The analysis of type-2 fuzzy controller for ITER PF ac/dc converter control system

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Abstract. This novel type 2 fuzzy controller (T2FC) have more attractive research to developed the membership functions (MF) and rule uncertainties in the complex tokamak International Thermonuclear Experimental Reactor (ITER) Poloidal Field (PF) system. The uncertainties always happened to design the MF in real time applications. This paper proposes the T2FC design strategy in single and parallel operation. During the operations it is inflexible to handle the extremely uncertain and cannot determine the membership grades by conventional type 1 fuzzy controller (T1FC). To address the uncertainties issues the T2FC is the robust technique to accommodate the rule and membership uncertainties.

1. Introduction

The type 1 fuzzy controller (T1FC) comprises the significant on a fuzzifier, inference engine, rules, and defuzzifier. They have numerous applications many complex systems analyzed successfully using conventional mathematical techniques \cite{1}. At current the researchers and engineers have motivations to enhance the Type 2 fuzzy controller (T2FC), the real applications based on the human experience and knowledge make uncertainty with the available rule information.

The design of (T1FC) is quite difficult to handle rule uncertainties. To challenge this problem, Zadeh \cite{2} proposed the new concept type 2 fuzzy systems which are the advanced of the type 1 system. Figure 1 shows the structure of the type 1 and type 2 fuzzy systems. The modeling of the system is being circumvented by fuzzy logic, using the expert knowledge and inference systems. However, the main drawback of the type 1 fuzzy controller cannot consider the designing of the rules and MFs uncertainty. Due to disclosing limitations of type-1 FLC and PI controller, the novel control strategy using type 2 fuzzy is the suitable candidate to address membership functions (MFs) and rules issues \cite{3}. To avoid the uncertainty of the controller parameters of the complex system as ITER PF converter research the type 2 fuzzy controller.

The robustness of the T2FC analyzed the controller behavior. The proposed T2FC is first time investigated in normal operation for ITER PF converter power supply system. The proposed control algorithms are verifying the performance of the proposed type 2 fuzzy controller by single and parallel operation mode.

This paper mainly focuses on the T2FC on the single and parallel operation to analyze the high-performance control algorithm for ITER PF ac/dc converter control system. The dynamic behavior of the T1FC and T2FC are investigated and analyze the PF control system. The framework of the paper
is as follows. Section II is the significant system operation description. Section III elaborates control type 2 fuzzy logic sets. Section IV describes type 2 fuzzy controller design strategy. Section V briefly discusses the simulation results. Section VI is the conclusion.

2. System operation description

Figure 2 shows the proposed strategy of the ITER PF converter system using type 2 fuzzy controllers. The system description consists of rectifier transfer, converters units, DC reactor, and superconducting coil. The two operations (single operation, and parallel operation) analyses of the ITER PF converter have been done. Due to the limitation of type 1 fuzzy controller and PI controller, the authors are proposed the novel control strategy to address the issues of rules and membership function uncertainties. For enhancing the capability reliable operations, the converters are controls by T2FC. The challenging task in the ITER PF converter is highly nonlinear with uncertainty in different operating conditions. The PI controller with fixed gains for particular operation conditions provides an acceptable performance, but the changing dynamics of the system make poor the transient performance with continuously varies the converter operation.

The power electronics literature designs many variations of the PI controller an addition to address the operating point issues, as feedforward path, multiple-state feedback and increasing the proportional gain [4]. Commonly approach improves the bandwidth, but regrettably approach put the system towards stability limitations.

The fuzzy controller comes to handle sort of modelling problem, with the help of inference system and knowledge of experts. Further for each operating point the fuzzy controller defines the appropriate sensitivity. In reference [1] typ1 fuzzy controllers have very good performance compared to that conventional PI controller. Type 2 fuzzy controller is generally designing to address the uncertainty issues.
3. Control type 2 fuzzy logic sets

The linguistic variable as well the numerical uncertainties are modelled by type 2 fuzzy sets in a superior method. In general, the type 1 fuzzy controller uncertainties in the actual degree of membership functions are quite difficult to design. Consequently, the plant extremely operating conditions are uncertain in nature.

Type 2 fuzzy Sets (T2FS) are denoted general (universe of discourse of X) described as:

\[ W = \{(x, u_i), \mu_X(x, u_i)\}, \forall x \in X, u_i \in I_x \subseteq [0, 1] \]  

Where \( x \in X, u_i \in I_x[0,1] \) and \( 0 \leq \mu_X(x, u_i) \leq 1 \), the type 2 fuzzy is design to reduce the computational burden. Membership function \( \mu_X(x, u_i) \rightarrow [0,1] \), i.e.

\[ \bar{W}: = \int x \in X \int_{u_i} 1/(x, u_i), e \in I_x \subseteq [0,1] \]  

\( \bar{W}: X \rightarrow \{[x, y]: 0 \leq x \leq y \leq 1\} \). Figure 3 the union of all the primary membership function footprint uncertainty of about \( \bar{W} \).

![Figure 3. Type-2 fuzzy set with LMF and UMF system.](image1.png)

A type 1 fuzzy controller is the limitations to model and minimize the effect of uncertainties, despite having brings the connection of uncertainty [5].

\[ FOU(\bar{W}) = U_{x \in X} I_x = \{[x, u_i]: u_i \in I_x \subseteq [0,1]\} \]

(3)

The FOU of \( \bar{W} \) is bounded the upper membership function (UMF) and lower membership function (LMF) by type-2 MFs in Figure 3. An embedded fuzzy set \( \bar{W}_e \) described \( u_i \) in the continuous universe of discourse X as

\[ \bar{W}_e = \int_{x \in X} [1/(u_i)]/x, u_i \in I_x \]

(4)

The \( \bar{W}_e \) is embedded in which enables the details description of the analytical control surface in such a way that the secondary membership function is always lies one value of the universe of discourse \( x \).

4. Type 2 fuzzy controller design strategy

The schematic diagram of the AC to DC single bridge operation for ITER PF converter system is shown in Figure 4. Figure 4 shows the type 2 fuzzy schematic diagram. The two parallel converters are provided the current in parallel operation mode. The major difference being in type 1 fuzzy controller and the type 2 fuzzy controller have the Fuzzy sets (FS) in rule base. Hence, the type reducer in type 2 FSs inference engine is design before defuzzification can be carried out. In practical situation, the type 2 fuzzy controller significantly could be simplified computations. The following N rules consisting type 2 fuzzy controllers as

![Figure 4. Schematic diagram of the single bridge operation.](image2.png)
\[ \overline{\text{Rule}}^i = IF \text{ e is } \tilde{X}_j^n \text{ and } ... \text{ and } \dot{\text{e}} \text{ is } \tilde{X}_j^n, THEN y \text{ is } Y^n \] (5)

Where \( \tilde{X}_j^n \) (\( i = 1, \ldots, J; n = 1, 2, \ldots, N \)) are type 2 Fuzzy Sets (FSs) and \( Y^n = [\underline{w}^n, \overline{w}^n] \) is an interval, the consequent of type 2 fuzzy centroid [6]. In type 2 fuzzy controller the typical computational inputs vectors \( X^n = (x_1^n, x_2^n, \ldots, x_n^n) \) involve the following steps.

1. Numerical compute the \( x_i^n \) membership interval on each.

\[ X_i^n, \left[ \mu_{\overline{X}_i^n}(x_i^n), \mu_{\underline{X}_i^n}(x_i^n) \right], \ i = 1, 2, \ldots, I \text{ and } i = 1, 2, \ldots, N \] (6)

2. The next step is to compute the firing interval of the nth rule,

\[ G^n(x^n) = \left[ \mu_{\overline{X}_i^n}(x_i^n), \ldots, \mu_{\underline{X}_i^n}(x_i^n), \mu_{\overline{X}_i^n}(x_i^n), \ldots, \mu_{\underline{X}_i^n}(x_i^n) \right] = [g^n, \overline{g}^n], \ n = 1, 2, \ldots, N \] (7)

3. There are many such techniques frequently used one is the center of sets (COS) type reducer [7-8], further extension principle has been derived.

\[ Y_{\text{cos}}(X^n) = \bigcup_{g^n \in G^n(x^n), \mu^n \in Y^n} \frac{\sum_{n=1}^{N} g^n \mu^n}{\sum_{n=1}^{N} g^n} = [y_e, y_p] \] (8)

\[ y_e = \min_{j \in [1, N-1]} \frac{\sum_{n=1}^{J} g^n \mu^n + \sum_{n=j+1}^{N} \overline{g}^n \mu^n}{\sum_{n=1}^{J} g^n + \sum_{n=j+1}^{N} \overline{g}^n} \] (9)

\[ y_p = \max_{j \in [1, N-1]} \frac{\sum_{n=1}^{J} g^n \mu^n + \sum_{n=j+1}^{N} \overline{g}^n \mu^n}{\sum_{n=1}^{J} g^n + \sum_{n=j+1}^{N} \overline{g}^n} \] (10)

\[ \{y^n\}_{n=1, \ldots, N} \text{ and } \{\overline{y}^n\}_{n=1, \ldots, N} \text{ All the values have been stored in ascending order, respectively.} \]

Figure 5 shows the membership function for type 2 FLC.

\[ y_p = \max_{j \in [1, N-1]} \frac{\sum_{n=1}^{J} g^n \mu^n + \sum_{n=j+1}^{N} \overline{g}^n \mu^n}{\sum_{n=1}^{J} g^n + \sum_{n=j+1}^{N} \overline{g}^n} \] (11)

\[ y_p = \max_{j \in [1, N-1]} \frac{\sum_{n=1}^{J} g^n \mu^n + \sum_{n=j+1}^{N} \overline{g}^n \mu^n}{\sum_{n=1}^{J} g^n + \sum_{n=j+1}^{N} \overline{g}^n} \] (12)

Where \( L \) and \( R \), are determined the switching point.

\[ y^L \leq y_e \leq y^{L+1}, y^R \leq y_p \leq y^{R+1} \]

Figure 6. Switching operation point computing (a) Upper to lower \( y_e \) and (b) Lower to upper \( y_p \).

In type 2 fuzzy controllers, similarly approach has been adapted such as in type 1 fuzzy controller. The additional type reducer sets adjust the significant most important point \( y_e \) and \( y_p \), respectively.

The set is defuzzified using the Karnik Mendal algorithms [8] in type 2 fuzzy. The main idea is to
design the KM algorithm is to allocate the switching point. Figure 6 shows the horizontal axis to increase the $y_{u}^{n}$ is upper bound to lower bound and $y_{l}^{n}$ lower bound to upper bound. Figure 6 the $y_{e}$ using KM algorithms to find the switching point L to calculate the lower and upper bounds. To decide which interval should be used depends on the calculation of $n \leq L$ for upper bound of the firing interval and $n > L$ switch to lower bound, respectively.

The defuzzified output is computed by the average formula:

$$\text{Output} (y) = \frac{y_{e}+y_{p}}{2} \quad (13)$$

(NM), Negative Small (NL), Zero (Z), Positive Large (PL), Positive Medium (PM), and Positive Small (PS). As in type 1 fuzzy controller the seven fuzzy membership are considered for fuzzification, similarly in type 2 fuzzy controller have been consider the seven rules. The fuzzy sets are well-defined such as: Negative Large (NL), Negative Medium (NM), Negative Small (NL), Zero (Z), Positive Large (PL), Positive Medium (PM), and Positive Small (PS).

As given in Table 1, Table 1 the 49 rules are chosen for the entire membership function. The firing strength and operation are used in type 2 fuzzy sets. The complex system has unknown time-varying dynamics occur, type 2 fuzzy controller is suitable to address the particularly dynamic and uncertainty [9]. However, due to increases of the fuzzy sets increases the computational complexity in operations [10]. To adapt the type 2 fuzzy controller alleviates the computational complexity for their simplicity and efficiency.

**Table 1.** Control rule table.

| e / ec | NL | PL | NM | NS | Zo | PS | PM | PL |
|-------|----|----|----|----|----|----|----|----|
| NL    | PL | PL | PL | PL | PL | PL | PM | PS |
| NM    | PL | PL | PL | PL | PL | PM | PS | ZO |
| NS    | PL | PL | PL | PM | PS | ZO | NS | NM |
| Zo    | PL | PL | PM | PS | ZO | NS | NM | NL |
| PS    | PM | PS | ZO | NS | NM | NL | PL | NL |
| PM    | PS | ZO | NS | NM | NL | PL | NL | NL |
| PL    | ZO | NS | NM | NL | PL | NL | NL | NL |
Table 2. Parameters for the ITER PF converter.

| Parameters       | System Value   |
|------------------|----------------|
| **Converter**    |                |
| Rated power      | 2*41 MVA       |
| Voltage ratio    | 66kV/1.05kV    |
| Short-circuit impedance | 16%          |
| **Transformer**  |                |
| Inductance (L)   | 200 µH         |
| Resistance (R)   | 275 µΩ         |
| **DC reactor**   |                |
| Inductance (L)   | 5.0mH          |
| Resistance (R)   | 2.5mΩ          |

5. Simulation results
The simulations parameters are given in Table 2. Figure 8 shows the performance of the T1FC and T2FC. The analysis of the single operations using T2FC improves the operation performance. The ITER PF tokamak system is highly nonlinear in nature. To design the membership function and rules by conventional controller have limitations, especially when extremely uncertainty occurs in membership grades. In this condition the human expert’s knowledge cannot handle using the conventional fuzzy controller. Type 2 fuzzy is the suitable alternative to handle real time application uncertainties.

![Figure 8. Performance comparison of the fuzzy controller (a) type1 fuzzy (b) type 2 fuzzy.](image-url)
Figure 9. Performance comparison of the fuzzy controller in parallel operation mode type 1 and type 2.

In Figure 9 shows the type 1 and type 2 fuzzy systems in parallel operation mode. For the analysis both controllers have same reference signal to show the performance. To evaluate the performance type 2 fuzzy controllers the rules and membership function make sure the significant improvement in type 2 fuzzy controller.

Figure 10 shows the current sharing between the two converters in parallel mode. The converters $I_{d1}$ and $I_{d2}$ supply currents to the output superconducting coil load. Alpha 1 and Alpha 2 shows the dynamics changes to control the firing angle of thyristor converter. However, the proposed Type 2 (T2) controller shows the superiority in handling the system uncertainties.

Figure 11 shows the transient response time of the both controllers. The analysis determine that the Type 2 fuzzy controller response time is faster than type 1 fuzzy controller.
6. Conclusions
Type 2 fuzzy controller are demonstrated the emerging recently technique. The novel mechanism for Type 2 fuzzy controllers is utilized in many applications due to their capability to model uncertainties. The recent advance technology of Type 2 fuzzy controller is investigated for ITER PF system. The simulation results showed the significant improvement in both operation single and parallel fuzzy controller’s strategy. Further the most significant importance is to design the type 2 fuzzy membership function and rules without any modification in the parameters and more effective way to handling uncertainties.

The possible research on fuzzy system is providing high quality control of the tokamak. The fuzzy controller approaches such that Type 2 fuzzy controller is well suited for the control strategy in normal operation system.

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