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Type-2 Fuzzy Self-Tuning Voltage Controller for a Synchronous Generator using Tabu Search

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ABSTRACT
This article presents the methodology of an application of a self-tuning interval type-2 fuzzy logic controller (IT2 FLC) as a voltage regulator for the excitation system of a synchronous generator. The tabu search is used for self-tuning the knowledge base of linguistic rules of the fuzzy control. A 5th order model is utilized for a 645 MVA synchronous generator. Tests were applied to the machine-infinite bus model with long or short transmission lines with the self-tuning IT2 FLC, presenting the best steady state and dynamic performance, when it is compared with a self-tuning type-1 fuzzy logic controller (T1 FLC), manually tuned IT2 FLC and a ST1 type conventional voltage regulator. The synchronous generator is subject to a three phase short circuit with 10 cycles fault duration for the short line with and without uncertainty in the terminal voltage, the self-tuning IT2 FLC presents the best performance. The system with a long transmission line is subject to a three phase short circuit with 6 cycles of fault duration, only the self-tuning IT2 FLC remains stable. The system was also subject to a wide range of operating conditions, taking the generator from no load up to the transmission power limit remaining stable only with the self-tuning IT2 and T1 FLC.

Keywords - Enhanced Karnick-Mendel algorithm, Interval type–2 fuzzy logic controller (IT2 FLC), Tabu Search (TS), Type-1 fuzzy logic controller (T1 FLC).

I. INTRODUCTION

A type-2 fuzzy set extends the original fuzzy set of Zadeh (now called by many type-1 fuzzy sets (T1 FS) of a FS whose membership value is a unique value (dot), for a FS whose degree of membership is a function). Type-2 fuzzy sets can handle the uncertainties presented in the systems because their degrees of belonging are as well type-1 fuzzy sets [1]. See [2] for an overview of type-2 fuzzy sets (T2 FS) and fuzzy systems.

Type-1 fuzzy systems allow designing in a friendly way, algorithms that go along with human thought and perception. These controls are nonlinear and allow some uncertainty in their linguistic input variables. However, once the membership functions of the fuzzy sets have been determined, all uncertainty in their input variables disappears [3]. The type-2 fuzzy controllers allow to maintain certain uncertainty in their fuzzy sets described by functions of membership with footprint uncertainty. This fact allows the type-2 controller a new level of freedom in handling uncertainty associated with its input variables above type-1 controllers [3]. Also, there is always uncertainty present in different forms in conventional fuzzy systems. There are at least four sources of uncertainty present in these systems: uncertainty associated with the words used in the rules, uncertainty associated with the consequent for a particular rule, uncertainty associated with the measurements of the physical variables of input to the fuzzy system and uncertainty associated with the data used to tune the fuzzy system parameters.

On the other hand, the linguistic rules table in the fuzzy control is designed by an expert, having more rules in the table makes it more difficult to tune, even for the expert, because there is no security of having a table of optimal linguistic rules, we proceed to find a method to optimize the rule table. Although, there are optimization methods such as genetic algorithms and neural networks, which are used for the optimization of membership functions. These methods do not serve to optimize the table of linguistic rules, this optimization can only be done by the tabu search [4] and [5]. This method can optimize an objective function and a specific search space at the same time.

The control proposed by type-2 fuzzy control allows the handling of uncertainties in membership functions and the tabu search method makes this self-tuning control, eliminating the need for an expert when installing or changing a voltage regulator.

One of the most used sources of energy is the synchronous generator which demands efficient regulators for the field voltage of these generators, currently most of the existing regulators are of the conventional type Proportional Integral (PI) and Proportional Regulators type ST1. However the conventional PI controllers can work in an integrated manner with the fuzzy controllers, and take advantage of their inference system by approximate reasoning for their own tuning [6].

Type-2 fuzzy sets have already been successful in many real-world applications. According to [7]: Since 2001 there have been a huge number of real-world applications for T2 FS systems. [8] provides references for the following applications: approximation, control, databases, decision making, embedded agents, health care, hidden Markov models, neural networks, noise cancellation, pattern classification, Quality control, special consulting and wireless communication. [9] Provides references and discussion on applications. Type-2 fuzzy logic control (T2 FLC) for industrial control, mobile-robot and intelligent control environments.

The application of the fuzzy logic based power systems stabilizer (FLPSS) to damp power system oscillation is presented in [10] . The classic fuzzy logic controller based PSS (FLCPSS), the polar FLC (PFLCPSS) and the interval type-2 fuzzy logic controller based PSS (IT2FLCPSS) are applied to the New England - New York interconnected power system and the obtained results are compared. For coordination purposes, genetic algorithm (GA) is used to tune the FLCPSS's gains. The non-linear simulation in the presence of noise.

In [11] the work aims to develop a controller based on interval type-2 fuzzy logic to simulate a compact digital fuzzy automatic voltage regulator (CDF-AVR) in transient stability power system analysis.

The novelty design type-2 fuzzy fractional order PID based power system stabilizer (PSS) using a meta-heuristic hybrid algorithm is presented in [12] for improving the electromechanical damping oscillation performance of the power system to enhance the dynamic stability.

The type-2 fuzzy logic systems applications for power system is presented in [13], It is explored how type-2 fuzzy logic systems can provide solutions of challenging power system problems; short-term load forecasting and voltage control in distribution networks.

The effects of uncertainty in dynamic control of a parallel robot is considered in [14]. More specifically, it is intended to incorporate the type-2 fuzzy logic paradigm into a model-based controller, the so-called computed torque control method, and apply the result to a 3 degrees of freedom parallel manipulator.

Type-2 fuzzy controller is used to excitation systems of synchronous generators is presented in [15], the simulations are applied for unit step input with a disturbance in two cases; with and without uncertainty. The comparations is done between traditional PID controller, fuzzy type-1 PID controller and fuzzy type-2 controller this controller obtains the best performance.

In [16] a type-1 fuzzy self-tuning voltage controller is presented by means of the tabu search (TS) and genetic algorithms for a synchronous generator, where the tabu search proves to be better technique than genetic algorithms because of its ability to remember appropriately each solution visited and its flexibility in front of any size of the search space.

Type-2 fuzzy controllers applied to excitation systems of synchronous generators was presented in master's thesis [17]. During this work a type-2 fuzzy controller in intervals was developed. This controller shows in most simulations to be superior to conventional type-1 fuzzy controller.

In this work the self-tuning type-2 fuzzy logic controller (IT2 FLC) with tabu search performance is compared with a manually tuned IT2 FLC, a self-tuning type-1 fuzzy logic controller (T1 FLC) and the ST1 regulator (Exciter with power source through controller rectifiers). The performance of both fuzzy controllers and the proportional regulator is measure in terms of integral square error (ISE), integral absolute error (IAE) and integral time absolute error (ITAE) for the error in terminal voltage and the dynamic performance.

Knowledge base of linguistic rules for the fuzzy controllers is changed from during the control process, this means that in each iteration of control will have a knowledge base of linguistic rules tuned.

The contributions of this article are: the application of tabu search in the IT2 FLC linguistic rules table in the excitation system of a voltage regulator of a synchronous generator connected to an infinite bus through a transmission line. The application of tabu search in the IT2 FLC and T1 FLC linguistic rules table increases the capacity of a long transmission line system. Self-tuning allows the system to be taken to its power capacity limit, this last result is compared with the reference [18], where the self-tuning IT2 FLC reaches a transmission capacity limit.

The automatic tabu search tuning of the linguistic base rules is of the greatest importance, because the manually tuned controller cannot take the system to the steady state power limit and the self-tuned IT2 FLC presents the best dynamic performance to the three phase fault.

II. SELF-TUNING TYPE-2 FUZZY CONTROLLER ELEMENTS

The self-tuning type-2 fuzzy controller elements are shown in Fig. 1.

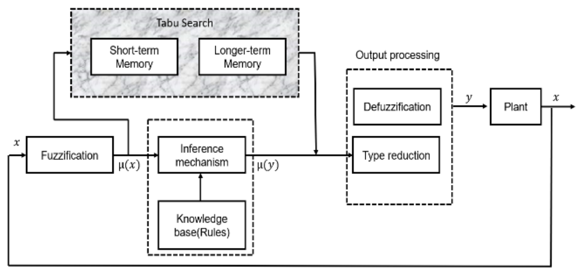


Fig. 1: Elements of type-2 fuzzy logic controller using tabu search in rule table optimization.

The elements that make it up are:

- Fuzzification.
- Inference system and knowledge base.
- Tabu search.
- Type reduction.
- Defuzzification.

Fuzzification

Fuzzy values are generated by mapping a real numeric value of the input vector, error, and change in the error of reference voltage $X = (e, \Delta e)^T \rightarrow [0\ 1]$. To the fuzzy sets present in the corresponding universes of discourse. Membership degrees are assigned. The Input universe for error of reference voltage shows in Fig. 2 and Fig. 3.The linguistic labels used for both entry spaces are:

NG = Large Negative. **NM** = Medium Negative.
NP = Small Negative. **CE** = Zero.
PP = Small Positive. **PM** = Medium Positive.
PG = Large Positive.

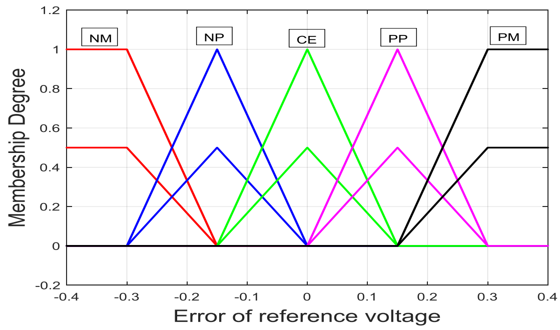


Fig. 2: Input Universe Labels with five type-2 triangular fuzzy sets.

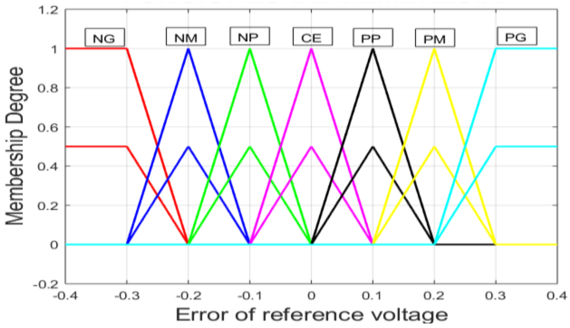


Fig. 3: Input Universe Labels with seven type-2 triangular fuzzy sets.

Type-2 fuzzy sets are characterized by their uncertainty footprint. It is necessary to express this uncertainty by means of two membership functions called: upper membership function (UMF) and lower membership function (LMF) [19]. The parameter δ_x defines uncertainty in the fuzzy sets used in this work. In Fig. 4 and Fig. 5 the triangular membership functions used in this work are presented.

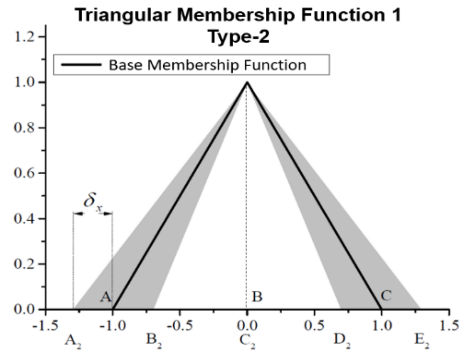


Fig. 4: Triangular Membership Function 1.

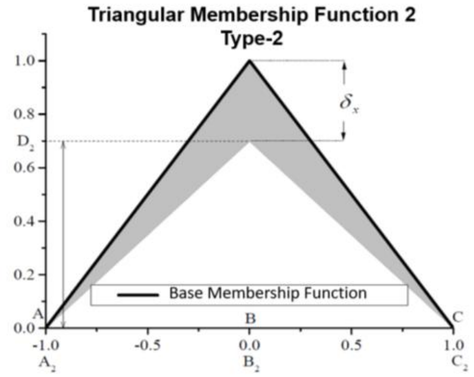


Fig. 5: Triangular Membership Function 2.

The points required to form a triangular membership function type 1 as shown in Fig. 4 are:

$$A_2 = A - \delta_x,\ B_2 = A + \delta_x,\ \ C_2 = B;$$

$$D_2 = C - \delta_x, \qquad E_2 = C + \delta_x;\ \ with\colon A < B < C$$

(1) represents LMF and (2) UMF for triangular membership function type 1.

$$LMF \begin{cases} 0 & D_2 \le x \ or \ x \le B_2 \\ \dfrac{x - B_2}{C_2 - B_2} & B_2 < x \le C_2 \\ \dfrac{x - D_2}{C_2 - D_2} & C_2 < x < D_2 \end{cases} \qquad (1)$$

$$UMF \begin{cases} 0 & E_2 \le x \ or \ x \le A_2 \\ \dfrac{x - A_2}{C_2 - A_2} & A_2 < x \le C_2 \\ \dfrac{x - E_2}{C_2 - E_2} & C_2 < x < E_2 \end{cases} \qquad (2)$$

The points required to form a triangular membership function type 2 as shown in Fig. 5 are:

$$A_2 = A,\ B_2 = B,\ C_2 = C;$$

$$D_2 = 1 - \delta_x,\ \ with\colon A < B < C$$

(3) represents LMF and (4) UMF for triangular membership function type 2.

$$LMF \begin{cases} 0 & C_2 \le x \ or \ x \le A_2 \\ \left(\dfrac{x - A_2}{B_2 - A_2}\right) D_2 & A_2 < x < B_2 \\ \left(\dfrac{C_2 - x}{C_2 - B_2}\right) D_2 & B_2 < x < C_2 \end{cases} \qquad (3)$$

$$UMF \begin{cases} 0 & E_2 \le x \ or \ x \le A_2 \\ \dfrac{x - A_2}{C_2 - A_2} & A_2 < x \le C_2 \\ \dfrac{x - E_2}{C_2 - E_2} & C_2 < x < E_2 \end{cases} \qquad (4)$$

Inference System and Knowledge Base

The Inference system is responsible for combining the fuzzy rules of the type IF-Then, which make up the knowledge base [20]. Each rule is interpreted as a fuzzy implication, i.e. a fuzzy relationship between the input space $X = [e\ \Delta e]$ and the y output space. For the controllers tuned by the tabu search, part from a manually tuned rule table, the knowledge base with 25 and 49 rules are shown in Fig. 6 and Fig. 7**,** these rules tables are taken of [21] in this master thesis explain how to make the linguistic rules tables.

$\Delta e \backslash e$	**NM**	**NP**	**CE**	**PP**	**PM**
NM	NG	NG	NM	NP	CE
NP	NG	NM	NP	CE	PP
CE	NM	NP	CE	PP	PM
PP	NP	CE	PP	PM	PG
PM	CE	PP	PM	PG	PG

Fig. 6: Knowledge base of 25 fuzzy rules.

$\Delta e \backslash e$	**NG**	**NM**	**NP**	**CE**	**PP**	**PM**	**PG**
NG	NG	NG	NG	NM	NM	NP	CE
NM	NG	NG	NM	NM	NP	CE	PP
NP	NG	NM	NM	NP	CE	PP	PM
CE	NM	NM	NP	CE	PP	PM	PM
PP	NM	NP	CE	PP	PM	PM	PG
PM	NP	CE	PP	PM	PM	PG	PG
PG	CE	PP	PM	PM	PG	PG	PG

Fig. 7: Knowledge base of 49 fuzzy rules.

Tabu Search

Tabu Search (TS) is a metaheuristic procedure whose distinctive feature is the use of adaptive memory and strategies to solve special problems. Its philosophy is based on the exploitation of various intelligent strategies for solving problems, based on learning procedures [4].

In this block the self-tuning of the linguistic rules table is performed, where the short and long term memory is used, in Section III this method is described in detail for tuning.

Type Reduction Algorithm

This output processing block of the controller represents a mapping of a type-2 fuzzy set to a type-1 fuzzy set. Here is the process of calculating the centroid of a type-2 fuzzy set is an extension of the calculation for a type-1. When it comes to fuzzy sets in intervals, the process of type reduction can be carried out by means of an iterative algorithm [3, 22, 23, 24], called Karnik and Mendel in its conventional and enhanced version. The present work the enhanced algorithm of Karnik and Mendel is used in the simulations.

Defuzzification

The defuzzification process is the average of the points, $\underline{y}$ and $\overline{y}$ found using the iterative algorithm Karnick & Mendel or Enhanced Karnick & Mendel.

The real value for the output variable is generated. There are different defuzzification methods such as [25]:

- Center of area/ Gravity.
- Center of sums.
- Center of largest area.
- First of maxima.
- Middle of maxima.
- Height.

The center of area method is used for self-tuning T1 FLC. In which each fuzzy output rule is expressed by a function type bar with its maximum membership value in the center of the output set, then averaging the weighted weights. This method is realized by algorithm Karnick & Mendel when $\delta_e = \delta_{\Delta e} = 0$.

For the output discourse universes 5 and 7 bars are used as shown in Fig. 8, the output discourse universe represents the voltage increase for the excitement field of generator. Type-2 fuzzy controllers have uncertainty in the bars and it is defined with a displacement as shown in Fig. 9.

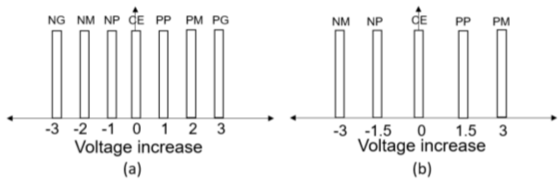


Fig. 8: Output universes. (a) 7 bars, (b) 5 bars.

The linguistic labels for the seven output bars are:

NG = Large Negative Action.
NM = Medium Negative Action.

NP = Small Negative Action.
CE = Zero Action.
PP = Small Positive Action.
PM = Medium Positive Action.
PG = Large Positive Action.

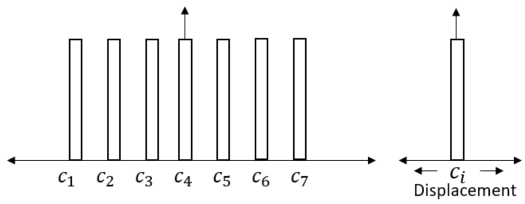


Fig. 9: Uncertainty in output bars.

III. AUTO-TUNING OF THE LINGUISTIC RULES TABLE USING TABU SEARCH

The first step to set TS is to define the search space (knowledge base of linguistic rules), once the search space is established it is necessary to know how TS defines the $N(x)$ neighborhoods in the various areas of the knowledge base linguistic rules. One of the advantages of TS is the exploration and exploitation of zones that allow to direct the search to areas never visited. This feature allows TS to work with small and large search spaces. The $N(x)$ environment types handled on the linguistic rules table (knowledge base) is linguistic actions as a neighborhood.

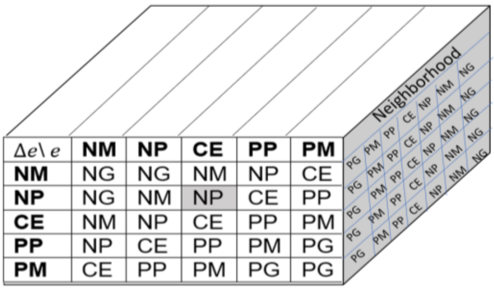


Fig. 10: Knowledge base of 25 linguistic rules, linguistic actions as a neighborhood.

Fig. 10 shows the neighborhood that contains each item in the linguistic rules table, where each position contains 6 items as candidates for the optimized rules table. The search space for this case is a cube formed from linguistic rules with all the possibilities of the linguistic actions of $n \times n \times n$ dimension.

x =NP, x is current solution.
$N(x)$ =PG, PM, PP, CE, NG, NM
X = search space of size $n \times n \times n$, where $n = 5$

Once the $N(x)$ neighborhoods and the TS search space have been established, the reference model will employ each of the actions established in the neighborhood and it will be evaluated by TS based on its objective function. However it is not enough to make a decision on the part of the search to establish a final solution (optimized rules table) it is necessary to analyze the different solutions, x' used throughout the application of TS in two periods that allow to reinforce. The TS criterion to form a final solution, such periods are: short-term period and long-term period.

In this work the objective function is composed of the error of the terminal voltage multiplied by a constant (alpha), plus the change of the terminal voltage error multiplied by a constant (beta).

$$Objetive\ Function = \alpha * error + \beta * \Delta error \quad (5)$$

3.1 Short-term Memory with Fuzzy Logic

The short-term memory is the memory in charge of recording the movements carried out on the table of linguistic rules [4], in this work the record of the previous short-term events are 32 (0.125s) previous iterations, the memory a short term evaluates the current elite solution. In the period of 32 iterations short-term memory chooses a certain number of neighboring elements $N(x)$ as future candidates to be part of the next elite solution, this choice will depend on factors such as the type of influence and tabu attribute [4] and [16].

3.2 Explicit and Attributive Memory

Explicit memory is responsible for recording the latest movements made, explicit memory meets two objectives to avoid cycles and avoid unnecessary searches. The dimension of this memory is $n \times n$ where n is the number of fuzzy partitions in the discourse universe of error or error change, so the memory dimension increases when making more partitions in the discourse universe.

The attributive memory takes the record of the period of time (tabu basis) that each action of the linguistic rules contained in a tabu list T will be active tabu. Like the memory explicit the dimension of this memory is $n \times n$.

3.3 Aspiration Criterion

This criterion is used to know when the solutions of the linguistic neighborhood may or may not be in the elite solution, this criterion has two variations, which are of high and low influence.

For the low influence criterion, the movement that is carried out respects the tabu states of the linguistic actions, which means that the linguistic actions that are active tabu cannot be eliminated and also not added to the elite solution. If the movement is tabu, the movement is not made so the resulting action is the action that was in the solution.

The criterion of high influence, tabu states are respected, unless the resulting movement has a value in the objective function less than the current one. Therefore, the active tabu state of the action is violated. By changing the criterion of aspiration from low influence to high influence, does not guarantee better results

Fig. 10 shows the knowledge base of 25 linguistic rules. For a time of 2.6 s the rule is activated in the position (NP, CE), for which this position is found as active tabu and the objective function is $fo_{(NP)} = 0.0146$, the objective function of the candidates are:

$fo_{(NM)} = 0.013 \qquad fo_{(NG)} = 0.014 \qquad fo_{(CE)} = 0.017$

$fo_{(PP)} = 0.023$ $\quad fo_{(PM)} = 0.047$ $\quad fo_{(PG)} = 0.075$

The low influence aspiration criterion does not allow the movement to be made even though the NM action presents a better result for the objective function due to the position is found as an active tabu. The high influence aspiration criterion makes the NP change by NM because this action presents a better result in the objective function, this criterion allows to violate the restriction of the active tabu if the movement presents a better solution to the current one. Here only a linguistic neighborhood is shown, but the same procedure is performed for all linguistic neighborhoods.

3.4 Long-term Memory with Fuzzy Logic

The objective of this memory is the record frequency measurements for the creation of penalty and incentives, and to carry out intensification and diversification strategies [4].

The long-term memory is associated with diversification, intensification and the creation of penalty's and incentives, in this work the intensification is responsible for evaluating all the possible movements of each linguistic neighborhood of the table of rules, in this way the intensification strategy is made and by having an evaluation of all the possible movements of the search space this avoids remaining in a local optimum, so the diversification is covered.

IV. VOLTAGE TYPE-2 FUZZY CONTROL FOR A SYNCHRONOUS GENERATOR

The voltage regulator for the excitation system of a 645 MVA synchronous generator [18] adjusts the output power needed to control the magnitude of the voltage at the generator terminals. This means that, before a change in the reference voltage V_{ref}, the voltage at the regulator output V_{reg} causes a change in the exciter voltage V_{fd}, which is applied to the field winding of the synchronous machine to adjust the voltage in terminals [26]. Therefore, the voltage regulator must present robustness and reliability to ensure proper operation in terminal voltage control in the event of any disturbance. Fig. 11 shows the voltage regulator system and governor of a synchronous generator.

To use the fuzzy control as a voltage regulator of the excitation system, a voltage control loop is implemented in the machine terminals together with a summing node and a reference value with which an error signal is obtained. Fig. 12 shows in general form the architecture of the control system for the voltage control in terminals of the synchronous machine.

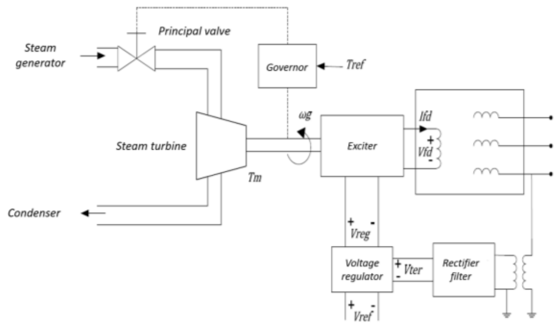


Fig. 11: Voltage regulator system and governor of a synchronous generator. **[26]**.

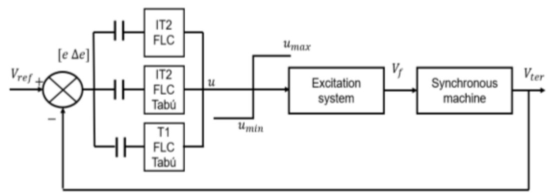


Fig. 12: Block diagram of the fuzzy controller as a voltage regulator.

Where $[e\, \Delta e]$ is the input vector for the controllers, and they are defined as:

$$e := error$$
$$\Delta e := error\ change$$

The controller output is $\dot{u}$ and refers to the increment of voltage required for the output variable and it is defined as:

$$\dot{u} = u(k) - u(k-1) \quad (6)$$

Where $u(k)$ is the value of the voltage in the current iteration and $u(k-1)$ refers to the value in the previous iteration, in addition $\dot{u}$ can take positive or negative values to increase the output variable to the required value.

$$u(k) = \dot{u} + u(k-1) \quad (7)$$

In this way it is possible to develop a fuzzy type PI controller.

To get the error and change in the error:

$$e = V_{ref} - V_{ter} \quad (8)$$

$$\Delta e = e(k) - e(k-1) \quad (9)$$

The limiter on the output of the controllers is intended to avoid any overvoltage to the excitation system and is a protection in the system, the limits are:

$$u_{min} = 0\,P.U\,;\; u_{max} = 4\,P.U \tag{10}$$

Where u is the exciter voltage for the generator V_{fd}.The set of equations that represent the synchronous machine are expressed in per unit (P.U). So, the voltage in terminals is also included.

V. SOURCES OF UNCERTAINTY TO SIMULATE IN THE CONTROLLER.

The main justification for the use of type-2 fuzzy sets within fuzzy controllers is the presence of uncertainty. In present article one tests is carried out with uncertainty in the terminal voltage V_{ter}.Uncertainties are shown in the block diagram of the Fig. 13.

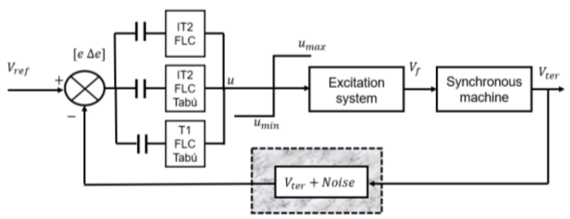


Fig. 13: Block diagram of the control system with sources of uncertainty.

The rand function of the form: $a + b * rand$; generates a random number normally distributed with a mean in a and standard deviation b. Then, for a constant voltage at generator terminals with a value of 1 P.U as the mean value in that voltage value and standard deviation value of 1% of the terminal voltage value, the function call would be as follows:

$$V_{ter\_noise}(k) = V_{ter} + V_{ter} * 0.01 * rand \tag{11}$$

Where $V_{ter\_noise}(k)$ is a vector to store the voltage with uncertainty in the iteration k.

With a value for the standard deviation equal to 1% of the current value in the terminal voltage, and as the simulation of the uncertainty is normally distributed. A variation band of $\pm3\%$ is established when the voltage value in terminals remains constant. This is because 99.7% of the values of a continuous random variable with a normal distribution reside in $\pm3\%$ times the standard deviation.

Noise is denoting as (12) and the system error is redefined (13).

$$Noise = V_{ter} * 0.01 * rand \tag{12}$$

$$Error = V_{ref} - (V_{ter} + Noise) \tag{13}$$

VI. TESTS AND RESULTS

Tests are performed using triangular membership functions as shown in Fig. 2 and Fig. 3 for the input discourse universes of fuzzy controllers, the type-1 fuzzy controller does not use uncertainty in its sets so $\delta_x = 0$, for type-2 fuzzy controllers, the uncertainties shown in Fig. 4 and Fig. 5 are used.

The manually tuned type-2 fuzzy controller uses the linguistic rule tables shown in Fig. 6 and Fig. 7, the self-tuning controllers start from these tables to perform the tuning using tabu search.

The parameters of the universe of error discourse, error change discourse, and universe of output discourse for the self-tuning type-1 fuzzy controller are shown in Table 1 for a short and long transmission line, these were taken from [17] where the tuning of these parameters is performed for an T1 FLC and an IT2 FLC, also it performs the tuning for uncertainties.

Where:

$A = Universe\ of\ error\ discourse.$

$B = Universe\ of\ \ error\ change\ discourse.$

$C = Universe\ of\ \ output\ discourse.$

$SL = Uncertainty\ to\ the\ left\ of\ the\ output\ bars.$

$SR = Uncertainty\ to\ the\ right\ of\ the\ output\ bars.$

Table 1 Parameters for the Type-1 Fuzzy Controller. Short and Long Transmission Line.

Parameters	Short transmission line	Long transmission line
A	0.3	0.7
B	0.003	0.005
C	3	3

Table 2 shows the parameters for the types of membership functions of the type-2 fuzzy controllers for a short transmission line. In Table 3 for a long transmission line, these were taken from [17].

Table 2 Parameters for Type-2 Fuzzy Controllers. Short Transmission Line.

Types of type-2 membership functions	Uncertainty in the input universes		Uncertainty in the output universes	
	δ_e	$\delta_{\Delta e}$	SL	SR
Type-2 **Triangular 1** A = 0.7; B = 0.005 and C = 3	0.3	0.0005	0.0	0.0
Type-2 **Triangular 2** A = 0.7; B = 0.005 and C = 3	0.1	0.2	0.3	0.1

Table 3 Parameters for Type-2 Fuzzy Controllers. Long Transmission Line.

Types of type-2 membership functions	Uncertainty in the input universes		Uncertainty in the output universes	
	δ_e	$\delta_{\Delta e}$	SL	SR
Type-2 **Triangular 1** A = 0.7; B = 0.005 and C = 3	0.3	0.0005	0.0	0.0
Type-2 **Triangular 2** A = 0.7; B = 0.005 and C = 3	0.1	0.2	0.3	0.1

6.1 Short transmission line

This section performs tests for a short transmission line using online tuning, this tuning uses an adaptive memory where the knowledge base of linguistic rules is modified during the control process, this means that in each iteration of control will have a knowledge base of linguistic rules tuned.

Results are presented with a short transmission line in Table 4 with the generator with load and subject to a three phases short circuit on the bus that occurs at 1s of simulation time, with duration of 10 cycles.

The Initial conditions are:

$$V_{ter} = 1\,P.U \qquad \theta = 6.8077^{o}$$

$$P_A = 1\,P.U \qquad P_R = -0.1474\,P.U$$

Table 4 Error index of the short transmission.

Fuzzy controller and type of membership function	Rules	Influence	Error index		
			ISE	IAE	ITAE
IT2 FLC triangular 1	25	high	0.1125	0.2187	0.2964
	25	low	0.1145	0.2343	0.3644
	49	high	0.1140	0.2172	0.2728
	49	low	0.1013	0.2108	0.4001
IT2 FLC triangular 2	25	high	0.1139	0.2218	0.3008
	25	low	0.5312	1.8281	9.4758
	49	high	**0.1137**	**0.2167**	**0.2721**
	49	low	0.1148	0.2524	0.4885
T1 FLC triangular	25	high	0.1139	0.2224	0.3047
	25	low	0.1463	0.3470	0.5770
	49	high	**0.1140**	**0.2174**	**0.2731**
	49	low	0.1144	0.2455	0.4518

As shown in Table 4, the best results were obtained with 49 linguistic rules and a high-influence aspiration criterion for tabu search for both self-tuning fuzzy controllers.

Fig. 15 and Fig. 16 shows the responses obtained. The responses of the self-tuning fuzzy controllers are almost identical, however the IT2 FLC has a lower cumulative error indexes, both self-tuning controllers surpass the IT2 FLC manually tuned and the ST1 regulator.

Fig. 14 shows the knowledge base of linguistic rules tuned in the 2.5 seconds of simulation for the T1 FLC and Fig. 17 for the IT2 FLC, both tables used the high influence criterion for tabu search.

$\Delta e \backslash e$	**NG**	**NM**	**NP**	**CE**	**PP**	**PM**	**PG**
NG	NG	NG	NG	NM	NM	NP	CE
NM	NG	NG	NM	NM	NP	CE	PP
NP	NG	NM	PG	PG	PG	PP	PM
CE	PG	PG	CE	NP	PG	PG	PG
PP	PG	PG	PG	PG	PG	PG	PG
PM	PP	NG	PG	NM	NM	PM	NG
PG	PG	PG	NP	PM	PG	PM	PG

Fig. 14: Knowledge base of 49 linguistic rules for T1 FLC at 2.5 s of simulation, criterion high influence.

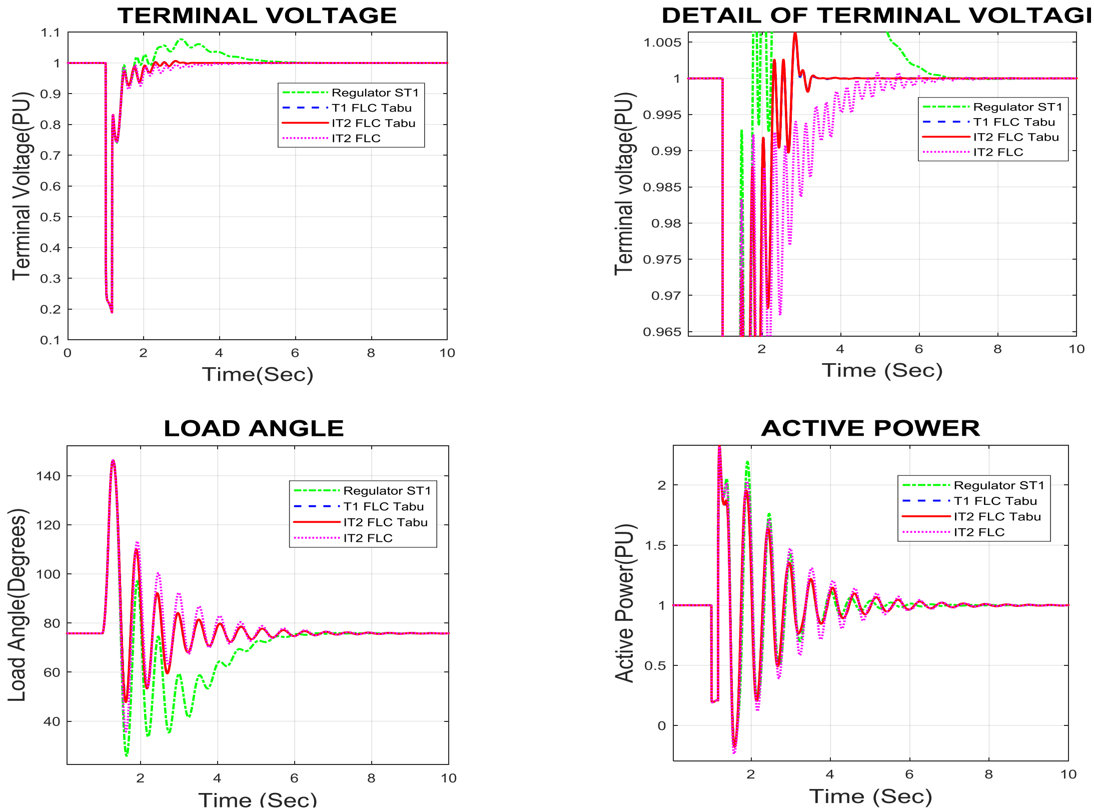


Fig. 15: Short transmission line with the generator with load and subject to a short circuit with 10 cycles of duration.

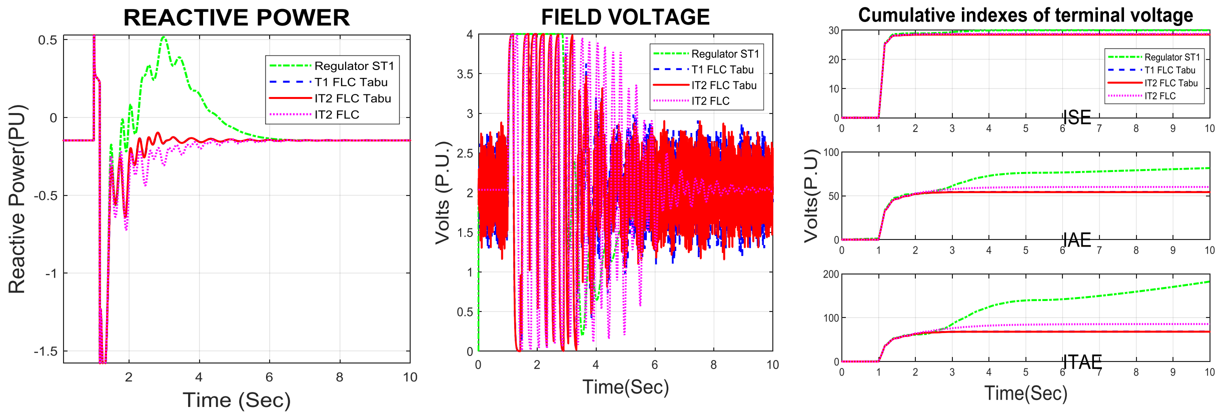


Fig. 16: Reactive power, field voltage and cumulative indexes of Fig. 15.

$\Delta e\backslash e$	NG	NM	NP	CE	PP	PM	PG
NG	NG	NG	NG	NM	NM	NP	CE
NM	NG	NG	NM	NM	NP	CE	PP
NP	NG	NM	PG	PG	PG	PP	PM
CE	PG	PG	PG	PG	PG	PG	PG
PP	PG	PG	PG	PG	PG	PG	PG
PM	PP	NG	PG	NM	NM	PM	NG
PG	PG	PG	NP	PM	PG	PM	PG

Fig. 17: Knowledge base of 49 linguistic rules for IT2 FLC at 2.5 s of simulation, criterion high influence.

6.2 Short transmission line, subject to a short circuit and uncertainty at terminal voltage

This test shows the results by adding uncertainty to the terminal voltage reading according to Fig. 13. Uncertainty of the order of $\pm 9\%$ is added in the voltage variation. This uncertainty suggests an error or damage to the transducer for the terminal voltage. The results are shown in Fig. 18 and Fig. 19.

For the IT2 FLC is used an uncertainty type 2 were obtained better results without adding uncertainty in the consequential so $\boldsymbol{SL} = \mathbf{0}$ and $\boldsymbol{SR} = \mathbf{0}$.

The self-tuning IT2 FLC presents the best dynamic state performance because it keeps constant the terminal voltage. The variation of the field voltage for all cases in the controllers indicates that the controllers are always varying in order to adjust to the reference terminal voltage.

In Fig. 19 the graph of accumulative performance indexes: The ISE index of the self-tuning type-2 controller indicates less overshoot; While the ITAE indicates that there will be lower terminal voltage errors throughout the simulation.

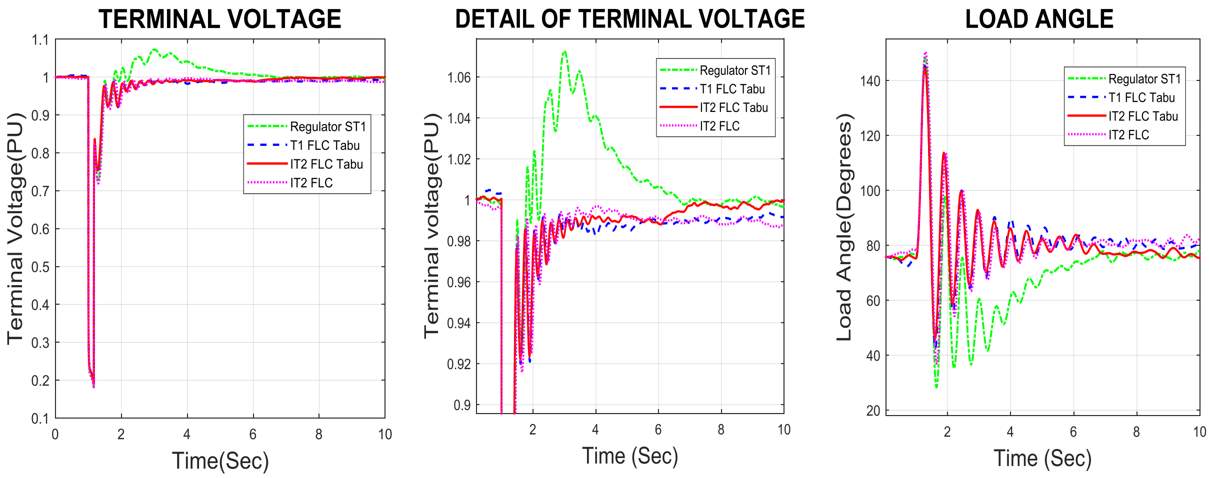
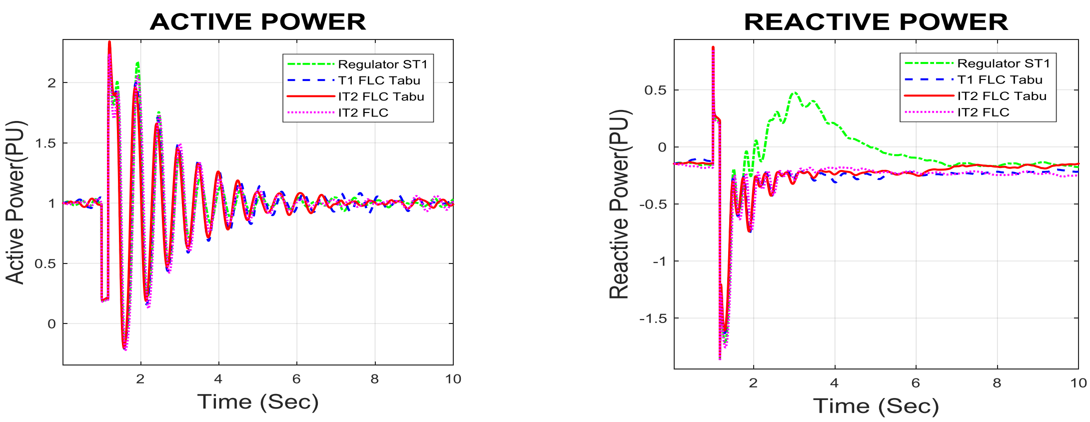


Fig. 18: Response of the system subject to short circuit with 10 cycles of duration; Short line; ± 9% uncertainty in the reading of the terminal voltage.



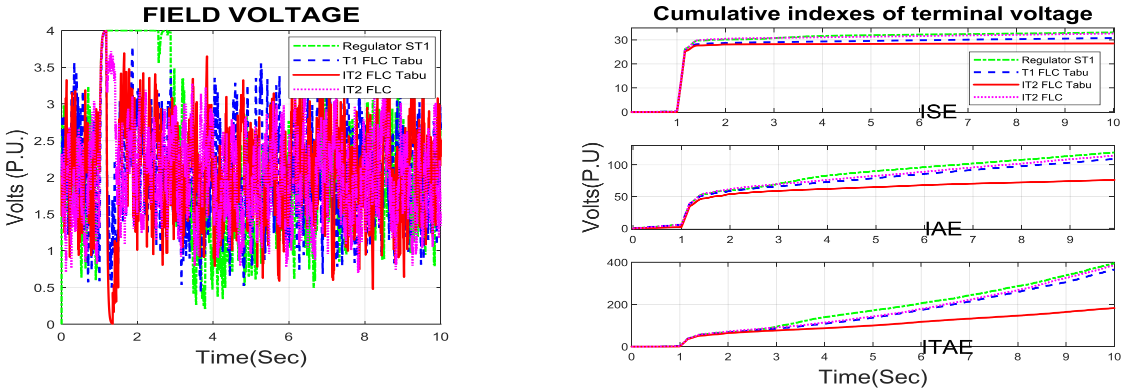


Fig. 19: Active power, reactive power, field voltage and cumulative indexes of Fig. 18.

6.3 Long transmission line, subject to a short circuit

This test the generator is connected to a long transmission line. The generator with load and subject to a three phases short circuit on the bus that occurs at 1s of simulation time, with 6 cycles of fault duration.

Results shows in Fig. 20 and Fig. 21. 25 linguistic rules are used for fuzzy controllers.

Self-tuning controllers start from the rule table of Fig. 6, 5 output bars are used as shown in Fig. 8 (b), for IT2 FLC a type 2 uncertainty is used. The criterion of high influence is used for the tabu search. The initial conditions are:

$$V_{ter} = 1\ P.U \qquad \theta = 52.3997^{o}$$

$$P_A = 0.75\ P.U \qquad P_R = 0.2726\ P.U$$

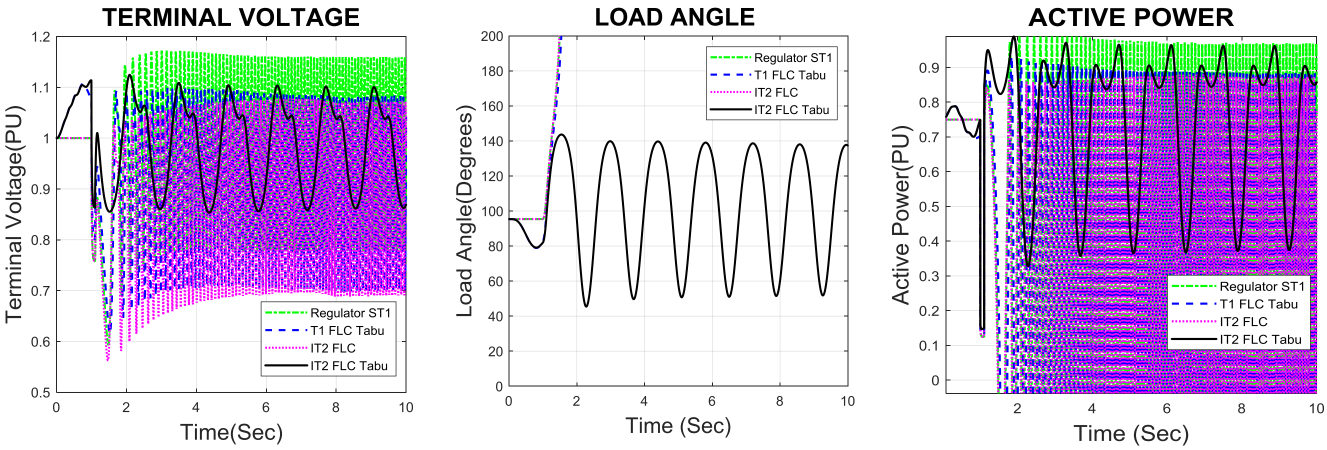


Fig. 20: Long transmission line with the generator with load and subject to a short circuit with 6 cycles of duration.

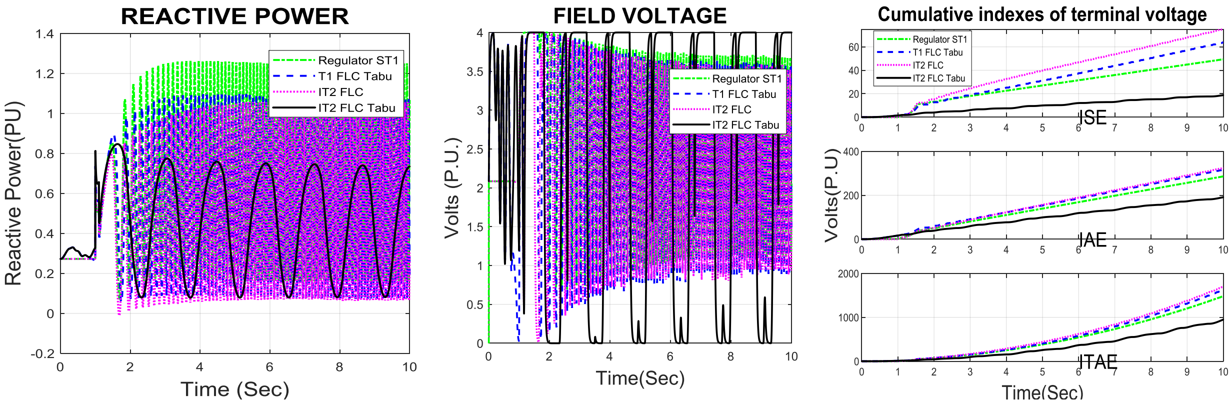


Fig. 21: Field voltage and cumulative indexes of Fig. 20.

The self-tuning IT2 FLC shows to be more robust than the other controllers because it supports more three phase short-circuit duration cycles without presenting instability and the system is operating near its theoretical operating limits.

Table 5 presents a comparison of the controllers with respect to the number of cycles they are capable of supporting before the load angle is triggered and the voltage in the terminal is destabilized, the purpose is observing the robustness of each one with respect to the tests carried out on the long transmission line.

Table 5 Robustness of controllers.

Controller	Number of cycles supported
ST1	1
IT2 FLC	3
T1 FLC Tabu	4
IT2 FLC Tabu	6

6.4 Long transmission line, load-taking from 0 – 1 P.U

Small increments are made in the turbine control from 0 to 1 P.U. The changes are not sudden, they are made by ramps in preset times.

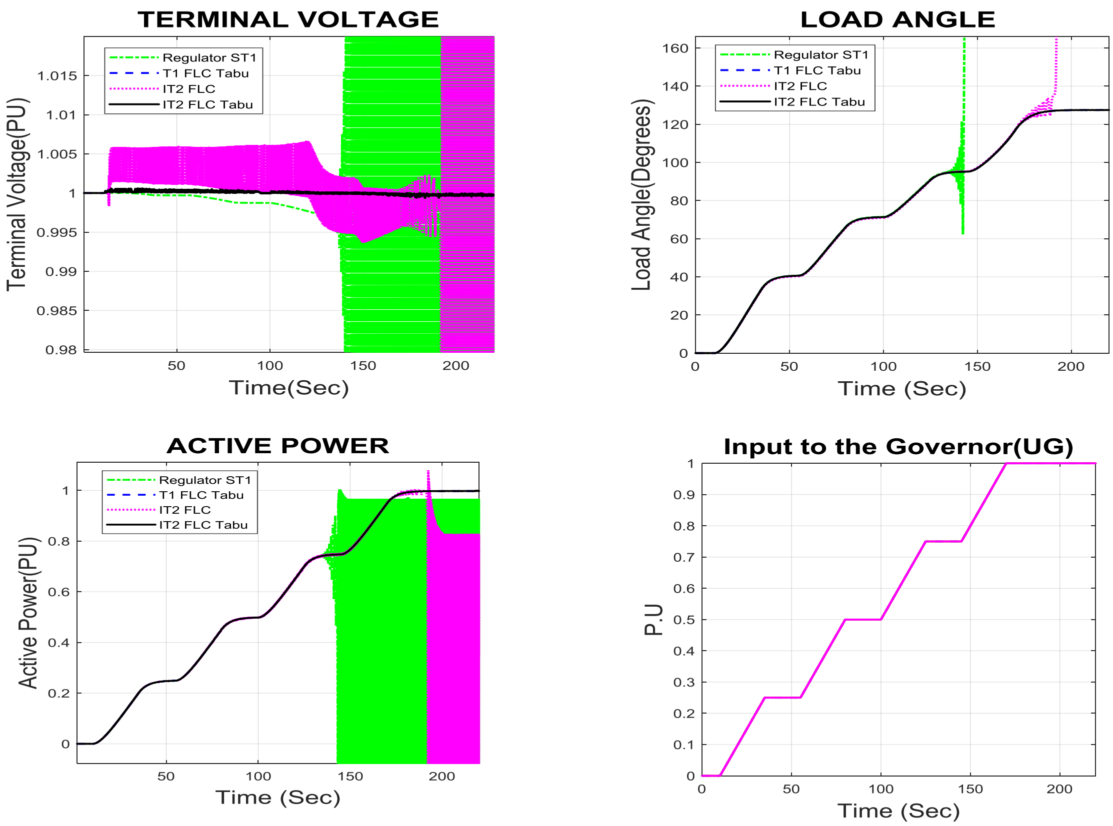


Fig. 22: Long transmission Line, load-taking from 0 – 1 P. U.

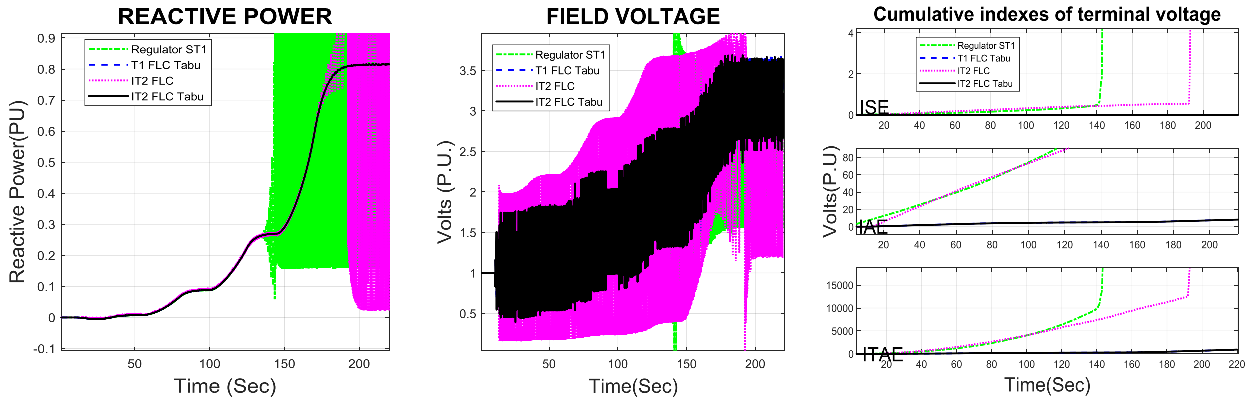


Fig. 23: Reactive power, field voltage and cumulative indexes of Fig. 22.

At the beginning the generator is without load and connected to the infinity bus by means of a long transmission line.

Fuzzy controllers use 49 linguistic rules and 7 output bars, for type-2 controllers a type 2 uncertainty is used, the self-tuning controllers depart from the linguistic rules table of Fig. 7 and use the criterion of high Influence for the tabu search. Better results were obtained without adding uncertainty in the consequential so $SL = 0 \; and \; SR = 0$.

The results obtained from this test are shown in Fig. 22 and Fig. 23. The robustness of self-tuning fuzzy controllers by tabu search is notorious because they increase the capacity in a long transmission line system. Table 6 shows the active power capacity that each controller supports. Results of this test coincide with the results obtained in [18], where it reaches 0.995 P.U of active power and a load angle of approximately 127^o, the self-tuning IT2 FLC reaches 1 P.U of active power and a load angle of 127.5^o.

Table 6 Active Power for a Long Transmission Line.

Controller	Active power	Load angle
ST1	0.6 P. U	81°
IT2 FLC	0.90 P. U	110°
T1 FLC Tabu	1 P. U	127.5°
IT2 FLC Tabu	1 P. U	127.5°

VII. CONCLUSIONS

- The high influence criterion for tabu search shows better results than the low influence criterion, because in the high influence criterion takes movements that have a lower value in the objective function to the current one, without considering the active tabu which do not allow the result to be improved in some circumstances.
- For a short transmission line, the self-tuning IT2 FLC shows better performance in response in time and error indexes, for the test with uncertainty in the terminal voltage, the self-tuning IT2 FLC keeps constant the terminal voltage. The variation of the field voltage for all cases in the controllers indicates that the controllers are always varying in order to adjust to the reference terminal voltage.
- In the graph of accumulative performance indexes: The ISE index of the self- tuning type-2 controller indicates less overshoot; While the ITAE indicates that there will be lower terminal voltage errors throughout the simulation.
- In the case of the long line system subject to a large disturbance, the self-tuning IT2 FLC shows to be more robust than the other controllers because it supports more three phase short-circuit duration cycles without presenting instability and the system is operating near its theoretical operating limits.
- The self-tuning T1 FLC and IT2 FLC controllers manage to increase the transmission capacity in a long transmission line system because they support up to 1 P.U. active power.
- The self-tuning in the linguistic rules table using tabu search allows the system to be taken to its capacity limit and improve the dynamic performance.
- The self-tuning IT2 FLC reaches the transmission capacity of reference [18].

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Appendices

A. 5th Order Model of Synchronous Machine

Generator and network

$$\frac{d\delta}{dt} = \omega_0 s$$
$$M\frac{ds}{dt} = \hat{T}_m - \hat{T}_e - k_d s$$
$$\frac{d}{dt}(e'_q) = \frac{1}{T'_{d0}}[V_{fd} - e'_q - (X_d - X'_d)i_d]$$
$$\frac{d}{dt}(e''_q) = e'_q - (X'_d - X''_d)(i_d) - e''_q$$
$$\frac{d}{dt}(e''_d) = \frac{1}{T''_{q0}}[(X_q - X''_q)i_q - e''_d \tag{14}$$

Where:

$$e''_d = V_d + r_a i_d - X''_q i_q$$
$$e''_q = V_q + r_a i_q - X''_d i_d$$
$$V_d = V_{bus} Sen(\delta) + r_e i_d - X_e i_q$$
$$V_q = V_{bus} Cos(\delta) + r_e i_q - X_e i_d$$
$$V_T^2 = V_d^2 + V_q^2$$
$$T_e = e''_d i_d + e''_q i_q - (X''_d - X''_q) i_d i_q \tag{15}$$

Excitation

$$T_X \frac{dV_f}{dt} = u - V_f \tag{16}$$

Voltage regulator

$$T_A \frac{du}{dt} = K_A(V_{ref} - V_T - V_{Exc}) - u$$

$$T_F \frac{d}{dt}V_{Exc} = K_F \frac{du}{dt} - V_{Exc} \tag{17}$$

Steam turbine and governor

$$T_{SM}\frac{d}{dt}P_{GV} = U_g - P_{GV}$$
$$T_{CH}\frac{d}{dt}P_{HP} = P_{GV} - P_{HP}$$
$$T_{RH}\frac{d}{dt}T_m = F_{HP}\frac{d}{dt}P_{HP} + P_{HP} - T_m \tag{18}$$

B. Machine Data

The data of the infinite bus machine system shown in Table 7 [18].

Table 7 System data.

Variable	Value	Variable	Value
ω_0	377.0	X_e	0.115
M	5.5294	r_e	0.024
k_d	3.0	T_{SM}	0.1
T'_{d0}	5.66	T_{CH}	0.15
T''_{d0}	0.041	T_{RH}	0.15
T''_{q0}	0.065	F_{HP}	0.33
X_d	1.904	K_A	400.0
X'_d	0.312	T_A	0.02
X''_d	0.266	K_p	0.008
X_q	1.881	T_P	1.0
X''_q	0.260	T_X	0.025
r_a	0.0	**Impedance Ω**	
Short transmission line		0.024 + j0.115	
Long transmission line		0.12 + j1.1	

C. Infinite Machine Bus System

For this work, the concept of the modified machine is used, which includes the transmission line model within the synchronous machine model. For this, the external impedances are introduced into the impedances of the stator of the machine (armature). In Fig. 24 it is shown that the load angle is taken from the generator to the terminal voltage after the impedance of the transmission line.

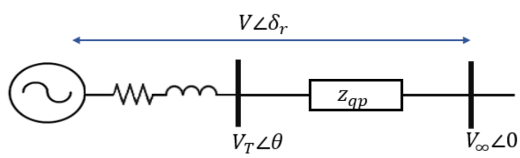

Fig. 24: Infinite machine bus system using the modified machine concept.