Simple PI Fuzzy Logic Controller Applied in DC-AC Converter

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***Abstract*—In this paper, a simple Proportional Integral Fuzzy Logic Controller (PI-FLC) applied to a DC-AC converter is presented. This approach uses Signed Distance Method, where the multi input single output (MISO) system can be reduced to single input single output (SISO) system without degrading the original performance of MISO PI-FLC system. The input-output relationship of SISO PI-FLC system then can be simply mapped using piecewise linear approximation. A comparison with the original PI-FLC is carried out by MATLAB-Simulink simulation to verify the performance of the proposed approach.**

***Index Terms*—Controller, PI, fuzzy logic, pieceweise linear, DC-AC converter**

I. Introduction

THE main objective of controllers in a DC to AC power converter is to ensure the output follows the sinusoidal reference with a good dynamic response. In addition it is desirable that an acceptable Total Harmonic Distortion (THD) to be obtained. To date, there are many types of controllers designed to achieve those goals. The most popular is the Proportional Integral (PI) controller. The PI controller has a good performance with simple implementation and can be applied in inexpensive processor board. However, it fails to perform satisfactorily in nonlinear load condition, large-signal disturbance and uncertainties. Furthermore, PI is the model-based controller, which limits its application in a system where the model is too ill-define.

In order to achieve a better performance, modern controllers have been proposed, namely Feedback Linearization[1], Deadbeat Controller[2], Sliding Mode Controller[3] and Repetitive Controller [4]. However, some of these controllers still require system model to perform satisfactorily. Among them, only Sliding Mode Controller (SMC) is non-model based controller. The idea of SMC is to force the system response to follow a sliding line so that its state error and its derivative can be driven to zero. Although it offers simple implementation, it suffers from very complex control theory and variable switching frequency [5].

Another type of non linear controller that has gain much interest recently is the fuzzy logic controller (FLC). Compared to the others controllers, FLC has several distinct advantages:

- it does not require model to design the controller
- it is able to handle nonlinearities and
- it is more robust operation than other nonlinear control.

A comparison study between SMC and FLC shows that both controllers produce a similar performance. However in some respect i.e., disturbance transient, and steady state it appears that FLC outperforms the SMC [5]. Furthermore, structure wise, FLC is much simpler than SMC.

This paper describes a SISO PI-FLC design to control a typical DC-AC converter. The approach uses a Signed Distance Method, where multi input single output (MISO) system can be reduced to single input single output (SISO) system without degrading the original performance of MISO PI-FLC system. The input-output relationship of SISO PI-FLC system then can be simply mapped using piecewise linear approximation. A comparison with the original PI-FLC is carried out by MATLAB-Simulink simulation to verify the performance of the proposed approach.

II. Fuzzy logic controller

Fuzzy Logic can be defined as a theory of vagueness and uncertainties. This theory provides an approximate yet effective, means of describing the behavior of the systems, which are too complex and ill defined to permit precise mathematical analysis.

Typically, FLC consists of three stages, namely Fuzzification, Rule Decision Making and Defuzzification. Fuzzification is a process to transform the non-fuzzy values (crisps data) from the physical measurement into a fuzzy linguistic range, i.e., Positive Big (PB), Positive Small (PS), Negative Small (NS) etc. The assignment of the crisps input into fuzzy form is realized by Membership Function (MF). The crisp input are first been normalized so that the input covers all the membership functions range. This can be realized by using input scaling factor that acts as forward gain.

Presently, there is no generalized standard procedure on how to select the appropriate shape of Membership Function for specific applications. Membership Function shape can be either trapezoid, triangular, singletone or bell-shape. However, triangular with 50% overlap between the adjacent MF is more preferred shape since it contributes to a less computational process time.

Rule Decision Making consists of two components. They are Rule Table and Rule Evaluator. The rules stored in Rule

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Table actually relate the input-output relationship. For instance, for two inputs with equal five fuzzy sets, there will be 25 rules that relate the input-output relationship. The rule evaluator will decide which rules should be fired with a help of linguistic rule: IF…THEN…. For n inputs, there will be a maximum of 2n rules fired.

The last stage is the defuzzifiction stage. Defuzzification is a stage where the fuzzy form is transform to physical values (crisps output). Two methods usually carried out to perform the task are Centroid Method and Mean Maximum Method.

III. PI FUZZY CONTROLLER

In general, FLC can be classified into three types of controllers, namely PI Fuzzy Logic Controller (PI-FLC), PD Fuzzy Logic Controller (PD-FLC) and PID Fuzzy Logic Controller (PID-FLC). Each name reflects their identical performance to their conventional PI, PD and PID control performance but with tuning adjustment features.

PID-FLC needs three inputs: error (e), change of error (Δe) and sum of errors (δe). This factor significantly expands the Rule Table and makes the design more complicated. Compared to PID-FLC, PI-FLC and PD-FLC are much simpler and more applicable. It is known, the PI-FLC is more practical than PD-FLC because PD-FLC usually produces system steady state error because of lack integral function in its control nature[6].

Fig. 1 shows the basic PI-FLC block diagram. It needs two inputs namely, error (e) and the change of error (Δe). The inputs will be normalized using input scaling factors, i.e Ke and K_{ce} before being fuzzified. The output of this type of FLC is the change of normalized controlled output (Δu). Then, normalized crisps output will be denormalized using output scaling factor, i.e K_{cu}.

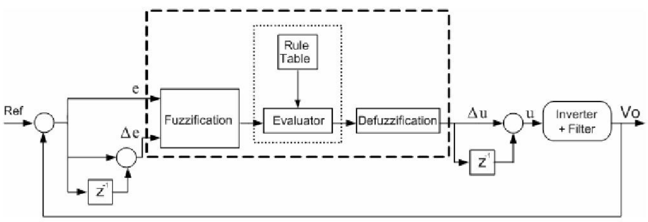

Fig. 1 Typical PI fuzzy logic controller block diagram

IV. SIGNED DISTANCE METHOD

Apparently the performance of PI-FLC is highly depends on the number of fuzzy rules. Increasing the number of fuzzy rules will definitely gives better control results, but in another hand, it adds additional computation time. The same case goes to when the rules are reduced. It will result on faster computation time but the output may be unsatisfactory.

To overcome the problem, B.J.Choi, et.al [7] has proposed a method called Signed Distance Method. In this method, any Multiple Input Single Output (MISO) system can be reduced to Single Input Single Output (SISO) system without degrading its original FLC performance. However, the method is only can be applied if the rule table has a Toeplitz structure [7] or near Toeplitz structure [8]. Table 1 shows the example of rule table that has Toeplitz structure. Since most of FLC rule tables applied in power converters have a Toeplitz structure [9,10], the proposed method is suitable to be adopted.

TABLE 1
RULE TABLE WITH TAEPLOITZ STRUCTURE

e / ce	PB	PS	Z	NS	NB
NB	Z	PS	PB	PB	PB
NS	NS	Z	PS	PB	PB
Z	NB	NS	Z	PS	PB
PS	NB	NB	NS	Z	PS
PB	NB	NB	NB	NS	Z

To derive the relation between the two inputs, the rule table can be redrawn into Fuzzy Associates Memory (FAM) structure [10] as shown in Fig. 2.

From the figure, *e(i+n)* and *Δe(j+n)*, where n = …,-2,-1,0,1,2,… are the center value of each membership function.

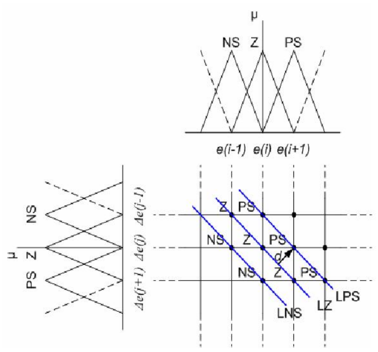

Fig. 2. Fuzzy Associate Memory (FAM) structure

LPS, LNS and LZ are a linear line that connects all the outputs that are in the same membership functions. The main linear line, LZ can be expressed as:

$$e(i)\lambda + \Delta e(j) = 0 \tag{1}$$

Where λ is the slope of LZ line.

Then the distance (*d*) of another linear lines; LNS, LPS etc can be computed as:

$$d_n = \frac{e(i+n)\lambda + \Delta e(j+n)}{\sqrt{1+\lambda^2}} \tag{2}$$

Thus, for PI-FLC that has 25 rules (5 fuzzy sets of *e* x 5 fuzzy sets of *Δe*), it can be reduced to only 5 rules. Table 2 shows the reduced rule table. The advantages of this method can be summarized as:

a) The number of rules are greatly reduced
b) The number of tuning parameter can be considered reduced
c) Computational complexity mitigates
d) Can be simply extended to n input

TABLE 2
REDUCED RULE TABLE

d	LNB	LNS	LZ	LPS	LPB
u	NB_p	NS_p	Z_p	PS_p	PB_p

V. FLC AS A PIECEWISE LINEAR

In SISO FLC system, input-output relationship can be simply mapped into a piecewise linear approximation as shown in Fig. 3. The figure depicted that LPSp and LPBp are the center value for membership function of LPS and LPB, respectively while PSp and PBp is the peak point of output fuzzy sets. However, there are a number of constraints that should be followed [11]:

a) The fuzzification process uses the triangular membership function.
b) Each of fuzzy membership function is overlapping each other by 50%.
c) The defuzzification process used is the centroid method.

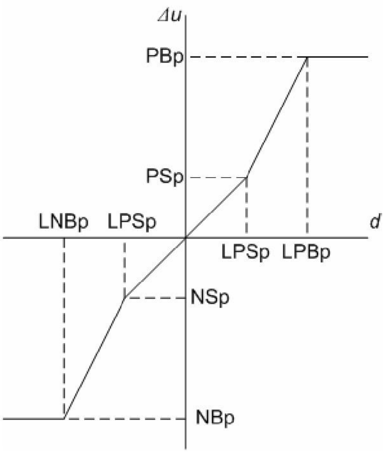

Fig. 3. Piecewise linear input-output relationship for SISO FLC system

VI. PROPOSED SISO PI FUZZY LOGIC CONTROLLER

This paper proposed of SISO PI-FLC, where it yields an identical performance of its original MISO PI-FLC system. The reduction of number of rules and the utilization of piecewiselinear approximation, result in a very fast computation time. Thus for digital implementation, the sampling time can be made faster. Fig. 4 shows the block diagram of the proposed controller.

Compared with conventional PI controller, PI-FLC can be tuned if the output is unsatisfactory. The tuning or adjustment can be made either via modifying rule table, membership function or by adjusting the scaling factors [7]. For the proposed method, scaling factors adjustment will be used. For small signal disturbance, the PI-FLC scaling factors are tuned equal to its conventional PI gains. By doing so, the controller's stability and dynamic performance are ensured.

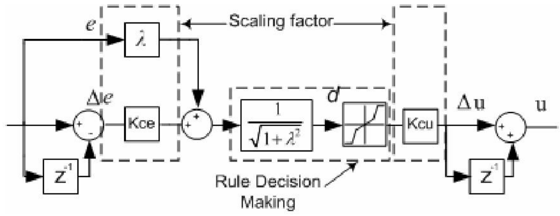

Fig. 4 Simplified PI-FLC block diagram

VII. DESIGN AND SIMULATION

The proposed control method has been designed and simulated using MATLAB-Simulink software package. The proposed control consists two feedback loops, namely the inductor current loop as the inner loop and output voltage loop as the outer loop. Table 3 summarised the paramater values used in this simulation.

TABLE 3
PARAMETER VALUES

Parameter	Value
V_{DC}	100V
L_{filter}	250μH
C_{filter}	33μF
Rated load	20 Ω
Reference Voltage	80V
Output Power	0.32KW
f_s	10 KHz
Sampling freq. for voltage loop	10 KHz
Sampling freq. for current loop	20 KHz

A. *Discrete PI controller design*

Generally, there are two methods used in designing discrete PI controller. The first method is by designing PI controller in its discrete mode. Here, the system must be fully converted to its discrete form before the discrete PI controller gain could be obtained. The second method is by designing the PI controller in its continuous mode. Then, the obtained continuous PI gains are converted to thier discrete form using bilinear transformation method. Since the second method offers simpler approach, thus it is more preferred. Furthermore, since the sampling period choosed for both control loops are small, the delay caused by the Zero Order Hold (ZOH) introduced in discrete system can be neglected.

The continuous PI controller has been designed using classical analysis approach. Adjusting the poles/zeros locations, so that the phase margin is within 40^o to 60^o (for stability) the controllers gain can be obtained as: K_{pv} = 0.05 ,K_{iv} = 2300, K_{pi} = 0.0315, K_{ii} = 126. The transfer function of the controller, then can be written as:

$$C_v(s) = 2300\left[\frac{0.00002174s+1}{s}\right] \quad (3)$$

$$C_i(s) = 126\left[\frac{0.00025s+1}{s}\right] \quad (4)$$

The transformation to its discrete transfer function form can be done simply by replacing the Laplace variable "s" with :

$$s = \frac{2}{T_s}\left[\frac{z-1}{z+1}\right] \quad (5)$$

T_s is the sampling period for each control loops. Thus, C(s) can be rewritten in discrete forn as:

$$C(z) = \frac{mz+n}{z-1} \quad (6)$$

Where the parameter m and n are given by

$$m = K_i\left[\frac{K_P}{K_i}+\frac{T_s}{2}\right] \quad (7)$$

$$n = K_i\left[\frac{T_s}{2}-\frac{K_P}{K_i}\right] \quad (8)$$

The transfer function of C(z) can be expressed as a difference equation and the block diagram representation of this difference equation is illustrated in Fig. 5:

$$u(k) = -n\left[\frac{-(m+n)}{n}e(k)+(e(k)-e(k-1))\right]+u(k-1) \quad (9)$$

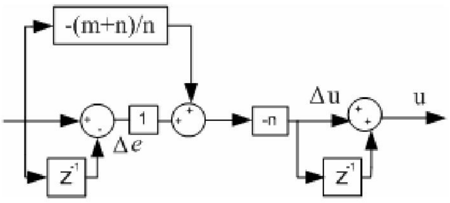

Fig. 5. Block diagram representation of equation (9)

B. SISO PI-FLC design

From Fig. 4 and Fig. 5, both show an identical structure. Thus the scaling factors can be set as λ = -(m+n)/n, K_{ce} = 1 and K_{cu} = -n and the slope of d/Δu function is set unity. By doing so, the controller is identical to a conventional PI controller, which ensure excellent small-signal performance. Through simulation, in order to obtain satisfactory small-signal and large signal performance, the breakpoint of the d/Δu mapping function is set at d = 20. For d less than 20, its slope is set equal to unity while for d beyond 20, the slope is set higher than unity as depicted in Fig.6.

The overall proposed control system can be depicted as in Fig. 7.

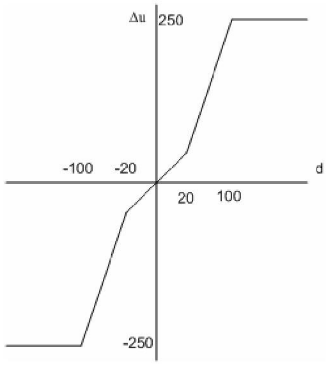

Fig. 6 d /Δu mapping function with breakpoint at d =20

C. MISO PI-FLC design

To verify the proposed approach, MISO PI-FLC has been designed. The scaling factors of the MISO PI-FLC are set equal to their SISO PI-FLC version. The membership function shape used is a triangular shape. The input fuzzy set for error and change of error are divided into five fuzzy sets as shown in Fig. 8. The MISO PI-FLC is developed using Takagi-Sugeno (TS) Type fuzzy logic which the output is a singleton. The developed rule table is as shown in Table 4.

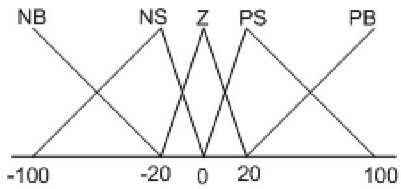

Fig. 8 Membership function for input error and change of error

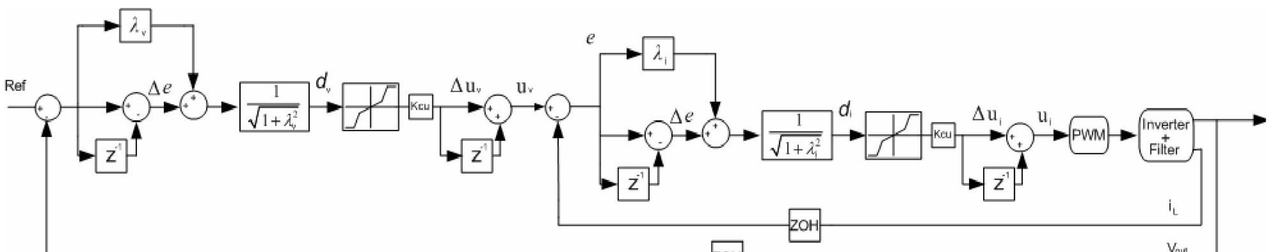

Fig. 7 Full system block diagram

TABLE 4
RULE TABLE

e / ce	NB	NS	Z	PS	PB
PB	0	192.5	250	250	250
PS	-192.5	0	20	77.5	250
Z	-250	-20	0	20	250
NS	-250	-77.5	-20	0	192.5
NB	-250	-250	-250	-192.5	0

VIII. RESULT

Fig.9(a) shows the output voltage for a conventional PI controller for from no-load to full-load condition which occurred at 0.025s while Fig.9(b) shows the voltage output of proposed control method for the same condition. It can be seen that both methods are able to compensate for the disturbance rather well. However, a detailed examination at the transient point reveals that the proposed controller performs better than the PI controller, as depicted in Fig. 10.

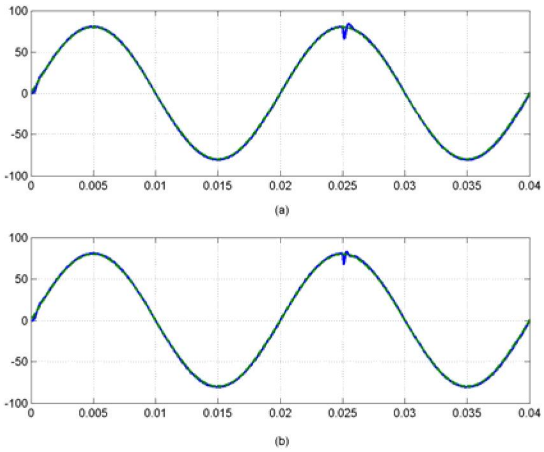

Fig. 9 Voltage output waveform (a) PI controller (b) Proposed controller

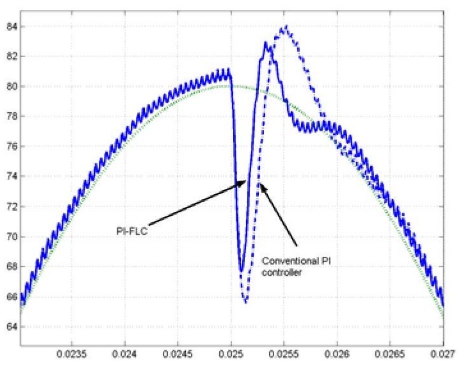

Fig. 10 Comparison between voltage output waveform of PI controller and the proposed method.

Fig. 11(a) and (b) show the comparison of the SISO PI-FLC with the MISO PI-FLC for large load step and small load step. As can be observed, there is hardly any difference between the two methods. The performance of both controllers are indistinguishable. This result verifies the approximation method proposed in this paper.

In order to verify whether the proposed controller is capable in handling cyclic load, a simulation with triac load has been carried out, as shown in Fig. 12, it can be seen that the proposed controller is capable in handling such load with acceptable performance.

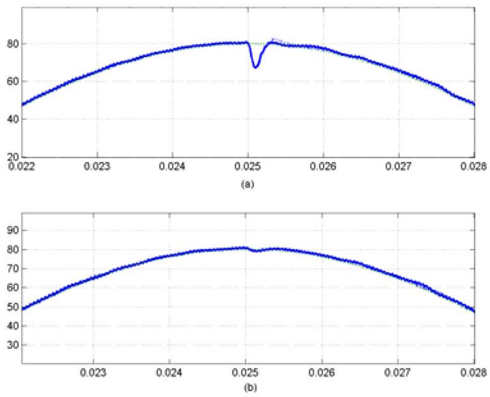

Fig. 11 Comparison of SISO PI-FLC with MISO PI_FLC :Voltage output waveform (a) Load step change from no load to full load (b) Small load step: 20Ω to 24Ω

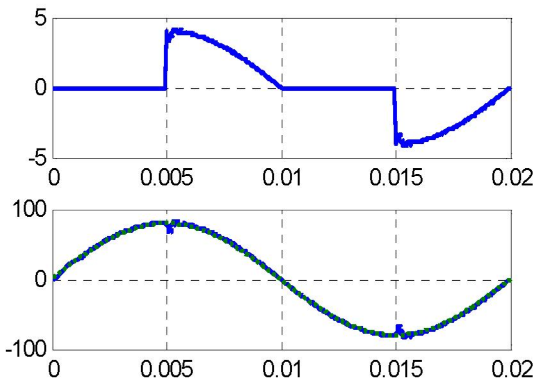

Fig. 12 Voltage output waveform for triac load

IX. CONCLUSION

In this paper, a simple SISO PI-FLC design for a typical DC to AC converter has been presented. The rule table and overall computation time are reduced significantly using signed distance method and piecewise linear approximation. Besides offering faster computation time, piecewise linear also provides a new insight in FLC behaviour. Therefore the FLC can be designed with minimum try and error effort. From the simulation results, it is verified that the proposed SISO PI-FLC can approximates the original MISO PI-FLC, without degrading its original performance. The proposed controller also yields excellent small signal performance (act as PI controller), large signal and capable of handling cyclic load.

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