweep' analysis of both the Fuzzifiers circuits are shown in the Fig.10(a) and Fig.10(b).

Simulated results on MATLAB and PSPICE shows that outputs of the designed FLC designed for captive power management are going to meet the system requirements.

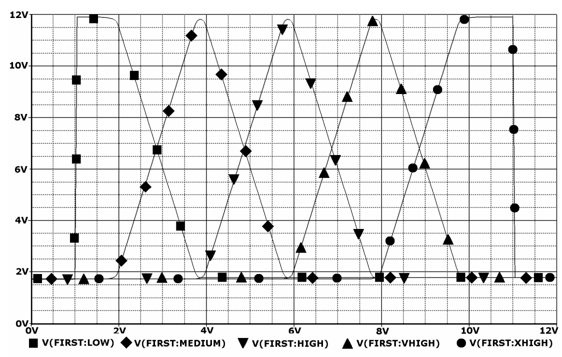

Figure 10(a). Transfer curves of *LOAD* Fuzzifier

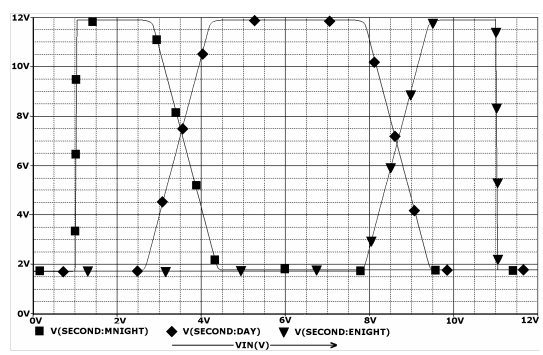

Fig. 10(b) Transfer curves of *TIME* Fuzzifier

One more analysis is considered here that is 'Time analysis', for the delay study shown in the Fig 11. This FLC is using tunable circuits which can be tuned for the various shapes of fuzzy sets and hence the same circuitry can be reused for the designing some other similar FLC for some other application. From that point of view, time analysis is important. Although this not so important here because here decision making is definitely required to be as fast as it can but triggering of relays has to be delayed and one after another to avoid sudden loading of D. G. Set which may lead to D. G. Set overload.

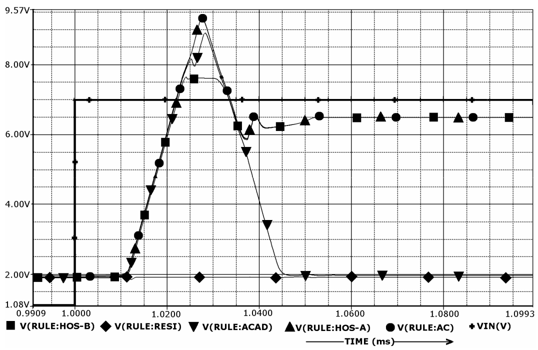

Figure 11. Time Delay after application of change at the input

## VI. FUTURE SCOPE

The FLC implemented for management of captive power for the college campus can be extended to management of load shedding at the regional power stations with improvements. In case of regional power stations, instead of low power relays / contactors, high power contactors or circuit breakers will have to be considered.

As discussed in the section II that industry is the biggest sector which prefers to rely on captive power than grid supply, and hence there exists the bigger scope of using such FLCs for the efficient use of captive power.

## ACKNOWLEDGMENT

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