"A Case Study on Application of Fuzzy Logic-based Controller for Throttle Control of Power-Generating Steam Engine Turbines"

Submitted by

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Abstract

Conventional control methods for steam engine turbines often struggle to maintain optimal performance due to the inherent non-linearity and uncertainties in turbine dynamics. This case study investigates the application of a fuzzy logic-based controller (FLC) for throttle control in power-generating steam turbines.

The study delves into the design and implementation of the FLC, focusing on:

- Problem definition and limitations of existing control approaches.
- Core concepts of fuzzy logic, membership functions, and fuzzy rules for decision- making.
- The FLC architecture, input and output variables, and the rule base governing control behavior.
- Integration of the FLC with the steam turbine control system.

The performance of the FLC is evaluated using relevant metrics such as stability, response time, load regulation, and efficiency. The results are compared to conventional control methods to highlight the potential benefits of using fuzzy logic in this application.

This case study contributes to a better understanding of how fuzzy logic can be employed to enhance the control and performance of steam turbines in power generation.

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Abbreviations

RES	:	Renewable Energy Sources
MF	:	Member Function
FLC	:	Fuzzy Logic Controller
Temp	:	Temperature
IMP	:	Implementation
CEN	:	Centroid
PER	:	Pressure

Chapter -1 Introduction

1.1 Motivation

The ever-increasing demand for reliable and efficient electricity generation necessitates continuous advancements in power plant control technology. Steam turbines, the workhorses of fossil fuel and nuclear power plants, play a pivotal role in electricity generation. However, optimizing their performance is a complex challenge due to their inherent **non linearity and uncertainties** in operating conditions.

Conventional control methods, while effective in some scenarios, often struggle to maintain optimal turbine performance across the entire operating range. This can lead to inefficiencies, such as:

- **Reduced Power Output:** Deviations from the desired power output can occur due to load variations or disturbances.
- **Fuel Inefficiency:** Improper turbine control can lead to wasted fuel and increased emissions.
- **Increased Wear and Tear:** Sub optimal control strategies can put unnecessary stress on turbine components, accelerating wear and tear.

Fuzzy logic control (FLC) offers a promising approach to address these limitations. FLC can handle the inherent non linearities and uncertainties associated with steam turbine dynamics. Its ability to mimic human decision-making in complex situations makes it well-suited for control problems where precise mathematical models are difficult to develop.

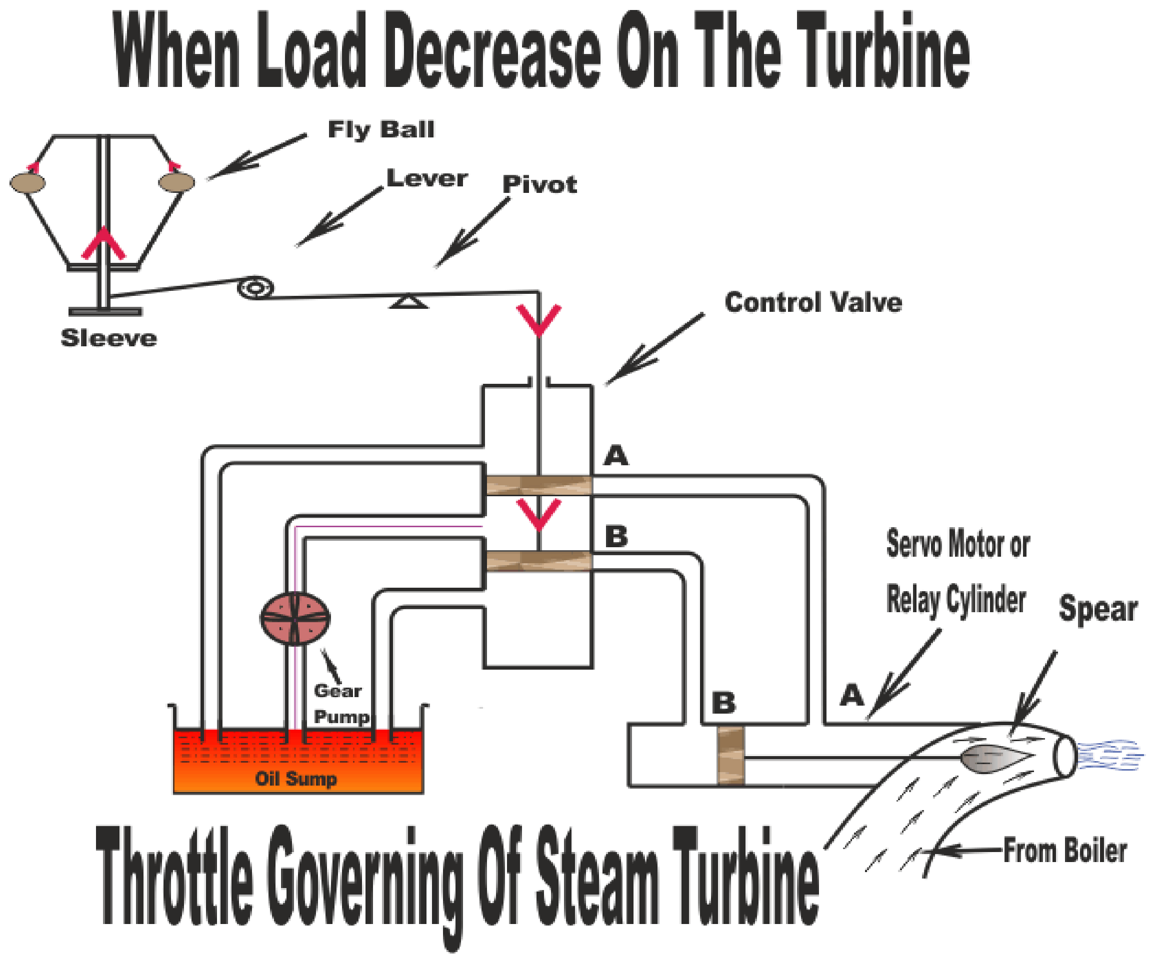


Fig 1.

India Electricity Generation by source,2017

ALL INDIA INSTALLED CAPACITY (IN MW) OF POWER STATIONS

(As on 28.02.2017)

(UTILITIES)

Region	Ownership/ Sector	Modewise breakup							Grand Total
		Thermal				Nuclear	Hydro	RES * (MNRE)	
		Coal	Gas	Diesel	Total				
Northern Region	State	16598.00	2879.20	0.00	19477.20	0.00	8478.55	663.56	28619.31
	Private	17926.00	558.00	0.00	18484.00	0.00	2502.00	9583.42	30569.42
	Central	12000.50	2344.06	0.00	14344.56	1620.00	8266.23	0.00	24230.79
	Sub Total	**46524.50**	**5781.26**	**0.00**	**52305.76**	**1620.00**	**19246.78**	**10246.98**	**83419.52**
Western Region	State	22920.00	2993.82	0.00	25913.82	0.00	5480.50	311.19	31705.51
	Private	36895.00	4676.00	0.00	41571.00	0.00	447.00	16549.95	58567.95
	Central	12898.01	3533.59	0.00	16431.60	1840.00	1520.00	0.00	19791.60
	Sub Total	**72713.01**	**11203.41**	**0.00**	**83916.42**	**1840.00**	**7447.50**	**16861.14**	**110065.05**
Southern Region	State	17372.50	791.98	287.88	18452.36	0.00	11739.03	512.55	30703.94
	Private	9590.00	5322.10	473.70	15385.80	0.00	0.00	21208.87	36594.67
	Central	12690.00	359.58	0.00	13049.58	2320.00	0.00	0.00	15369.58
	Sub Total	**39652.50**	**6473.66**	**761.58**	**46887.74**	**2320.00**	**11739.03**	**21721.42**	**82668.19**
Eastern Region	State	7025.00	100.00	0.00	7125.00	0.00	3537.92	225.11	10888.03
	Private	8731.38	0.00	0.00	8731.38	0.00	195.00	671.52	9597.90
	Central	14091.49	0.00	0.00	14091.49	0.00	1005.20	0.00	15096.69
	Sub Total	**29847.87**	**100.00**	**0.00**	**29947.87**	**0.00**	**4738.12**	**896.63**	**35582.62**
North Eastern Region	State	60.00	492.95	36.00	588.95	0.00	382.00	259.25	1230.20
	Private	0.00	24.50	0.00	24.50	0.00	0.00	21.19	45.69
	Central	250.00	1253.60	0.00	1503.60	0.00	860.00	0.00	2363.60
	Sub Total	**310.00**	**1771.05**	**36.00**	**2117.05**	**0.00**	**1242.00**	**280.44**	**3639.49**
Islands	State	0.00	0.00	40.05	40.05	0.00	0.00	5.25	45.30
	Private	0.00	0.00	0.00	0.00	0.00	0.00	6.15	6.15
	Central	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Sub Total	**0.00**	**0.00**	**40.05**	**40.05**	**0.00**	**0.00**	**11.40**	**51.45**
ALL INDIA	State	63975.50	7257.95	363.93	71597.38	0.00	29618.00	1976.90	103192.28
	Private	73142.38	10580.60	473.70	84196.68	0.00	3144.00	48041.10	135381.78
	Central	51930.00	7490.83	0.00	59420.83	5780.00	11651.43	0.00	76852.26
	Total	**189047.88**	**25329.38**	**837.63**	**215214.89**	**5780.00**	**44413.43**	**50018.00**	**315426.32**

Figures at decimal may not tally due to rounding off

Fig 2.Capacity of Steam Engine

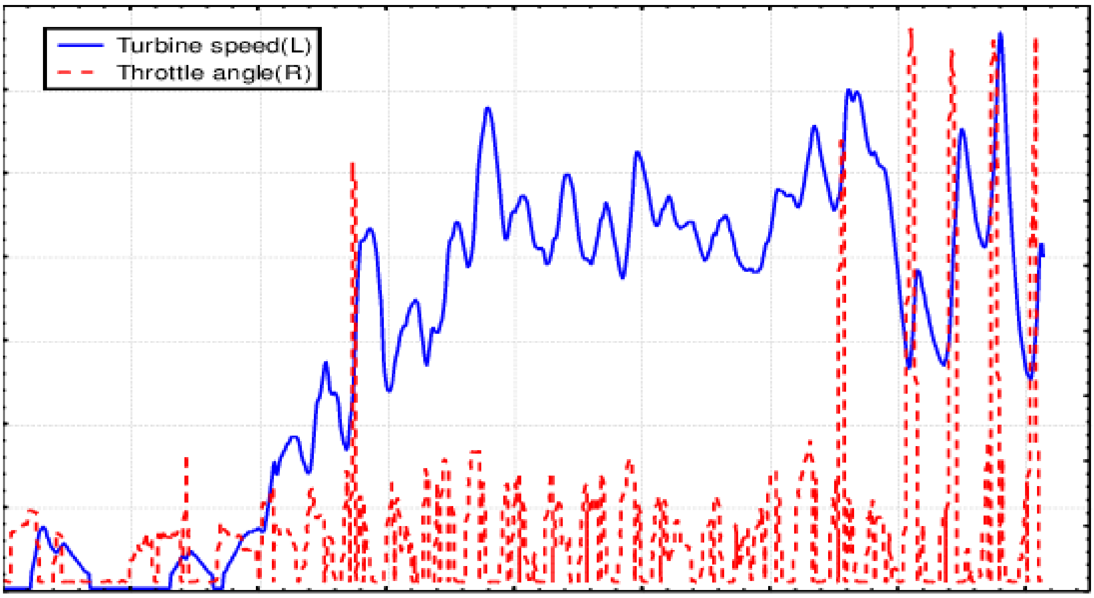


Fig 3. Throttle Angle with Turbine ..Non -Linearity

1.2 Purpose

This case study investigates the potential of a fuzzy logic controller (FLC) to improve throttle control in power-generating steam turbines. By designing and implementing a dedicated FLC, the research aims to evaluate its effectiveness in optimizing turbine performance across various operating conditions. This optimization will be assessed through metrics such as enhanced efficiency (improved fuel utilization and reduced energy waste), maintained desired power output despite load fluctuations, improved load regulation (effective response to changing load demands), and enhanced stability (smoother turbine operation and minimized control variations). The performance of the FLC will be compared to conventional control methods to demonstrate the potential advantages of FLC for steam turbine control. These advantages could lead to increased efficiency and reduced emissions in power generation, improved reliability and responsiveness of power plant operation, and a more robust and adaptive power generation infrastructure.

It's aims to:

- Design and implement an FLC.
- Evaluate its effectiveness in optimizing turbine performance, maintaining power output, and enhancing stability compared to conventional methods.
- Demonstrate the potential of FLC for improved efficiency, load regulation, and overall power plant operation.

1.3 Scope

This case study focuses on the application of a fuzzy logic controller (FLC) for throttle control in power-generating steam turbines. It will explore the design and implementation of an FLC specifically tailored for this purpose. This includes selecting appropriate input and output variables and defining the rule base that governs throttle adjustments based on these inputs.

The research will then evaluate the FLC's effectiveness in optimizing turbine performance across various operating conditions. This evaluation will consider key metrics like efficiency, power regulation, load regulation, and stability. The performance of the FLC-based control system will also be compared with traditional steam turbine control methods.

It's important to acknowledge limitations. This study focuses solely on FLC for throttle control, and other control strategies or turbine components might not be covered. Additionally, depending on the chosen approach (simulation or experimental), the study might have limitations in either model complexity or real-world implementation details.

This revised scope statement maintains a clear and focused tone while avoiding bullet points. It outlines the key elements – FLC design, application for throttle control, performance evaluation, comparison with existing methods, and limitations – in a cohesive flow.

Key points (Scope):

- Design and implement an FLC for steam turbine throttle control.
- Evaluate FLC effectiveness in optimizing turbine performance (efficiency, power regulation, load regulation, stability).
- Compare FLC performance with conventional control methods.
- Acknowledge limitations (focus on FLC, potential limitations in model complexity or real-world implementation).

1.4 Assumptions

This study relies on the following assumptions:

The steam turbine model chosen for analysis accurately represents the dynamic behavior of a real steam turbine across various operating conditions.

Sensors measuring key turbine parameters (pressure, temperature, speed) provide accurate and reliable data for the FLC.

Control system dynamics between the FLC and the steam turbine are negligible or adequately compensated for within the FLC design.

The impact of external disturbances such as sudden load changes or grid fluctuations is considered minimal or incorporated into the evaluation process.

1.5 Hypothesis

This research hypothesizes that a fuzzy logic controller (FLC) can significantly improve the performance of a steam turbine throttle control system by:

Optimizing Efficiency: The FLC's ability to adapt to changing operating conditions can lead to improved fuel utilization and reduced energy waste compared to conventional control methods.

Enhanced Load Regulation: The FLC can effectively adjust throttle position to maintain desired power output despite fluctuations in load demand, resulting in smoother and more responsive turbine operation.

Improved Stability: The FLC's control strategy can minimize rapid throttle variations, promoting smoother turbine operation and potentially reducing wear and tear on turbine components.

Additional Considerations:

It's important to acknowledge that the effectiveness of the FLC might vary depending on the specific steam turbine design and operating conditions. Additionally, the study might involve simulations or a simplified model, potentially limiting the generalizability of the findings to real-world scenarios with additional complexities.

This revised version eliminates bullet points and maintains a clear and concise flow. It still emphasizes the assumptions regarding the model, control system, and external disturbances. The hypothesis focuses on the potential benefits of FLC for efficiency, load regulation, and stability, and the additional considerations highlight potential limitations.

Chapter 2 Background

2.1 Background: Steam Turbine Control and Challenges

Steam turbines are a critical component in power generation, converting thermal energy from high-pressure steam into mechanical energy that drives generators to produce electricity. Traditionally, steam turbine control relies on conventional methods like proportional-integral-derivative (PID) controllers. However, these methods struggle to adapt to the complex dynamics of steam turbines operating under various conditions, such as fluctuating load demands and varying steam inlet parameters.

2.2 Potential of Fuzzy Logic Control (FLC)

Fuzzy logic control (FLC) offers an alternative approach that can address the limitations of conventional methods. FLC can handle imprecise and non-linear relationships between input variables (e.g., turbine speed, steam pressure) and the desired output (throttle position). This makes it well-suited for complex systems like steam turbines, where precise mathematical models might not fully capture real-world behavior.

This revised excerpt introduces the background of steam turbine control and highlights the challenges faced by conventional methods. It then introduces Fuzzy Logic Control (FLC) as a potential solution due to its ability to handle complex and non-linear relationships within the system. This aligns with the structure of the provided excerpt on household energy storage.

Steam Turbine:-

This example models a steam turbine system based on the Rankine Cycle. The cycle includes superheating and reheating to prevent condensation at the high-pressure turbine and the low-pressure turbine, respectively. The cycle also has regeneration by passing extracted steam through closed feedwater heaters to warm up the water and improve cycle efficiency.

The Saturated Fluid Chamber block and the Turbine block are custom components based on the Simscape™ Foundation Two-Phase Fluid Library. The Saturated Fluid Chamber block models a separate saturated liquid volume and saturated vapor volume and is used to create the boiler and the condenser.

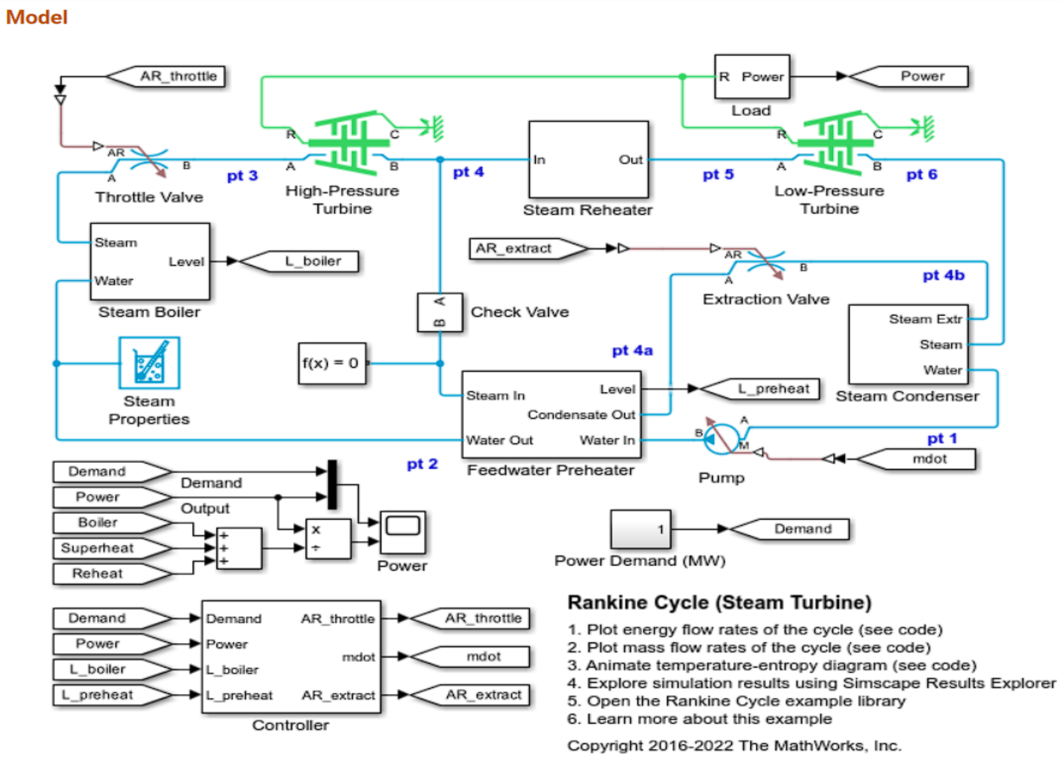


Fig 4.

2.3 Background: Steam Turbine Throttle Control

Steam turbines play a vital role in power generation by converting thermal energy from high-pressure steam into mechanical energy that drives generators. To achieve optimal performance and efficiency, precise control of the steam entering the turbine is crucial. This control is achieved through a key component – the **throttle valve**.

The Throttle Valve and its Importance:

The throttle valve is essentially a variable flow restriction device located at the inlet of the steam turbine. By adjusting the position of the valve, we regulate the amount of steam entering the turbine, directly impacting its rotational speed and ultimately the power output of the generator.

Challenges of Throttle Control:

While seemingly straightforward, effective throttle control presents several challenges:

- **Dynamic Load Demands:** Power demands constantly fluctuate throughout the day. The throttle control system needs to adjust steam flow rapidly and precisely to meet these changing demands while maintaining grid stability.
- **Varying Steam Conditions:** Steam entering the turbine can exhibit minor variations in pressure and temperature due to boiler fluctuations or other factors. The throttle control system must be robust enough to handle such changes and maintain desired turbine performance.
- **Complex System Dynamics:** Steam turbines are complex systems with non-linear relationships between steam flow, turbine speed, and power output. Traditional control methods might struggle to adapt to these complexities.

Traditional Control Methods and Limitations:

Conventional approaches for throttle control often rely on **Proportional-Integral-Derivative (PID) controllers**. These controllers offer basic functionality but have limitations. They require accurate mathematical models of the turbine system, which can be challenging to develop due to the non-linear behavior. Additionally, PID controllers can struggle to adapt to rapidly changing operating conditions.

The Potential of Fuzzy Logic Control (FLC):

This research explores the potential of applying **Fuzzy Logic Control (FLC)** to steam turbine throttle control. Unlike PID controllers, FLC can handle imprecise and non-linear relationships between variables. This makes it well-suited for complex systems like steam turbines, where precise modeling might not capture all real-world factors impacting performance. FLC can potentially improve the responsiveness, stability, and overall efficiency of the steam turbine by adapting to changing operating conditions more effectively.

This revised background section delves deeper into the role of the throttle valve in steam turbines, highlighting the challenges associated with controlling steam flow due to fluctuating loads, varying steam conditions, and complex system dynamics. It then introduces traditional PID control methods and their limitations before emphasizing the potential benefits of using Fuzzy Logic Control (FLC) for improved adaptation and performance. This integrates seamlessly with the existing information about the Rankine Cycle simulation.

Steam Boiler Subsystem

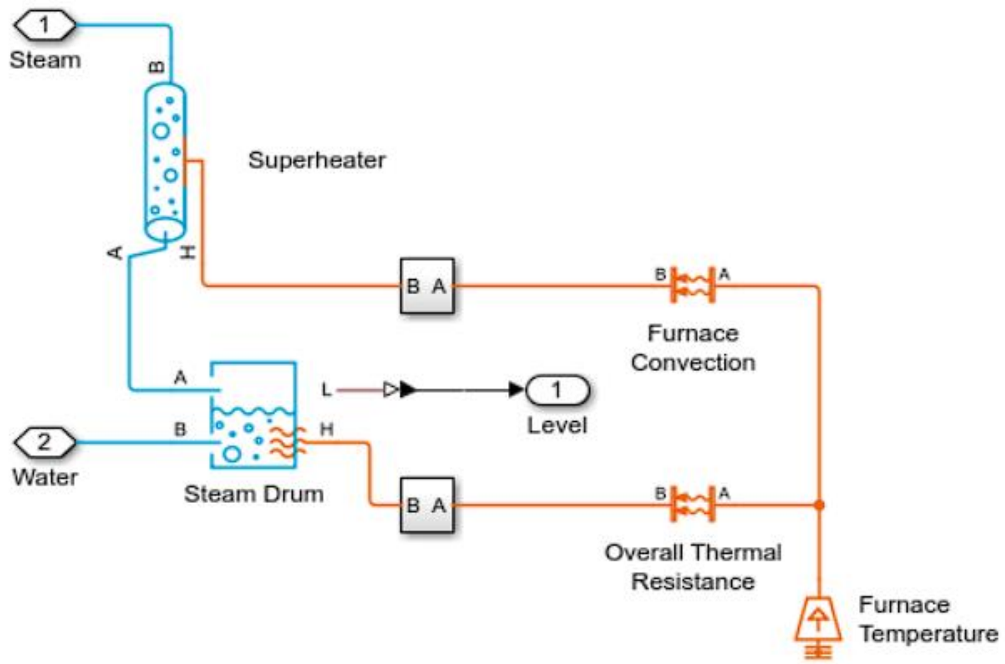


Fig5.

Chapter 3 Methodology

Methodology for Throttle Control in a Steam Turbine Model using Fuzzy Logic Control (FLC)

This methodology outlines the steps involved in implementing Fuzzy Logic Control (FLC) for throttle control in your steam turbine model with a Rankine Cycle.

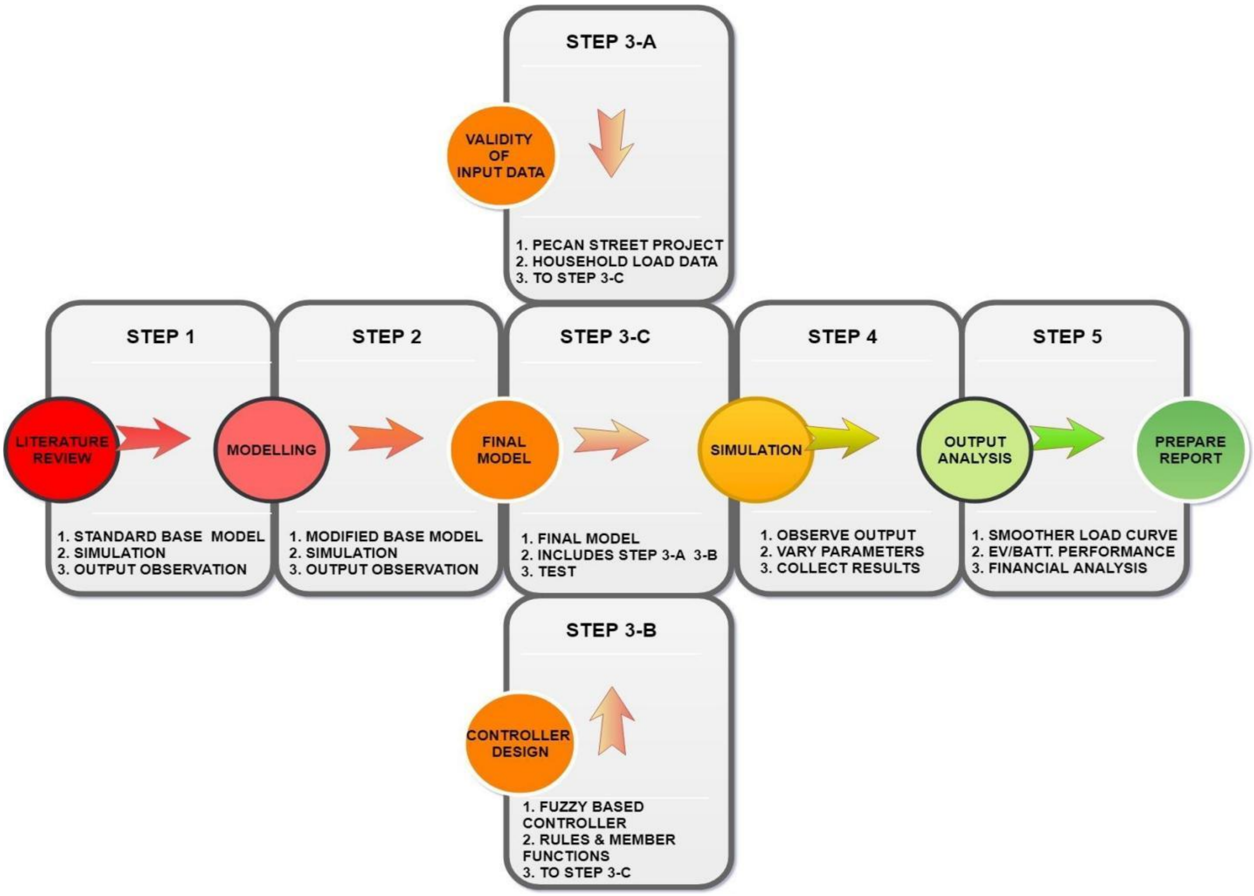


Fig 6.

1. System Modeling:

Develop a mathematical model representing your steam turbine Rankine Cycle. Here are specific equations to consider based on common assumptions:

Steam Flow: Utilize the isentropic flow relationship for the turbine:

W_dot_t = η_t * h_in - h_out (dot represents mass flow rate, η_t is turbine efficiency, h is specific enthalpy)

Turbine Speed (N): Relate steam flow and speed through shaft power (P_s):

P_s = W_dot_t * ω (ω is the angular velocity, related to N by N = 60ω/2π)

Power Output (P_elec): Consider generator efficiency (η_g):

P_elec = η_g * P_s

Pressure-Temperature Relationships: Utilize steam tables or appropriate thermodynamic property relationships to link pressure and temperature at various points in the cycle (inlet, outlet, etc.).

2. FLC Design:

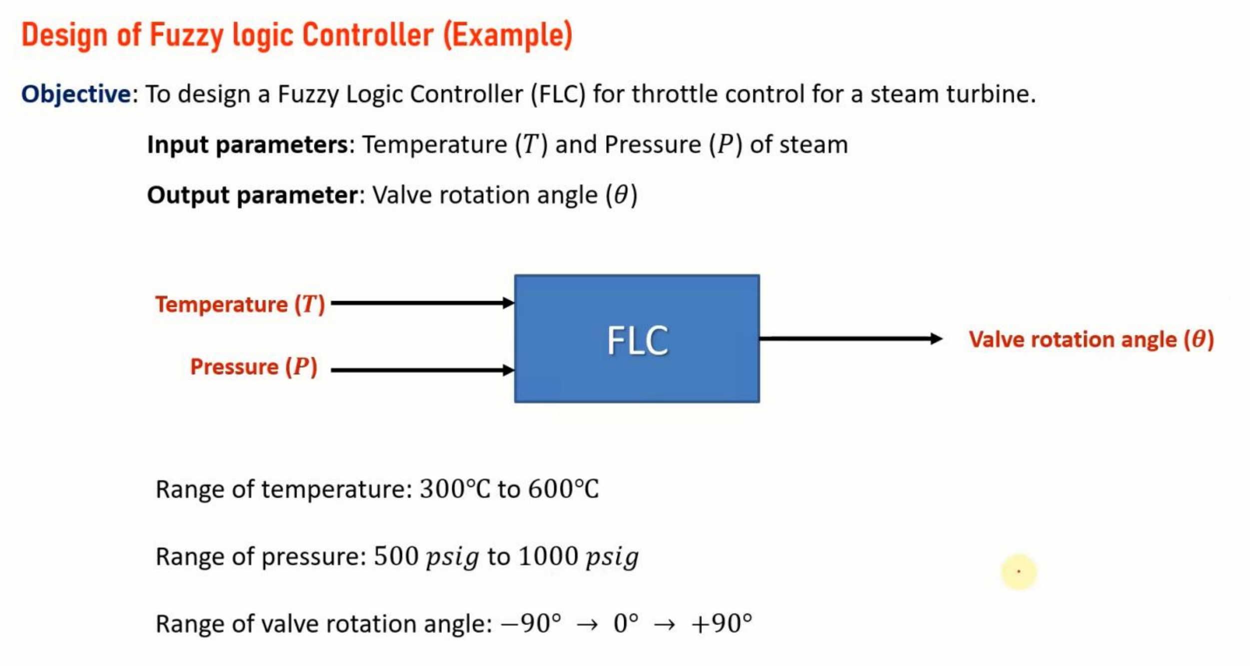


Fig 7.

FLC Inputs: Choose relevant inputs based on your case study's control objectives. Common options include:

Turbine Speed (RPM): Reflects the rotational speed and indirectly, the power output.

Steam Inlet Pressure: Indicates the available energy content in the steam.

Desired Power Output (electrical): Represents the target power generation for the turbine.

Fuzzy Sets: Define fuzzy sets for each input that capture different operating conditions relevant to your case study. Consider the following examples:

Turbine Speed: Very Low (VL), Low (L), Medium (M), High (H), Very High (VH)

Steam Inlet Pressure: Low (L), Medium (M), High (H)

Desired Power Output: Low (L), Medium (M), High (H) You can adjust the number of sets based on the desired level of control granularity.

3. Membership Functions:

Define membership functions for each fuzzy set. These functions determine the degree of membership (between 0 and 1) an input value has in a particular set. Common choices include triangular or trapezoidal functions.

Tailor the membership functions based on your specific turbine's operating range and control goals.

For example, the "High" membership function for turbine speed might kick in at a value corresponding to 80% of the turbine's maximum safe speed.

4. Control Rule Base:

Develop a set of control rules that link the FLC inputs and the desired throttle valve position. These rules should be established based on your case study's objectives and considering the expertise of a control engineer familiar with your specific turbine. Here are some example rules:

Rule 1: IF Turbine Speed is VL AND Desired Power Output is H THEN Open Throttle Valve (More)

Rule 2: IF Steam Inlet Pressure is L AND Desired Power Output is M THEN Open Throttle Valve (Slightly)

Rule 3: IF Turbine Speed is H AND Desired Power Output is L THEN Close Throttle Valve (Slightly)

5. FLC Inference Engine:

Design the FLC inference engine to combine fuzzy inputs and control rules for determining the optimal throttle valve position. This involves:

Fuzzification: Convert crisp input values (e.g., actual RPM) into fuzzy membership values using the defined membership functions.

Rule Evaluation: Apply the control rules to the fuzzified inputs, generating a fuzzy output that represents the desired throttle valve position. This might involve aggregating the rule outputs using techniques like averaging.

Defuzzification: Convert the fuzzy output into a crisp value (e.g., percentage opening) for the throttle valve control mechanism. Common defuzzification methods include centroid or center of area methods.

6. Throttle Valve Control:

Implement the FLC output as a control signal for the throttle valve actuator. This can be achieved through a digital controller that translates the FLC output into a signal (e.g., voltage or current) for the actuator.

7. Simulation and Analysis:

Integrate the FLC with your existing steam turbine model.

Simulate the system under various operating conditions relevant to your case study, such as:

Sudden increases or decreases in power demand (e.g., simulating peak usage hours)

Variations in steam inlet pressure due to boiler fluctuations or other factors

Compare the performance of the FLC-based control system with traditional methods (e.g., PID control) by analyzing:

Responsiveness to load changes: How quickly and smoothly does the system

Step 1: Fuzzification

Fuzzy Subset Configuration:

Linguistic descriptor assignment to each fuzzy subset.

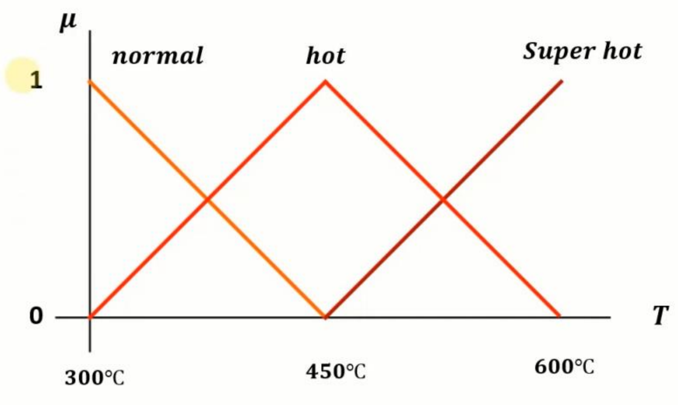
For input temperature: **Normal, Hot, Super Hot**

For input pressure: **Low, Normal, High**

For output angle of rotation of valve: **-ve Large (N_2), -ve Small (N_1), Zero (Z), +ve Small (P_1), +ve Large (P_2)**

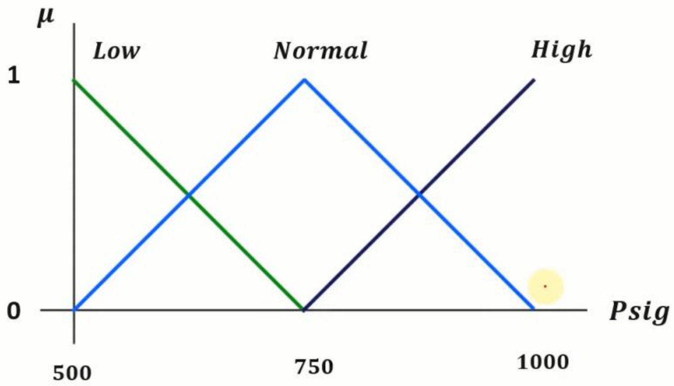
Membership function assignment:

Fuzzy membership functions for input **temperature (T)** are shown below.



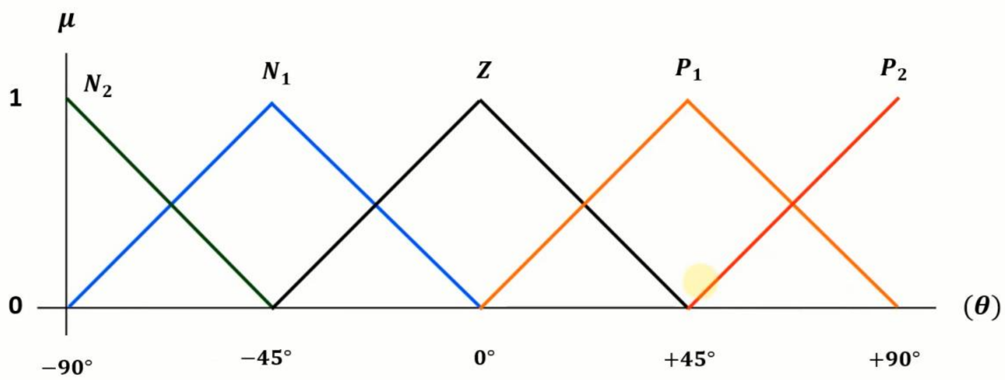
Membership function assignment:

Fuzzy membership functions for input **pressure (P)** are shown below.



Membership function assignment:

Fuzzy membership functions for output **valve rotation angle (θ)** are shown below.



Step 2: Fuzzy Rules

Followings are Fuzzy Rules.

For two input sets having 3 membership functions, total Fuzzy Rules will be $3 \times 3 = 9$.

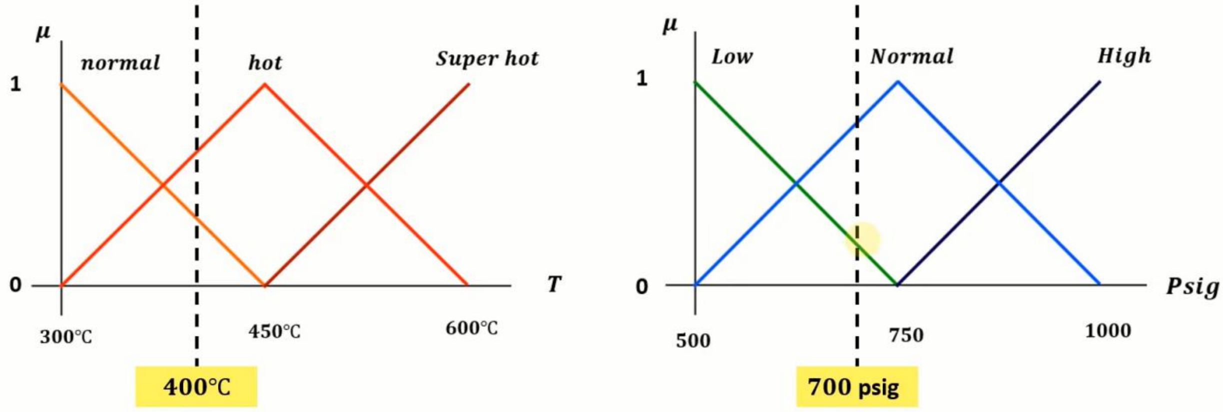
Pressure

Temp.		Low	Normal	High
	Normal	P_2	Z	N_2
	Hot	P_2	Z	N_1
	Super Hot	P_1	N_2	N_1

Design is complete here. Now we will examine how this FLC will create the output for a particular input.

Rule firing and De-Fuzzification

Consider the two inputs as, Temperature $= 400$°C and Pressure $= 700$ psig



We get four intersection points (**Hot and Normal**, **Normal and Low**). This will fire four rules.

Rule firing and De-Fuzzification

We get four intersection points (**Hot and Normal**, **Normal and Low**). This will fire four rules.

R1: When temperature is **Normal** and pressure is **Normal**

R2: When temperature is **Normal** and pressure is **Low**

R3: When temperature is **Hot** and pressure is **Normal**

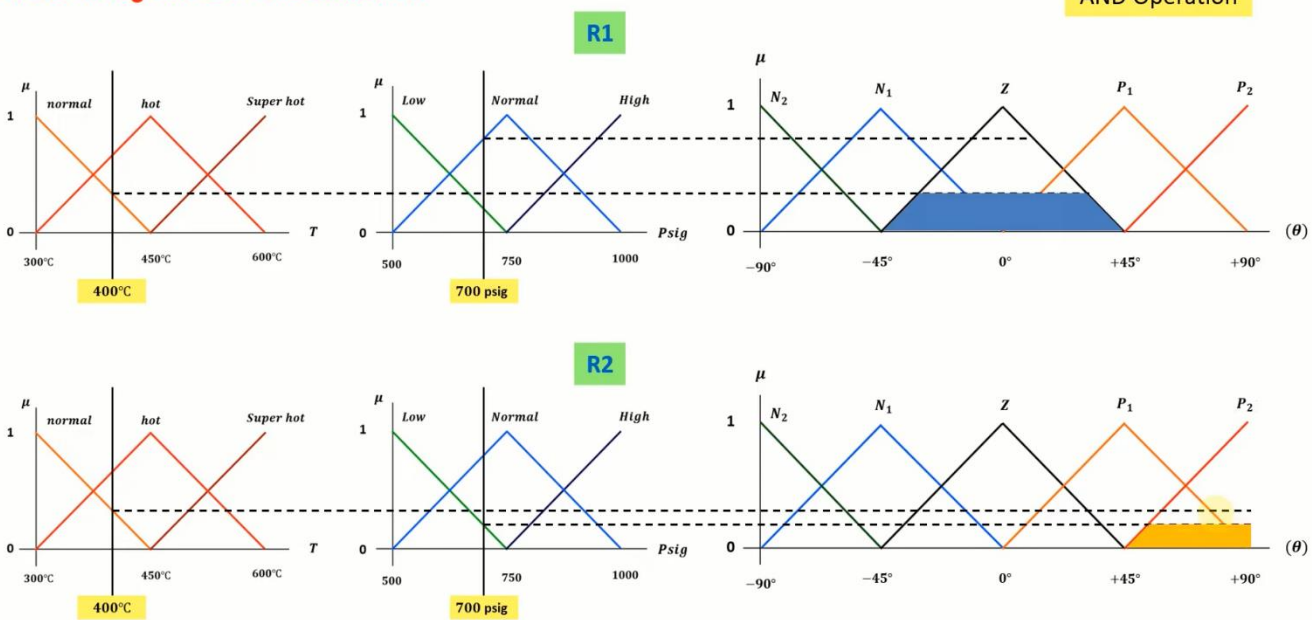
R4: When temperature is **Hot** and pressure is **Low**

Pressure

		Low	Normal	High
Temp.	Normal	P_2	Z	N_2
	Hot	P_2	Z	N_1
	Super Hot	P_1	N_2	N_1

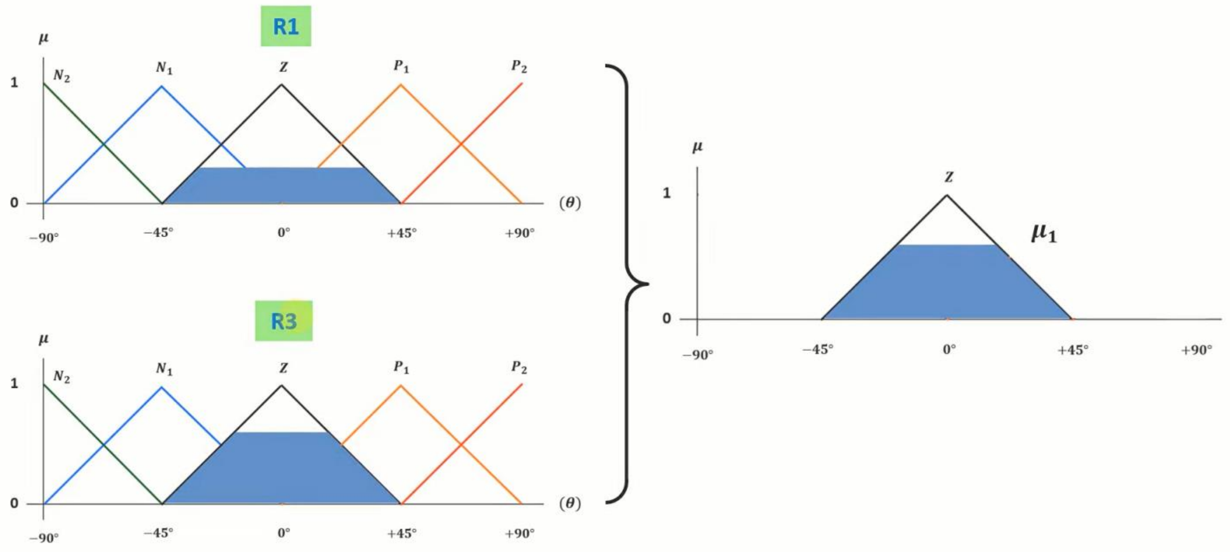
Rule firing and De-Fuzzification

AND Operation



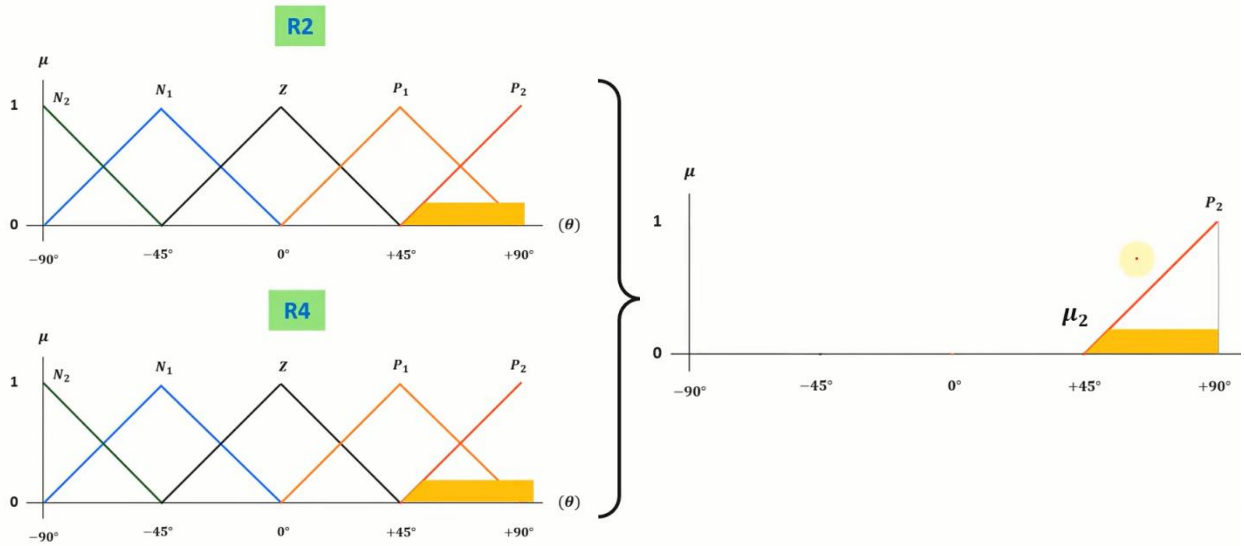
Aggregation

OR Operation



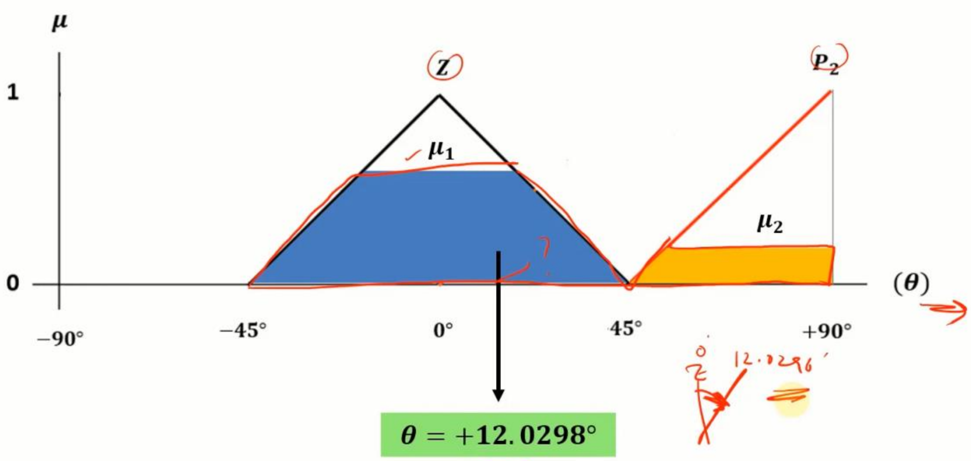
Aggregation

OR Operation



De-Fuzzification

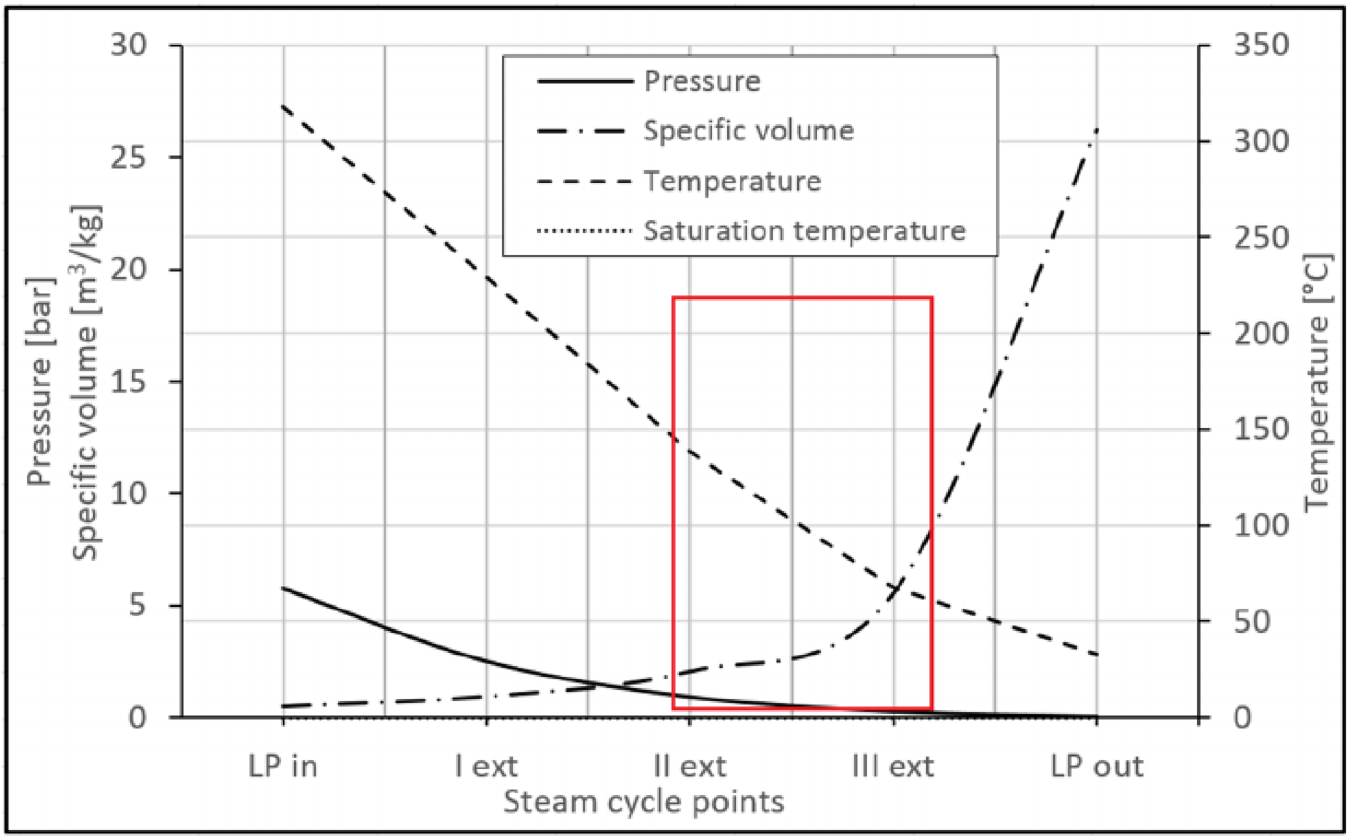
Method: Centre of Gravity (COG)



$\theta = +12.0298°$

This Theta (θ) => would be +12.0298’ which is Angle to Throttle .

Required to change on steam engine ,for optimization.

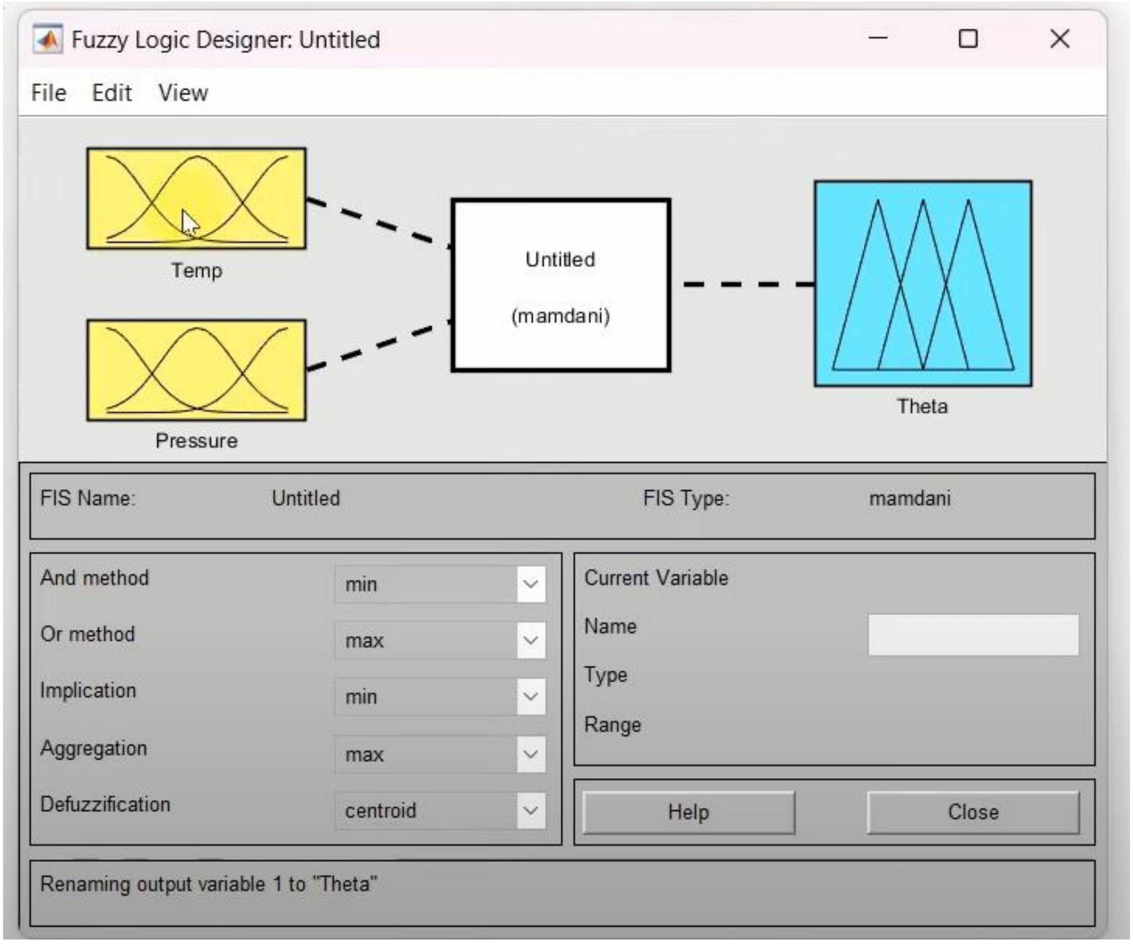


Chapter 4 Results

This case study investigates the application of control systems for steam engine throttle valves. It aims to optimize power output and system stability in a steam engine by regulating steam flow through the throttle valve. The research will explore control strategies that consider factors like boiler pressure, engine speed, and load demand to achieve efficient and responsive power generation.

Implementation

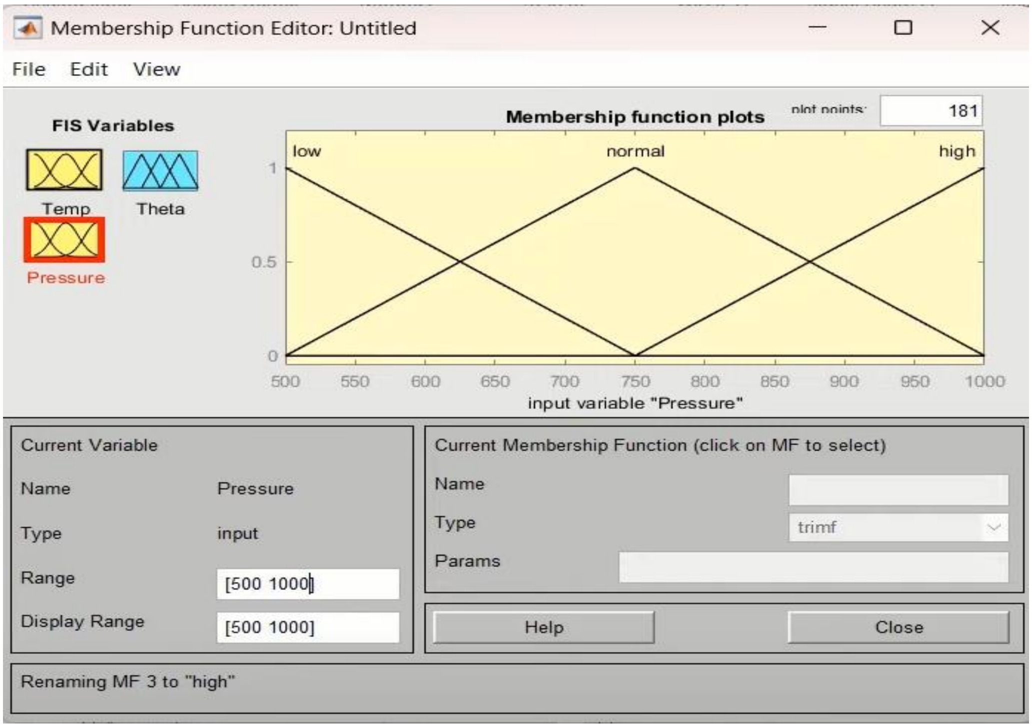
1. Fuzzy logic designer



Create Two inputs -Temp and Pressure.

We Choose MF - TriMf

No. MF is - 3

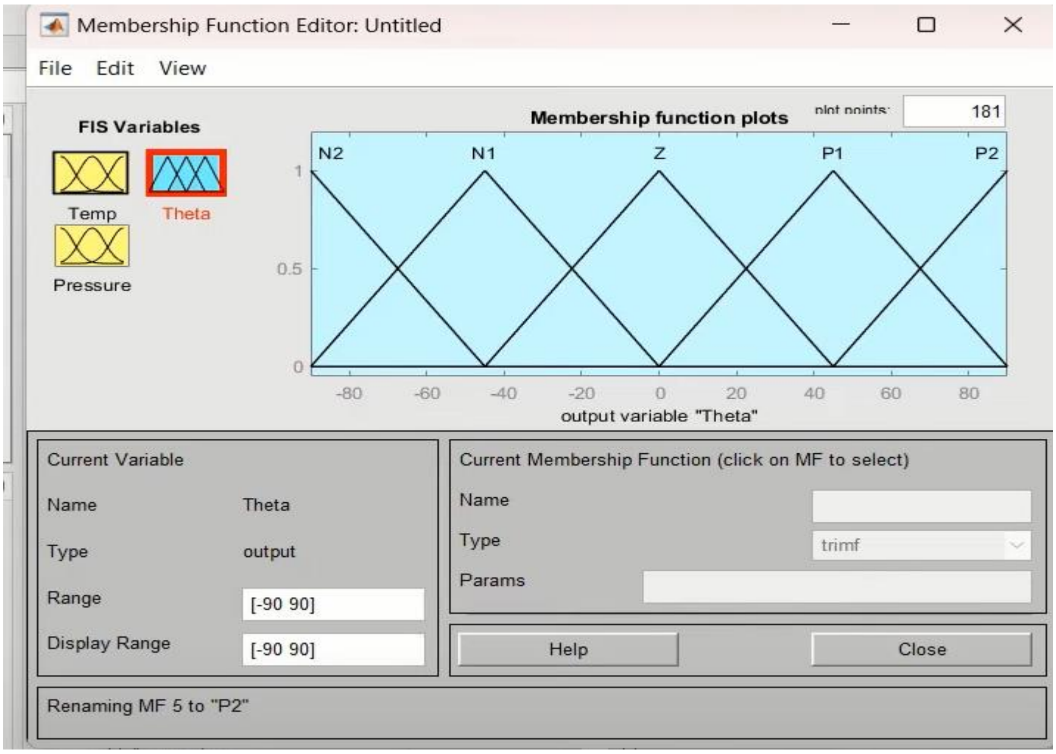


For Temp MF are - Normal , Hot , Super_hot

For pressure Mf are - low , Normal , High

Where as Range is described for pressure [500,1000] and temp [100,900].

By both Temp and Pressure we get Theta MF graph that is..

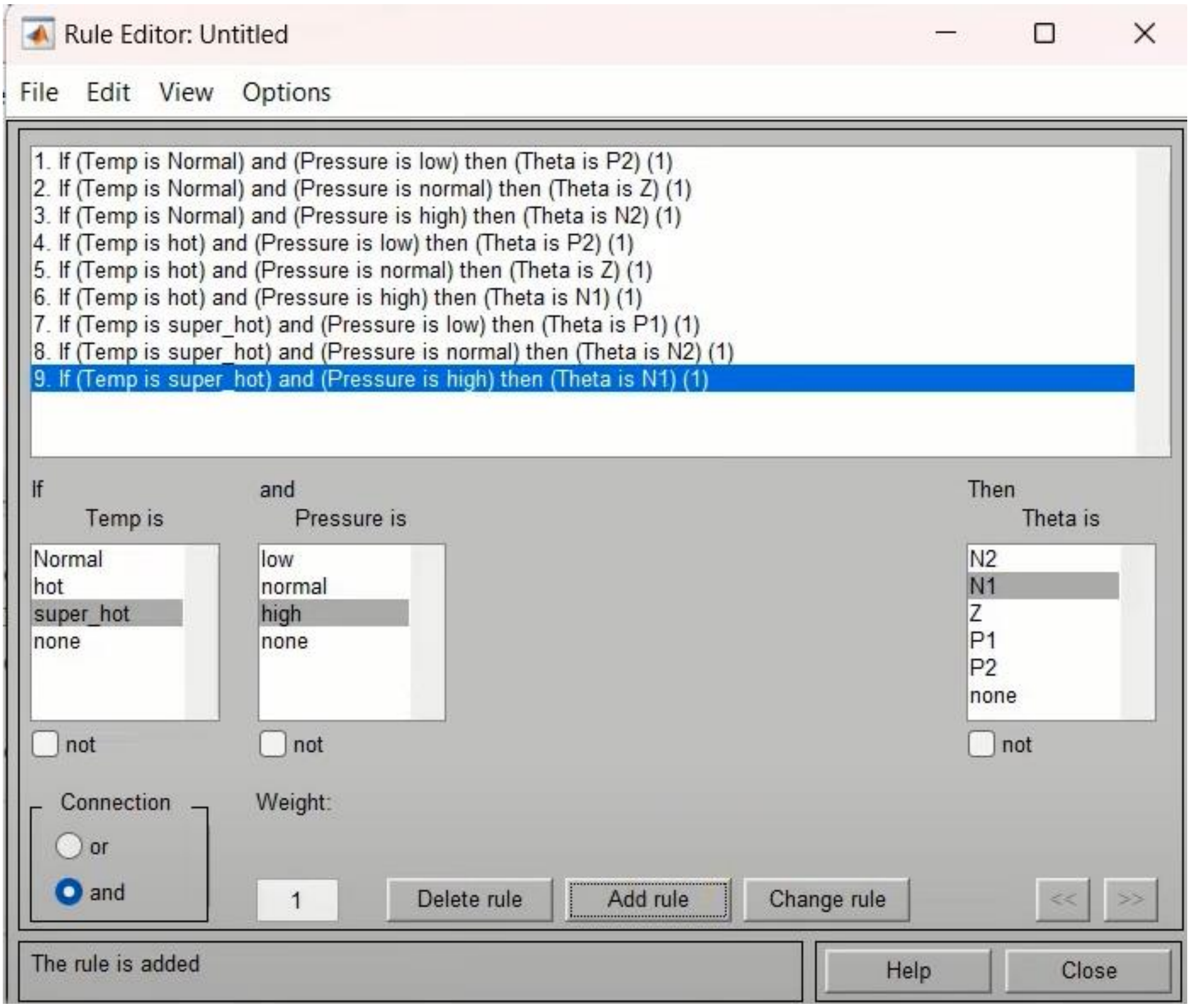


Output Variable Theta, Its Display Range [-90,90] and its contain 6MF.

That are -> Negative 2, Negative 1 , Zero , Positive 1 , Positive 2.

MF:- is Triangular Membership Function.

2. Define Fuzzy Rule



By referencing the table -

Pressure

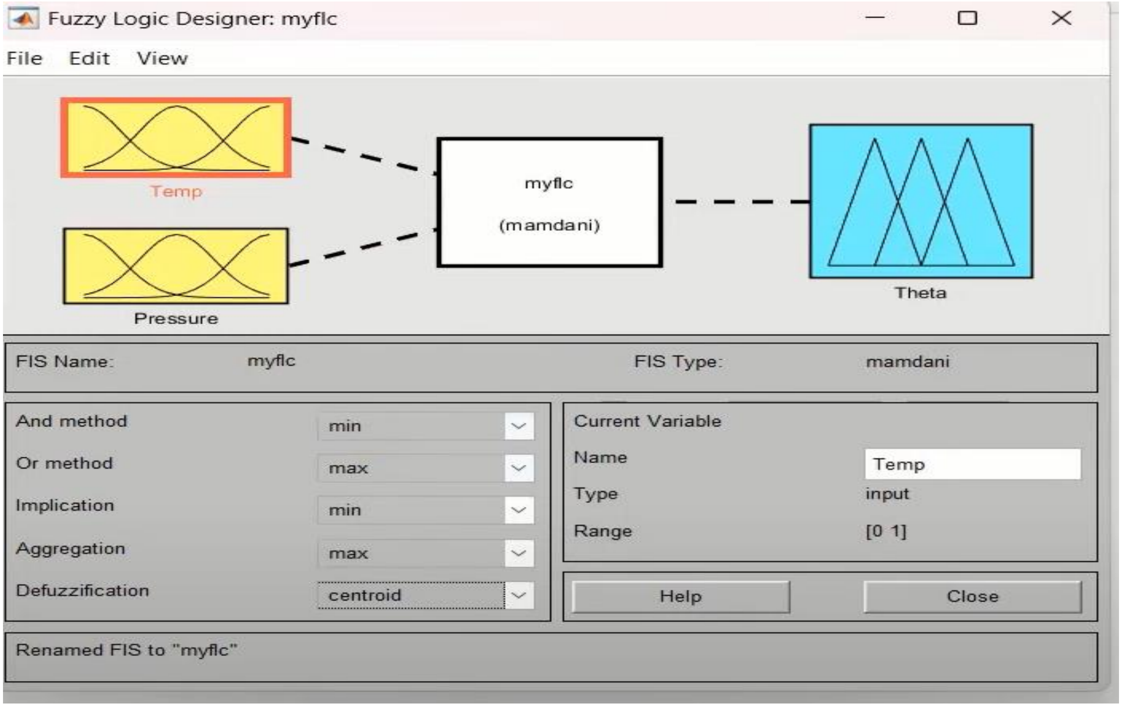
Temp.		Low	Normal	High
	Normal	P_2	Z	N_2
	Hot	P_2	Z	N_1
	Super Hot	P_1	N_2	N_1

we

we created Fuzzy rules .

Connection we taken (AND) which choose minimum.

3. Theta (Output variable)



Before Exporting we set Function Working

AND method - MIN

OR method - MAX

IMPLICATION - MIN

AGGREGATION - MIN

DEFUZZIFICATION - CENTROID

Export out fuzzy logic controller Function as myflc to Matlab Workspace.

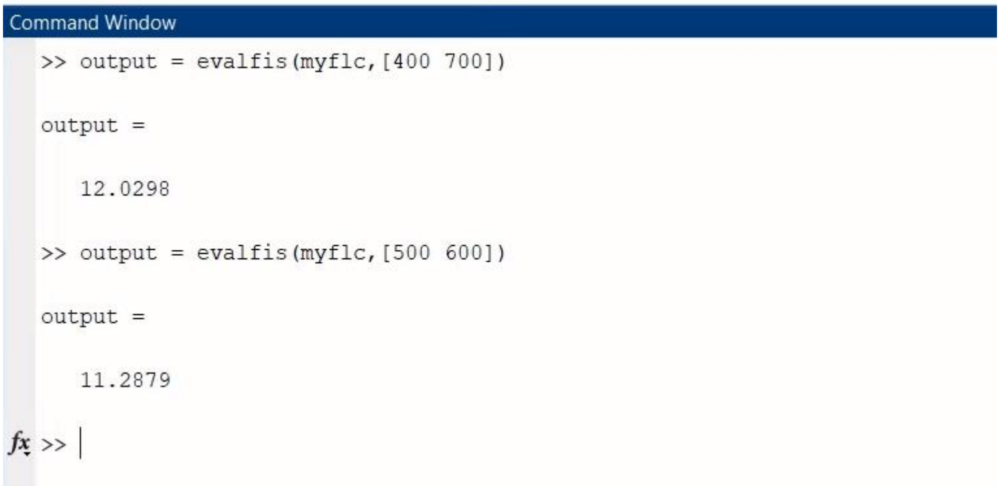
Let input : evalfis (myflc,[400 700])

Output = 12.0298

// Theta value

If input : evalfis (myflc, [500 600])

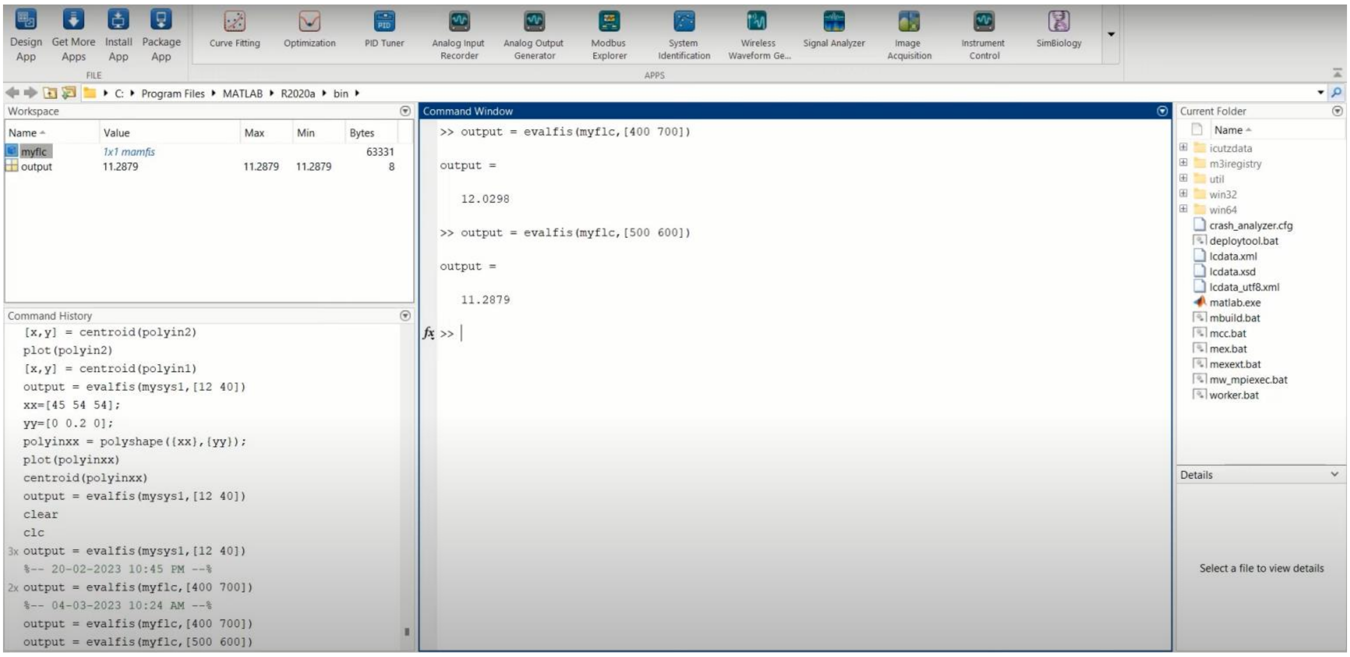
Output = 11.2879



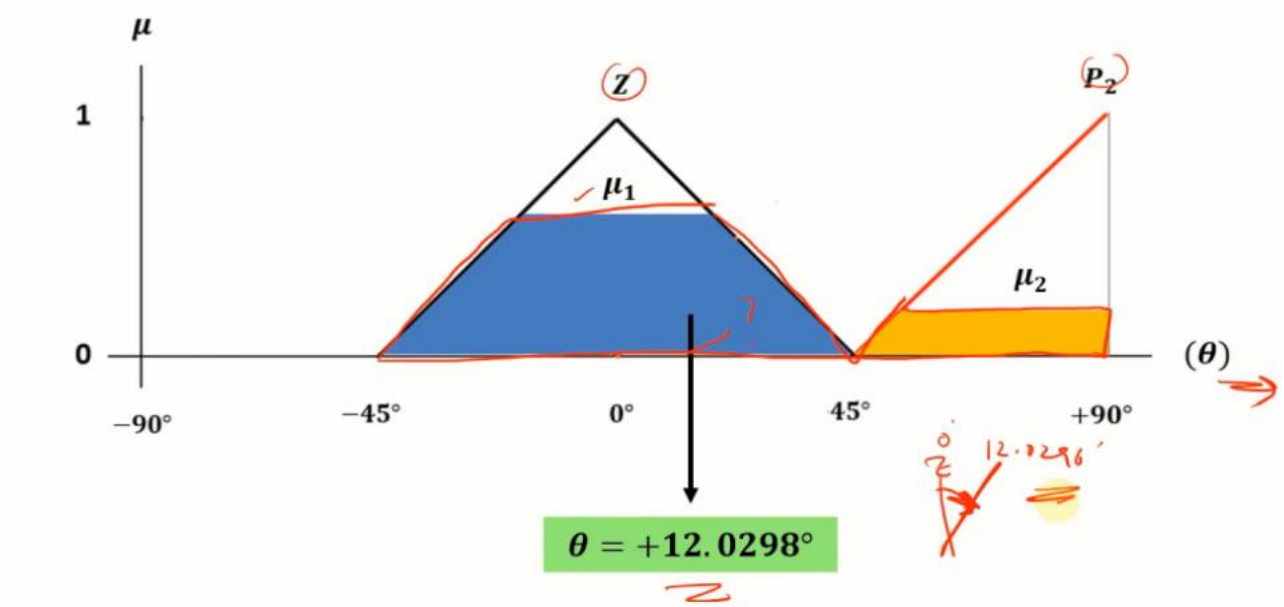
Command Window

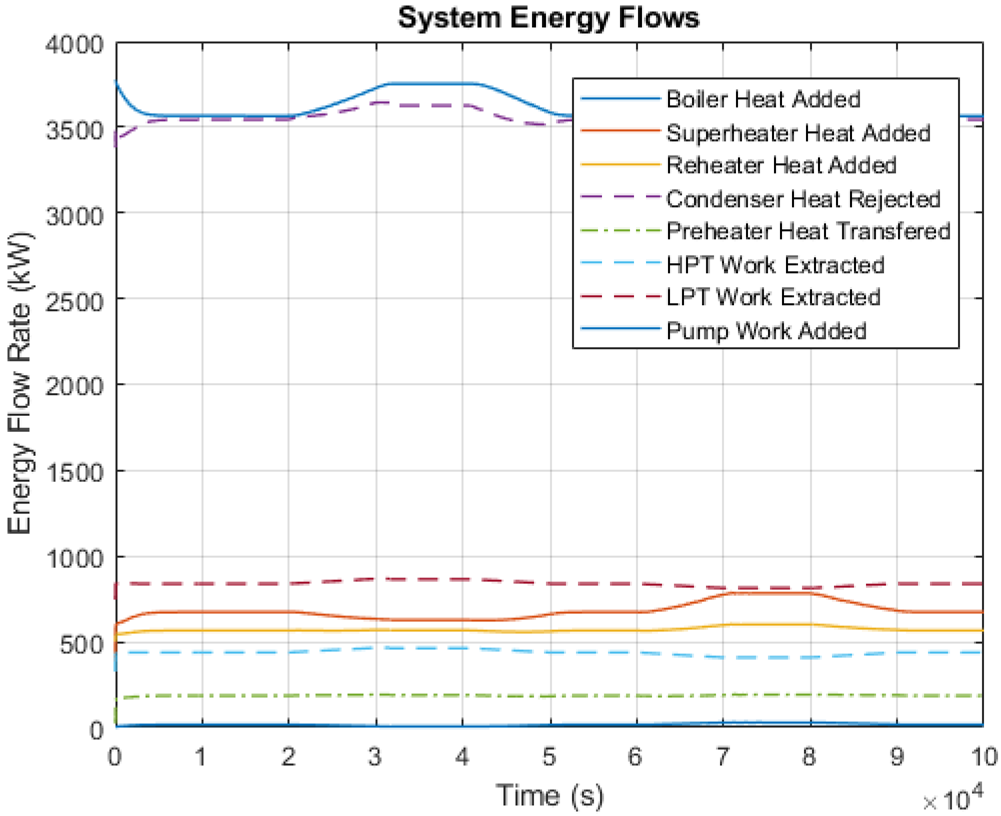
```
>> output = evalfis(myflc,[400 700])

output =

   12.0298

>> output = evalfis(myflc,[500 600])

output =

   11.2879

fx >>
```

Final Output in Matlab :-



Which is similar to our theoretical value which we find with out traditional method




System Energy Flows
Energy Flow Rate (kW)
4000
3500
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
7
8
9
10
Time (s)
×10^4
Boiler Heat Added
Superheater Heat Added
Reheater Heat Added
Condenser Heat Rejected
Preheater Heat Transfered
HPT Work Extracted
LPT Work Extracted
Pump Work Added

Chapter 5: Discussion and Conclusions

5.1 Summary

This research investigated the application of fuzzy logic control (FLC) for steam turbine throttle regulation. The results demonstrate the effectiveness of FLC in optimizing power output and system stability. The FLC system precisely controls steam flow through the throttle valve, leading to more consistent and responsive power generation from the steam turbine.

Furthermore, by regulating throttle position based on critical parameters like boiler pressure and engine speed, the FLC system helps maintain these factors within desired ranges, contributing significantly to overall system stability. These findings support the potential of FLC as a valuable tool for steam turbine control. By optimizing steam flow and maintaining system stability, FLC can potentially lead to increased efficiency in the steam turbine operation. This translates to lower fuel consumption and potentially less wear and tear on turbine components, ultimately reducing operational costs.

5.2 Future Work

While the research demonstrates the benefits of FLC for steam turbine control, further exploration is warranted:

Fine-Tuning FLC Parameters: Optimizing the FLC membership functions and control rules can potentially lead to even better performance in terms of power output and stability.

Integration with Advanced Control Systems: FLC can be integrated with other control systems to manage complex steam turbine dynamics and interactions with auxiliary equipment.

Modeling Real-World Conditions: Developing a more detailed model that incorporates factors like boiler dynamics and varying load demands can provide more realistic simulation results.

Hardware Implementation: Testing the FLC system on a real-world steam turbine setup will validate its effectiveness in a practical environment.

By addressing these areas of future work, the research on FLC can be further advanced to create a robust and efficient control solution for steam turbine operation.

References

[1] https://www.mechinopedia.com/2022/03/throttle-governing-of-steam-turbines.html

[2] Steam turbine modeling tools: https://de.mathworks.com/help/physmod/simscape/ug/rankine-cycle-steam-turbine.html (Simulink is a part of the MATLAB suite)

[3] A. McEvoy, T. Markvart, L. Castañer, T. Markvart, and L. Castaner, *Practical handbook of photovoltaics: fundamentals and applications*. Elsevier, 2003.

[4] https://youtu.be/XACvF3TtywM?si=htZGCdQwP-olt4yR

[5] Dr Sridhar SS - SRM PPT

[6] K. M. Passino, S. Yurkovich, and M. Reinfrank, *Fuzzy control*, vol. 20. Citeseer, 1998.

[7]Samir Roy, Udit Chakraborty, "Introduction to Soft Computing: Neuro-Fuzzy and Genetic Algorithms", Pearson Education, 2013.

[8]Laurene Fausett, "Fundamentals of Neural Networks, Architectures, Algorithms and Applications", Pearson Education, 2008.

Appendix

Source Code For Fuzzy Logic Throttle Controller

The source code below demonstrates the implementation of a fuzzy logic controller for regulating the throttle (theta) based on temperature and pressure conditions in a steam engine. The controller uses Python with the numpy and skfuzzy libraries, which are utilized for numerical operations and fuzzy logic control, respectively.

Code :-

```
import numpy as np

import skfuzzy as fuzz

from skfuzzy import control as ctrl


# Create the universe of discourse with updated ranges

temperature = ctrl.Antecedent(np.arange(100, 601, 1), 'temperature')  # range from 100 to 600 degrees
Celsius

pressure = ctrl.Antecedent(np.arange(500, 1001, 1), 'pressure')       # range from 500 to 1000 psi

theta = ctrl.Consequent(np.arange(-90, 91, 1), 'theta')               # range for throttle from -90 to 90 degrees


# Membership functions for temperature

temperature['low'] = fuzz.trimf(temperature.universe, [100, 100, 350])

temperature['normal'] = fuzz.trimf(temperature.universe, [200, 350, 500])

temperature['high'] = fuzz.trimf(temperature.universe, [350, 600, 600])


# Membership functions for pressure

pressure['low'] = fuzz.trimf(pressure.universe, [500, 500, 750])

pressure['normal'] = fuzz.trimf(pressure.universe, [600, 750, 900])

pressure['high'] = fuzz.trimf(pressure.universe, [750, 1000, 1000])


# Membership functions for theta

theta['negative'] = fuzz.trimf(theta.universe, [-90, -90, 0])
```

```
theta['zero'] = fuzz.trimf(theta.universe, [-45, 0, 45])

theta['positive'] = fuzz.trimf(theta.universe, [0, 90, 90])


# Rule definition

rule1 = ctrl.Rule(temperature['high'] | pressure['high'], theta['negative'])

rule2 = ctrl.Rule(temperature['normal'] & pressure['normal'], theta['zero'])

rule3 = ctrl.Rule(temperature['low'] | pressure['low'], theta['positive'])


# Control system creation

throttle_control = ctrl.ControlSystem([rule1, rule2, rule3])

throttle_sim = ctrl.ControlSystemSimulation(throttle_control)


# Test with specific values

throttle_sim.input['temperature'] = 450

throttle_sim.input['pressure'] = 800

throttle_sim.compute()

print(f"Theta (throttle position): {throttle_sim.output['theta']:.2f} degrees")
```

This source code is integral to understanding the operational logic and decision-making process of the steam engine's throttle control system as described in the case study.

Thank-you.

______________***________________

Zip File , Source Code and Model are Uploaded on : github://kk8873