FUZZY CONTROL OF A THREE-PHASE STEP-UP DC-DC CONVERTER WITH A THREE-PHASE HIGH FREQUENCY TRANSFORMER

Fabrício Hoff Dupont; Adriano Péres; Sérgio Vidal Garcia Oliveira
Universidade Regional de Blumenau – FURB
Departamento de Engenharia Elétrica e Telecomunicações – DEET
Blumenau – Brasil
fadupont@yahoo.com.br – aperes@furb.br – svgo@ieee.br

Abstract – **This paper presents a closed loop fuzzy logic control technique applied to three-phase step-up DC-DC converter with a three-phase high frequency isolation transformer. This converter was developed for industrial applications where the dc input voltage is lower than the output voltage, for instance, in installations fed by battery units, photovoltaic arrays or fuel cell systems. The converter's main characteristics are: reduced input ripple current, step-up voltage, high frequency isolating transformer, reduced output voltage ripple due to three pulsed output current and the presence of only three actives switches connected at the same reference, this being a main advantage of this converter. By means of a specific switch modulation, the converter allows two operational regions. A Fuzzy logic control strategy is applied to input-current and output- voltage regulation. The chosen controller algorithm is a PI-like fuzzy control based on the error and change of error of the reference signal. The Takagi-Sugeno inference process was choosen due to lower processing required to obtain the results. Theoretical expressions and simulations results are presented for a 6.8 kW prototype, operating in region R2 in continuous conduction mode.**

Keywords – **Fuzzy control, Takagi-Sugeno, three-phase DC-DC converters, high-frequency transformer.**

I. INTRODUCTION

As proposed in [1], the fuzzy logic results from Zadeh's concerns about the fast reduction of information quantities present on mathematical models as the systems complexity grew up. This concern has been called "principle of incompatibility" and suggests that our ability to make precise and significant statements about the behavior of a system decreases until the threshold at which precision and significance become mutually exclusive characteristics [2].

The conventional controllers depend heavily of analysis and mathematical modeling. However, even the best mathematical modeling reach the best results, due to great amount of details that it includes, more complex becomes its analysis and design. Therefore is necessary that exists a compromise between mathematical complexity of the models and the error tolerance acceptable.

The increasing development of more sophisticated devices also increased the complexity of its description. During the initial part of design, many idealizations and simplifications are assumed, minimizing the development time and the math effort involved. These idealizations are based on knowhow of designer. As counterpart, the control laws use a simplified model, resulting in a limited performance of controllers [3].

When the open loop model has a good representation of converter's dynamic, classical control techniques can be applied. By means of frequency typed responses, like Nyquist and Bode, the classical control performances can be reached. However, in an artificial intelligent based control the designer's expertise of the process under control is the background for it [4].

Although fuzzy logic had enough performance to be applied over complex processes, it applications does not be though only for it. In [5] is affirmed that the fuzzy logic utilization in well modeled processes can reduces the design time. In simulations performed, the simple conversion of a classic control for its fuzzy equivalent showed slight improvements in performance. Other issue that must be highlighted the non-linear characteristics of fuzzy controllers that are very useful for non-linear process too. Besides those that presents a simple model in control point of view [6]. However, the main fuzzy logic controllers' inconvenient is the absence of a normalized design procedure like that used on classical developments. By these reasons the fuzzy logic applied to power electronics converters is growing and has taken the attention of researchers.

The most common method of power electronics converter control is the duty-cycle monitoring [7], where the converter's output voltage is monitored and compared with a reference value. The resulting error is processed by the control algorithm that returns a value of duty-cycle that will be used for the PWM command pulses. The objective of this type of control is the maintenance of output voltage within the tolerance limits as stable as possible.

Other often used control method is the current mode control – as proposed by [8] – which can eliminate the disturbance of the input voltage but not the disturbances of the current load. Applications of fuzzy logic based controllers achieved very promising results in addressing the non-linearity in power converters [9-12].

In this paper is presented a fuzzy closed loop control strategy for the Three-phase step-up DC-DC isolated converter [13, 14] based on a Takagi-Sugeno inference process. The classical control methodology of local average modeled converter is presented in [15] and can be used as base of comparison for the obtained results by the fuzzy controller developed in this paper.

II. THE THREE-PHASE STEP-UP DC-DC CONVERTER WITH A THREE-PHASE HIGH FREQUENCY TRANSFORMER

The step-up DC-DC converter with high frequency three-phase isolation, shown in Fig. 1, was mainly developed to increase the power density handled by converters. This converter has all the main advantages of three-phase solutions, in addition to the reduced number of switches, improved efficiency and reduced volume. Due to its characteristics as a current source, this converter is very suitable for applications with alternative energy sources such as fuel cells and photovoltaic panels. Its main features are:

- Volume and weight reducing of the input and output filters due to high frequency operation;
- RMS current reduction when compared to a single-phase converter of the same power rating;
- Lower input current ripple due to the characteristic of non-pulsed current source;
- Low output voltage ripple;
- Keys connected at a common point, simplifying the driver circuit;
- Voltage applied to the switches is reduced due to the isolation transformer.

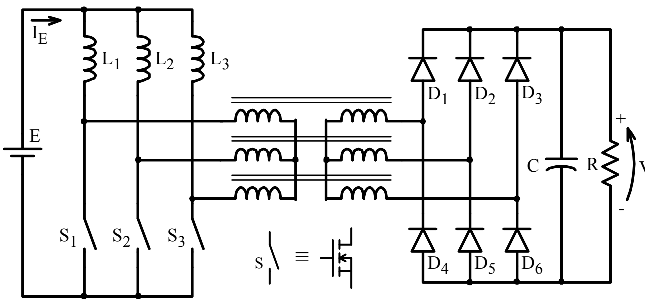

Fig. 1 The step-up DC-DC converter with a three-phase high frequency transformer diagram

Depending on the amount of simultaneously active switches, the converter can operate in three distinct regions, as presented by Table 1.

TABLE 1
Operating regions of the converter

Region	Duty Ratio	Simultaneity
R1	$D \le 1/3$	forbidden region
R2	$1/3 < D \le 2/3$	up to 2 switches
R3	$D \ge 2/3$	up to 3 switches

Since the converter input presents a current source characteristic it's essential that at least one switch is always on. This prevents damages to the components of the converter due to the over voltages caused by the inductors.

A. Converter modeling

The work [15] presents the mathematical modeling of the three-phase step-up DC-DC converter. Like in the classic designs of controllers, the model should be linearized in a particular operating point. As seen above, this simplification results in inaccuracies and, in most cases, offers no immunity to large signals disturbances and limits the converter to works only in that operating point for which it was designed.

The equations that describe the small signal model are presented below. The transfer function of input current-control $G_i(s)$ is presented in (1), where $d(s)$ is the control variable and $I_E(s)$ is the input current of the converter.

$$G_i(s) = \frac{I_E(s)}{d(s)} = G_{pi} \frac{s + \omega_{Zi}}{\left(\frac{s}{\omega_o}\right)^2 + \frac{s}{Q \cdot \omega_o} + 1} \quad (1)$$

The line-to-output or input current-to-output voltage Vo(s) transfer function is presented in (2).

$$G_v(s) = \frac{V_o(s)}{I_E(s)} = G_{Zo} \frac{s + \omega_{Zv}}{s + \omega_{Pv}} \quad (2)$$

Where:
ω_o: cutoff frequency
Q: quality factor
G_{pi}: gain of the current transfer function
ω_{Zi}: zero of the current transfer function
G_{Zo}: gain of the voltage transfer function
ω_{Zv}: zero of the voltage transfer function
ω_{Pv}: pole of the voltage transfer function

These parameters can be obtained by means of equations (3)-(9), respectively.

$$\omega_o = \frac{(1-D)}{n} \sqrt{\frac{3}{L \cdot C}} \quad (3)$$

$$Q = \frac{(1-D) \cdot R}{n} \sqrt{\frac{3 \cdot C}{L}} \quad (4)$$

$$G_{Pi} = \frac{1}{V_T} \frac{V_o \cdot n \cdot C}{(1-D)^2} \quad (5)$$

$$\omega_{Zi} = \frac{2}{R \cdot C} \quad (6)$$

$$G_{Zo} = \frac{(1-D) \cdot R \cdot r_C}{n(R + r_C)} \quad (7)$$

$$\omega_{Zv} = \frac{1}{r_C \cdot C} \quad (8)$$

$$\omega_{Pv} = \frac{1}{(R + r_C)C} \quad (9)$$

Where:
D: Duty ratio
n: turns ratio of the transformer
C: output filter capacitor
L: input inductance
R: load resistance
V_T: peak-voltage of the triangular wave
V_o: output voltage
r_C: series resistance of the output filter capacitor

B. Control strategy

The control of the converter is done by two loops: one internal for current and other external for the voltage regulation. Fig. 2 shows the diagram with the control and feedback loops for the converter circuit. $G_i(s)$ and $G_v(s)$ are the controllers transfer functions for current and voltage, respectively. V_{ref} and I_{ref} are the references values that should achieved by the controllers.

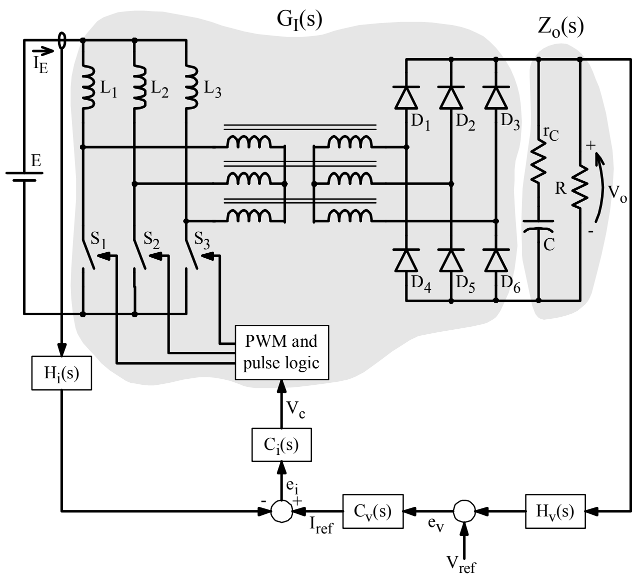

Fig. 2 The converter control strategy

The goal of the internal control loop is to impose an input current based on the reference generated by the voltage loop, which compares the converter's output voltage with a reference value. In other words, the voltage controller compares the output voltage reference value with the output voltage of the converter and generates a current reference. The current controller receives the error signal of the comparison between the reference and input current of the converter and generates a value of duty ratio such that the input current follows the reference generated by the voltage loop.

C. Classic continuous controller

As a comparison base for the performance test of fuzzy controllers proposed in this paper, the same transfer functions of the current and voltage controllers shown in [13] [15] will be used. They are described by (10) and (11), respectively.

$$C_i(s) = \frac{V_c(s)}{V_{iHall}} = 555555\frac{(s+1191)}{s(s+100397)} \tag{10}$$

$$C_v(s) = \frac{I_{Ref}(s)}{V_{vHall}(s)} = 3410\frac{(s+194)}{s(s+5250)} \tag{11}$$

As observed, the voltage loop presents a slower dynamics than the current loop. The reason for this is that the voltage loop should slowly change the value of the current reference to avoid interference from external loop.

III. FUZZY CONTROL

The main parts of a fuzzy controller are depicted in Fig. 3. The fuzzification part is responsible of converting the crisp values of input signals to fuzzy values, with a membership degree μ associated with a fuzzy variable. The rule base handles the control algorithm. At last, the defuzzification part converts a fuzzy value back to a crisp value used in the control action.

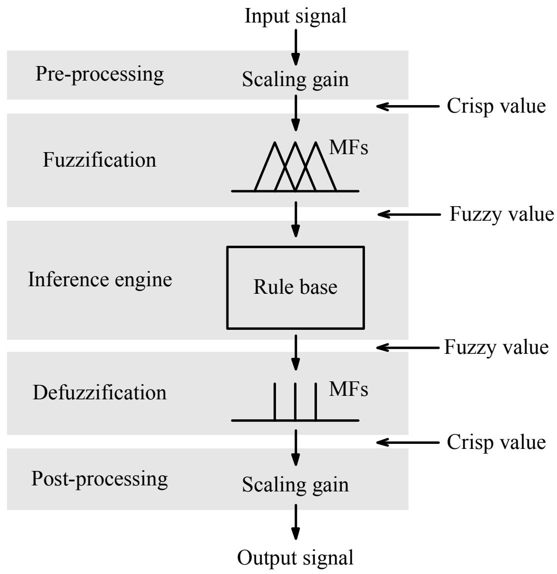

Fig. 3 Internal block diagram of a fuzzy logic controller

Among the many fuzzy control algorithms developed, one of the most commonly used is the Fuzzy PI controller, which receives its name because of its similarity with the classic PI controller.

A. Control Algorithm of Fuzzy PI

Since the integral action is usually necessary to achieve the best performance for the drivers and remove the steady state error of a system, the algorithm of fuzzy PI control are known to be more practical that the PD controller [16]. (12) describes the algorithm of control for a continuous classical PI control.

$$u = Kp\left(e + \frac{1}{Ti}\int e(t)\ dt\right) \tag{12}$$

Which can be rewritten as:

$$u = Kp \cdot e + Ki\int e(t)\,dt \tag{13}$$

Where:
e: error signal
u: control signal
Kp: proportional gain
Ki: integral gain
Ti: integral time

Deriving (13) and bringing to the discrete domain results in (14). The backward difference was used to approximate the error derivative due to its simplicity and computational efficiency. Other, and even more accurate, implementations can be found in literature, such as [17].

$$\Delta u(k) = Kp\left(\frac{\overbrace{e(k)-e(k-1)}^{\Delta e(k)}}{T_s}\right) + Ki \cdot e(k) \tag{14}$$

Where:
k: sample number
Δu: $u(k)-u(k-1)$
Δe: $e(k)-e(k-1)$

This controller configuration is also known as incremental, since the output of the controller is a change in the control action, such as:

$$u(k) = u(k-1) + \Delta u(k) T_s \tag{15}$$

If $e(k)$, $\Delta e(k)$ and $\Delta u(k)$ are seen as fuzzy variables, the control algorithm of (14) becomes a fuzzy PI controller, which is illustrated by Fig. 4.

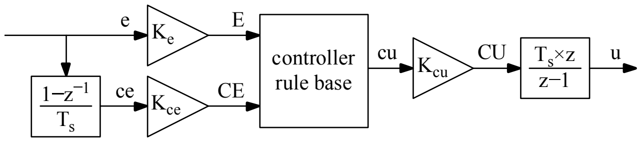

Fig. 4. Block diagram of the fuzzy PI controller.

The signals *e*, *ce* and *cu* represents the error, change in error and change in control action, respectively. The control signal at a given time instant *k* becomes the sum of all previous increments.

$$u(k) = \sum_{j=1}^{k} \left(cu(j) \cdot K_{cu} \cdot T_s \right) \tag{16}$$

And *cu* is given by (17).

$$cu(k) = f\left[K_e \cdot e(k),\ K_{ce} \cdot ce(k)\right] \tag{17}$$

Where:

cu: change in control action

f : fuzzy operation

K_e: gain of the error variable

K_{ce}: gain of the change in error variable

K_{cu}: gain of the change in control action variable

The function *f* denotes the rule base mapping, which is generally non-linear. For the purposes of an initial analysis, we can make the rule base as a linear mapping between input and output. This simplifies the analysis and allows that (17) can be written in the form of (18).

$$cu(k) = K_e \cdot e(k) + K_{ce} \cdot ce(k) \tag{18}$$

Replacing (18) in (16), is obtained:

$$u(k) = \sum_{j=1}^{k} \left[\left(K_e \cdot e(k) + K_{ce} \cdot ce(k) \right) \cdot K_{cu} \cdot T_s \right] \tag{19}$$

Replacing *ce* by the derivate of error and rearranging the terms, equation is obtained:

$$u(k) = K_{ce} \cdot K_{cu} \left[e(k) + \frac{K_e}{K_{ce}} \sum_{j=1}^{k} \left(e(j) \cdot T_s \right) \right] \tag{20}$$

Comparing (20) with (12), the gains can be related as:

$$K_{ce} \cdot K_{cu} = Kp \tag{21}$$

$$\frac{K_e}{K_{ce}} = \frac{1}{Ti} \tag{22}$$

B. Membership functions

The central point of the fuzzy logic is the concept of linguistic variable. Besides representing a fuzzy value, the variables carry some linguistic qualifiers and allow the fuzzy modeling directly expresses the semantic meanings used by experts [18]. The membership functions are used to describe the degrees of membership of the values within the fuzzy sets.

[19] shows that, despite the membership functions can take many forms, the triangular ones shows the best performance, and don't require many calculations for their processing. To the controller studied in this paper, seven linguistic variables were chosen, represented by: NB (negative big), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium) e PB (positive big). These variables were linearly distributed in the normalized universe of discourse, as depicted by.

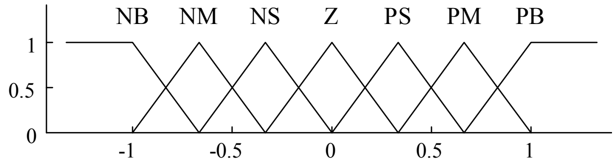

Fig. 5 Membership functions of variables.

C. Rule base design

The set of rules is the central component of any fuzzy system control and represent the "intelligence" of the control algorithm [5]. The fuzzy rules are composed of two or more fuzzy sets called antecedent, and associated with them, a set called consequent. This form of non-linear mapping of inputs and outputs allows the creation of static non-linear control functions [6]. When a set of entries are read, each rule that contains some degree of truth in its premises will be executed.

[6] emphasizes that the rule base design is a heuristic search for the best mapping of input and output variables. Moreover, it is important to note that the implementation of fuzzy rules is declarative rather than procedural (as in traditional programming). The order in which rules are programmed in the controller is not important and does not change the driver's performance.

To assist in the design of the rule base [19] proposes a method of analysis for the time response for the controller rule base. From this analysis, is found the control rule matrix of TABLE 2.

TABLE 2
Rule matrix for the fuzzy PI controller

		e						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
ce	**PB**	0	0.33	0.66	1.0	1.33	1.66	2.0
	PM	-0.33	0	0.33	0.66	1.0	1.33	1.66
	PS	-0.66	-0.33	0	0.33	0.66	1.0	1.33
	Z	-1.0	-0.66	-0.33	0	0.33	0.66	1.0
	NS	-1.33	-1.0	-0.66	-0.33	0	0.33	0.66
	NM	-1.66	-1.33	-1.0	-0.66	-0.33	0	0.33
	NB	-2.0	-1.66	-1.33	-1.0	-0.66	-0.33	0.0

This matrix is used both for the current loop controller and the voltage loop controller. The dynamics differences between the voltage and current loops are handled through the adjustment of gains of the controllers.

Usually the number of rules is directly linked to the number of control variables and represents the total number of possible combinations. In some applications it is possible to use a lower number of rules. However this decision is not recommended and may lead the system to instability. Since the rules represent the knowledge of the system, removing any of them implies the reduction of system knowledge and can lack in future modifications of the system as a whole.

D. Defuzzification method

Several inference or defuzzification methods are proposed in the literature. However, none was superior to everyone in all situations [20].

For the Takagi-Sugeno inference processes, one of the most used defuzzification method is the weighted average of all rule outputs, expressed by (23) for n number or rules.

$$u = \frac{\sum_{i=1}^{n} w_i z_i}{w_i} \tag{23}$$

Where w_i is the firing strength of a rule, given by:

$$w_i = AND\left(\mu_e, \mu_{ce}\right) \tag{24}$$

The AND method used in this article is the product of the membership values of error (μ_e) and change in error (μ_{ce}). z_i is a constant obtained from the rule base.

E. Tuning strategy

Due to the large number of variables that can be adjusted and lead to changes in the control system performance, its project depends on some starting points. Hardly a fuzzy controller will be in its optimum point of operation without having several sessions of trial and error before its correct parameters adjustment. In addition to the proposed by (21) and (22), other items that can be changed in fuzzy controllers are:

- Adjustment in the set of rules may affect the performance of the controller. However, this adjustment is a little complicated.
- Change the membership function may not rebound in significant performance improvements. Moreover, it is not so convenient to adjust the membership functions.
- Tuning of gains directly affect the controller performance, also it's an easier adjustment than the other two options. This is the most common means for the adjustment of fuzzy controllers.

Besides, [16] suggests the following result observation and parameters adjustment:

- The variation of K_e does not affect much the rise and settling time. But when K_e is big it causes certain overshoot.
- When K_{ce} is small, the system response presents a short rising time but with a big overshoot. When K_{ce} is large, the overshoot disappears but with a slow system response.
- K_{cu} has great influence in the system rise time. Usually a large K_{cu} causes fast system response (and results in a short rise time). Otherwise, a low value of K_{cu} causes a very slow system response.

IV. SIMULATIONS AND PERFORMANCE ANALYSIS

PSIM simulations were done aiming to validate the theory presented above. The characteristics of the used converter are:

- Output power: 6.8 kW
- Output nominal voltage: 450 V
- Input nominal voltage: 47 V
- Switching frequency: 20 kHz
- Transforming relation: 21:4
- Magnetizing inductance: 198 µH
- Leakage inductance of the primary winding: 165 nH
- Series resistance of primary winding: 0,1 mΩ
- Output capacitance: 2 mF
- Series resistance of output capacitor: 1 mΩ
- Input inductance: 127 µH
- Current sensor gain: $16{,}5\times10^{-3}$
- Voltage sensor gain: 6×10^{-3}

The fuzzy controllers were compiled into a DLL containing an inference engine of the Takagi-Sugeno type with the membership functions and rule based shown above. The simulations were performed until 1.1 s with a fixed time step of 5 µs. In 410 ms the load value is reduced by half and its nominal value is reapplied in 800 ms.

For quantitative comparison of performance between the classical and fuzzy controllers discussed in this article IAE and ITAE criteria are used, defined in (25) and (26).

$$\text{IAE} = \int |e|\, dt \tag{25}$$

$$\text{ITAE} = \int t \cdot |e|\, dt \tag{26}$$

The IAE criteria take into account the results mainly at the beginning of the response The ITAE criteria take into account the initial transient as well, but it emphasizes the steady state errors. All simulations were done using the same time step in order to maintain the same criterion for comparison.

To judge the controllers with the same degree of equality (all PI), the filters of classical controllers will be passed to the feedback loops. Thus, the transfer functions of the current and voltage controllers will be, respectively:

$$C_i(s) = 5.5336\frac{(s+1191)}{s} \tag{27}$$

$$C_v(s) = 0.6495\frac{(s+194)}{s} \tag{28}$$

And the filters of their feedback loops are:

$$LPF_i(s) = \frac{100397}{s+100397} \tag{29}$$

$$LPF_v(s) = \frac{5250}{s+5250} \tag{30}$$

From (27) the proportional and integral gains for the current controllers can be obtained by inspection:

$$CC_i = \begin{cases} Kp_i = 5.5336 \\ Ki_i = 6590 \end{cases} \tag{31}$$

The same can be done for the voltage controller (28):

$$CC_v = \begin{cases} Kp_v = 0.6495 \\ Ki_v = 126 \end{cases} \tag{32}$$

Where CC_i and CC_v are the classical controllers for current and voltage, respectively.

A. Classical PI control

Using the gain presented in (31) and (32) the simulation of classical PI controllers is done. This simulations serves as a comparative bases for the fuzzy controllers presented in sequence. The output voltage of the converter is illustrated by Fig. 6.

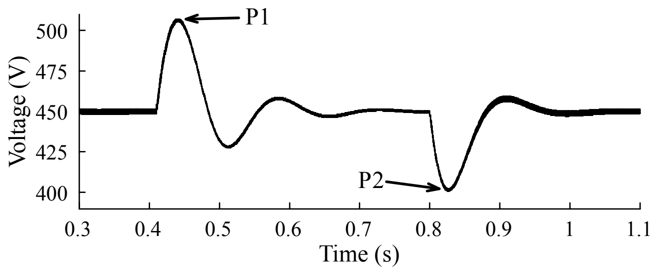

Fig. 6 Output voltage for the classical controller CC_v.

And the input current is depicted by Fig. 7.

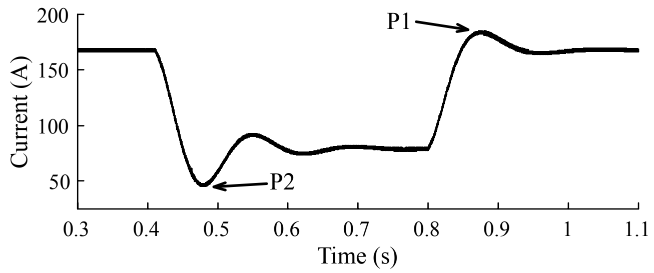

Fig. 7 Input current for the classical controller CC_i.

B. Fuzzy PI control (direct conversion)

As shown, a starting point in the design of fuzzy controllers is its conversion from a classical controller previously developed. This section presents the results from the replacement of the proportional and integral gains, presented in the previous section, into (21) and (22). Given a value for one of the gains, the other can be easily determined.

After some tests, were found that the gains who results in better performance are: Ke_{1i} = 0.4 and Ke_{1v} = 0.02 for current and voltage controllers, respectively. Solving for these two cases, the gains of fuzzy controllers that emulate the classic control of the previous section are defined by:

$$FC_{1i} = \begin{cases} Ke_{1i} = 0.4 \\ Kce_{1i} = 335.9\times10^{-6} \\ Kcu_{1i} = 16475 \end{cases} \tag{33}$$

$$FC_{1v} = \begin{cases} Ke_{1v} = 0.02 \\ Kce_{1v} = 103.1\times10^{-6} \\ Kcu_{1v} = 6300 \end{cases} \tag{34}$$

Where FC_{1i} and FC_{1v} are fuzzy controllers for current and voltage, respectively, from the direct conversion of the classical controllers.

The simulated output voltage is illustrated by Fig. 8.

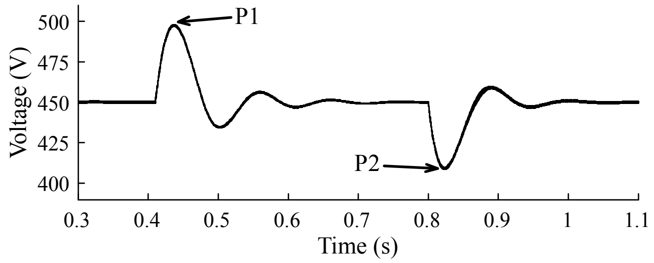

Fig. 8 Output voltage for the fuzzy controller FC_{1v}.

And the input current is shown by Fig. 9.

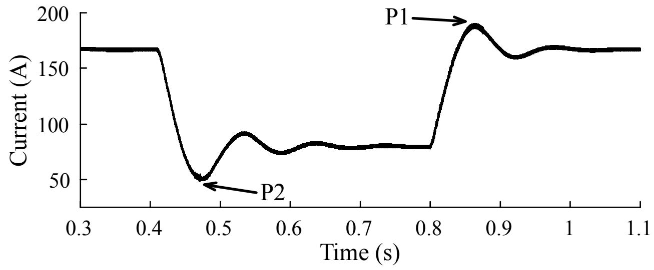

Fig. 9 Input current for the fuzzy controller FC_{1i}.

C. Fuzzy PI control (further tuning)

Applying the additional suggestions for tuning previously presented, heuristic adjustments were made through simulations based on trial and error. After several tests trying to improve the performance of the controllers, the following sets of gains were obtained:

$$FC_{2i} = \begin{cases} Ke_{2i} = 0.9 \\ Kce_{2i} = 300\times10^{-6} \\ Kcu_{2i} = 16500 \end{cases} \tag{35}$$

$$FC_{2v} = \begin{cases} Ke_{2v} = 0.12 \\ Kce_{2v} = 600\times10^{-6} \\ Kcu_{2v} = 7000 \end{cases} \tag{36}$$

Where FC_{2i} and FC_{2v} are fuzzy controllers for current and voltage, respectively, obtained by trial and error adjustments. It is emphasized that only the gains were tuned. The membership functions and the rule base have been kept exactly the same.

The simulated output voltage is depicted by Fig. 10.

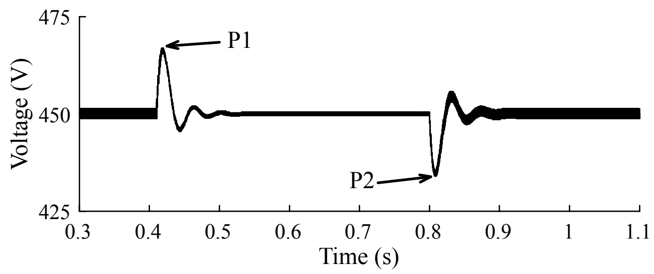

Fig. 10 Output voltage for the fuzzy controller FC_{2v}.

And the input current is shown by Fig. 11.

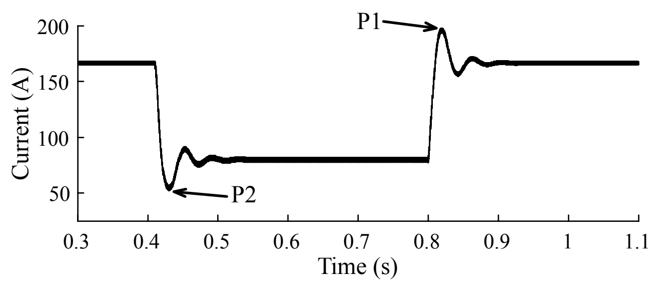

Fig. 11 Input current for the fuzzy controller FC_{2i}.

D. Analysis

From the data obtained in the simulations presented so far, the quantitative parameters of comparison are determined. TABLE 3 shows the IAE and ITAE parameters of the voltage controllers.

TABLE 3
Performance analysis of the voltage controllers.

Criteria	CC_v	FC_{1v}	FC_{2v}
IAE	41.40×10^{-3}	30.81×10^{-3}	3.91×10^{-3}
ITAE	26.07×10^{-3}	19.34×10^{-3}	2.42×10^{-3}

The simple conversion of the classic controller in its fuzzy equivalent resulted in an improved performance. Besides, with only the adjustment of the gains, a significantly higher performance for the controller FC_{2v} was achieved.

For the current controllers, the IAE and ITAE parameters are described by TABLE 4.

TABLE 4
Performance analysis of the current controllers.

Criteria	CC_i	FC_{1i}	FC_{2i}
IAE	3.13×10^{-3}	3.42×10^{-3}	5.19×10^{-3}
ITAE	2.20×10^{-3}	2.44×10^{-3}	3.56×10^{-3}

Due to the slower dynamics of the voltage loop compared with the current loop, the current controllers have almost the same performance parameters. In this case, it is observed that the controller FC_{2i} shows a slightly worse result, which is not even a relevant difference.

The markers in Fig. 6 to Fig. 11 highlight the points of peaks (P1) and valleys (P2) of the quantities shown. TABLE 5 lists these points for the output voltage of the converter.

TABLE 5
Peaks and valleys of the output voltage.

	CC	FC_1	FC_2
Peak (P1)	507.25 V	498.07 V	466.97 V
Valley (P2)	400.93 V	408.61 V	434.01V

Again should be highlighted the significant improvement of performance for the controller FC_2, which presented an overshoot of 17 V – 40 V less the overshoot measured for the controller *CC*.

For the input current, the points of peaks and valleys are listed in TABLE 6.

TABLE 6
Peaks and valleys of the input current.

	CC	FC_1	FC_2
Overshoot (P1)	184.97 A	190.12 A	198.06 A
Undershoot (P2)	44.87 A	48.26 A	52.38 A

To complete the comparison, the waveforms of the output voltage for the three presented controllers are superimposed. For the proposed application, the Fig. 12 clearly shows the superiority of the fuzzy controller FC2 in the control of output voltage.

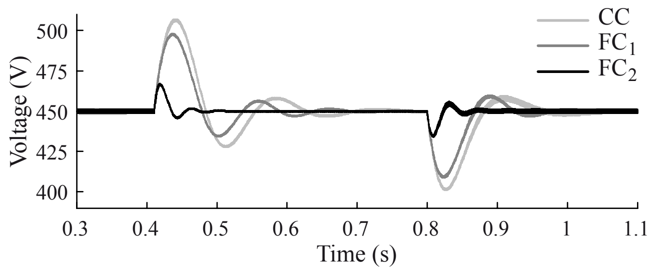

Fig. 12 Comparison of output voltages.

Fig. 13 presents the complete comparison of waveforms for the input current to the three controllers.

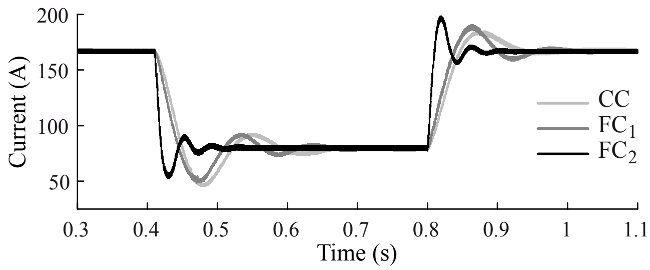

Fig. 13 Comparison of input currents.

V. CONCLUSIONS

This paper presented a comparison between the classical and fuzzy controllers for the three-phase step-up DC-DC converter with a high frequency isolation transformer. The main points of this converter and its benefits were reviewed. Also, the theory of fuzzy control was briefly reviewed with the objective to offer a basis for the development of the proposed current and voltage controllers.

The simple conversion of the classic controller for its fuzzy equivalent has shown a slight improvement in performance. Based on gains obtained to the equivalent fuzzy controller, adjustments were made based on trial and error and a second fuzzy controller was obtained. This controller presented significant improvements in overall system performance, as demonstrated in simulation results.

Through its resolution ability among uncertainty and vagueness, fuzzy controllers can be used in applications with low resolution A/Ds, reducing costs when compared to other digital controllers using traditional techniques that rely on accuracy.

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