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PWM DC-AC Converter Regulation using a Multi-Loop Single Input Fuzzy PI Controller

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ABSTRACT

This paper presents a PWM dc-ac converter regulation using a Single Input Fuzzy PI Controller (SIFPIC). The SIFPIC is derived from the signed distanced method, which is a simplification of a conventional fuzzy controller. The simplification results in a one-dimensional rule table, that allows its control surface to be approximated by a piecewise linear relationship. The controller multi-loop structure is comprised of an outer voltage and an inner current feedback loop. To verify the performance of the SIFPIC, a low power PWM dc-ac converter prototype is constructed and the proposed control algorithm is implemented. The experimental results show that the SIFPIC performance is comparable to a conventional Fuzzy PI controller, but with a much reduced computation time.

Keywords: PWM, dc-ac converter, Fuzzy controller, Multi-loop scheme, Signed distance method

1. Introduction

The PWM dc-ac converter is the heart of a dc/ac conversion system. The main feature of a well-designed dc-ac converter is its ability to provide clean and stable sinusoidal output voltage regardless of the type of load connected to it. In addition, it must also have the ability to recover from transients caused by external disturbances as quickly as possible. Nowadays, with the proliferation of power converters connected as loads, a PWM dc-ac converter is required to deliver non-linear output current. These highly distorted currents may cause deterioration in the quality of the inverter output voltage.

Over the past few decades, a large number of dc-ac converters have been regulated using proportional integral (PI) controllers[1,2]. The design procedures for these controllers are well defined and are widely accepted by the control community. Generally, in order to design a proper PI controller, a precise mathematical model of the actual system to be controlled is required. Depending on the tuning methods[2], its performance is guaranteed for a small signal disturbance but often deteriorates when subjected to a large disturbance. Furthermore, it is known that PI controllers can not cope with system nonlinearities and uncertainties satisfactorily[3].

Fuzzy controller is a non-linear controller that does not require a precise mathematical model for its design [4]. It is obviously of great importance when the mathematical model is difficult to obtain due to the complexity and

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uncertainties of the system. In essence, fuzzy controller is a linguistic-based controller that tries to emulate the way a human thinks in solving a particular problem. The applications of fuzzy controllers for dc-ac converter regulation have been reported by several researchers, for example[5,6,7]. One of the most important advantages of this controller is its high degree of robustness and immunity to external disturbances [8,9].

A combination of linear control techniques into a fuzzy controller design has given birth to a hybrid controller, namely the (conventional) Fuzzy PI Controller (CFPIC). This particular fuzzy controller exhibits a similar small-signal performance to its PI counterpart but has superior response for large-signal disturbances[4]. However, CFPIC implementation demands a high performance processor. This is due to the fact that the accuracy of its control action is mainly determined by the number of inferences dictated by its rule table. A large set of rules yields more accurate control at the expense of longer computational time. Additionally, CFPIC also requires the normal fuzzy processes such as fuzzification and defuzzification.

In this paper, a Single Input Fuzzy PI Controller (SIFPIC) for dc-ac converter regulation is proposed. The SIPFIC is a simplification of CPFIC; it is primarily achieved by applying the 'signed distance method'[9] and reducing the CFPIC control surface to a piecewise linear approximation. The input to SIFPIC is only one variable known as "distance". This is in contrast to the CFPIC which requires an error and the derivative (change) of the error as its inputs. The reduction in the number of inputs simplifies the rule table to one-dimension, which then allows for the piecewise linear approximation to take place.

As for the controller structure, multi-loop feedback is employed. Two variables are measured; the output voltage and inductor current. The voltage loop is regulated using a PI controller while the current loop is controlled by the SIFPIC.

Compared to a CFPIC, the SIFPIC is expected to reduce the computational burden of the processor because it has fewer rules to compute. Moreover, the rules can be approximated as a piecewise control surface and can be constructed using a simple look-up table. To verify this idea, a low power dc-ac converter prototype is constructed. Both controllers, i.e. a CFPIC and a SIFPIC, are implemented using a digital signal processor. Typical results for the response of the controllers under load disturbances are obtained and compared.

2. Signed distance Method and Piecewise Linear Approximation

Table 1 shows a typical rule table for a conventional Fuzzy controller with error (e) and change of error ($\dot{e}$) as its inputs. Such a rule table is known to inherit the "Toeplitz" structure and is common among power converters.

Table 1 Rule table for two-input Fuzzy controller

$e \backslash \dot{e}$	NB	NS	Z	PS	PB
PB	Z	PS	PB	PB	PB
PS	NS	Z	PS	PB	PB
Z	NB	NS	Z	PS	PB
NS	NB	NB	NS	Z	PS
NB	NB	NB	NB	NS	Z

L_{NS} L_Z L_{PS}

By observing Table 1, it can be deduced that instead of using two-variable input sets ($e, \dot{e}$), the corresponding output ($\dot{u}_o$) can be obtained using a single variable input, called the "signed distance" (d) [9]. The signed distance represents the absolute distance magnitude of the parallel diagonal lines (in which the input set of e and $\dot{e}$ lies) from the main diagonal line (L_Z). The distance can be expressed as:

$$d = \frac{\dot{e} + \lambda e}{\sqrt{1 + \lambda^2}} \quad (1)$$

where λ is the slope for L_Z. The positive and negative signs of the distance, d, are determined by the position of actual states. Thus, with the distance as the sole input, Table 1 can be reduced to Table 2 where L_{NB}, L_{NS}, L_Z, L_{PS} and L_{PB} are the diagonal lines of Table 1. They represent the new input of this rule table, while NB, NS, Z, PS and PB represent the output of the corresponding diagonal lines.

Table 2 New rule table with distance, *d* as the sole input

d	L_{NB}	L_{NS}	L_Z	L_{PS}	L_{PB}
$\dot{u}_o$	NB	NS	Z	PS	PB

The reduction of the rule table to one-dimension as depicted in Table 2 allows its control surface to be approximated as a piecewise linear. This is in contrast to the conventional fuzzy controller which has a control surface that is related to its membership functions, spacing, inference methods, fuzzification and defuzzification. The parameters have a very complex relationship between them and the tuning combinations to achieve optimum control performance can be very heuristic in nature. For the conventional fuzzy controller with two inputs, the resulting control surface is normally visualized as a three dimensional graph.

For the rule table obtained from the signed distance method, the control surface can be represented by only a two-dimension plot. Consequently, it is possible to generate a control surface without having to delve into complex computations associated with fuzzification, inference and defuzzification processes. In fact, the control surface can be constructed using a simple look-up table. To preserve the non-linearity properties of the control surface, appropriate piecewise linear approximation is employed [10].

3. Single Input Fuzzy PI Controller

Fig. 1 illustrates the proposed Single Input Fuzzy PI Controller (SIFPIC) structure with the piecewise linear control surface, ψ. The input to the control surface is the distance, d, which can be calculated using equation (1).

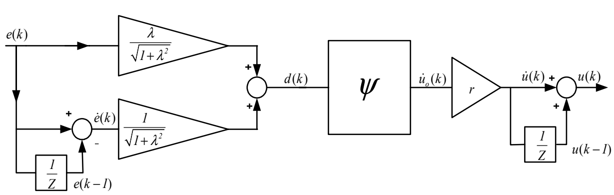


Fig. 1 The SIFPIC block diagram

Note that the SIFPIC structure in Fig. 1 is very similar to the discrete PI controller, when the control surface (ψ) is replaced with a unity gain. Therefore, it is possible to convert the SIFPIC to a PI controller if the relationship between these two controllers can be established.

3.1 Design for Discrete PI Controller

The PI controller is designed firstly in continuous time mode. Consider the continuous time transfer function of the PI controller as expressed in (2).

$$C(s) = K_i\left[\frac{(K_p/K_i)s+1}{s}\right] \tag{2}$$

Using the bilinear transformation, given in (3), i.e.:

$$s = \frac{2}{T_s}\left[\frac{z-1}{z+1}\right] \tag{3}$$

and applying it to (2), an equivalent discrete form, *C(z)* for *C(s)* will be derived as:

$$C(z) = \frac{mz+n}{z-1} \tag{4}$$

The parameters m and n are given by:

$$m = K_i\left[\frac{K_p}{K_i}+\frac{T_s}{2}\right] \tag{5}$$

$$n = K_i\left[\frac{T_s}{2}-\frac{K_p}{K_i}\right] \tag{6}$$

In (3), (5) and (6), T_s is a sampling time. Furthermore, equation (4) can be expressed in a difference equation as:

$$\dot{u}(k) = (m+n)[e(k)+\frac{(-n)}{(m+n)}\dot{e}(k)] \tag{7}$$

From (7), a discrete PI controller block diagram can be drawn as in Fig. 2

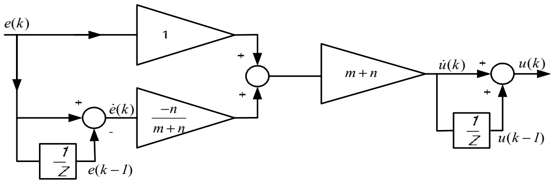


Fig. 2 Discrete PI controller structure

3.2 SIFPIC Design for Small-signal Disturbance

Block diagrams of a SIFPIC and a discrete PI controller have been illustrated in Figs. 1 and 2, respectively. Clearly, both structures are identical if the control surface of the SIFPIC is set as unity gain. For small-signal operation, it is desirable to obtain λ and r parameters in SIFPIC that equal its PI controller. By comparing Figs. 1 and 2, the following equation for the SIFPIC output can be written:

$$\dot{u}(k) = (r)(\psi)\left(\frac{\dot{e}(k)}{\sqrt{1+\lambda^2}} + \frac{\lambda e(k)}{\sqrt{1+\lambda^2}}\right) \tag{8}$$

If only small-signal disturbance is considered, the control surface (ψ) is set to unity. Equation (8) can be reduced to:

$$\dot{u}(k) = (r)\left(\frac{\lambda e(k)}{\sqrt{1+\lambda^2}} + \frac{\dot{e}(k)}{\sqrt{1+\lambda^2}}\right) \tag{9}$$

By comparing (7) and (9), parameter r can be obtained as:

$$r = m + n \tag{10}$$

In the same manner, parameter λ can be obtained by comparing equations (7) and (9), i.e:

$$\frac{1}{\sqrt{1+\lambda^2}}\dot{e}(k) = \frac{-n}{m+n}\dot{e}(k) \tag{11}$$

$$\lambda = \sqrt{\left(\frac{m+n}{-n}\right)^2 - 1} \tag{12}$$

Equation (12) can be further simplified by expressing $\frac{m+n}{-n}$ term in K_p, K_i and T_s:

$$\frac{m+n}{-n} = \frac{T_s}{\frac{K_i T_s - 2K_p}{2K_i}} = \frac{2K_i T_s}{K_i T_s - 2K_p} \tag{13}$$

From (13), since the value of K_i is typically much larger than K_p for converter regulation, then $m+n$>-n. This follows that $\frac{m+n}{-n}$ >>1 will always valid. Therefore equation (13) can be reduced to:

$$\lambda \approx \frac{m+n}{-n} \tag{14}$$

3.3 SIFPIC Design for Large-signal Disturbance

In contrast to its small-signal design, the design of SIFPIC to handle large-signal disturbances does not involve analytical formulation. It is basically achieved by heuristically tuning the slope and the break-point of the piecewise linear graph, which is its control surface. A similar approach has been used by Perry[4] in designing the conventional fuzzy controller for large-signal disturbance. Fig. 3 shows an example of how the slope and the break-point of the SIFPIC can be adjusted.

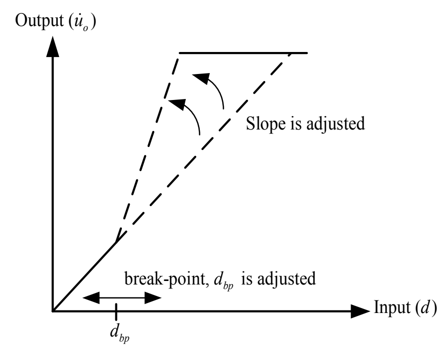


Fig. 3 Control surface for SIFPIC

As can be shown in Fig. 3, the slope is fixed at unity value for small input values $(d < d_{bp})$. This is to ensure that for small-signal disturbances, the SIFPIC will perform as a PI controller. To cope with large-signal disturbance $(d \geq d_{bp})$, the slope is increased. A higher slope value yields a faster rate of change for $\dot{u}_o$. This in turn results in faster converter response for large-signal transient.

4. Multi-loop SIFPIC for DC-AC Converter Regulation: Design Example

Fig. 4 depicts the single-phase dc-ac converter utilizing the SIFPIC. The outer loop senses the output voltage, v_o, and is regulated by a PI controller. The output from the PI controller becomes the reference, i_{Lref}. The inner loop measures the inductor current, i_L and it is compared to i_{Lref} before being fed to the SIFPIC. The controller calculates the required pulse width for the control action and sends it to a PWM generator to turn on and off the power switches accordingly. Table 3 summarizes the circuit and parameters values used in the system.

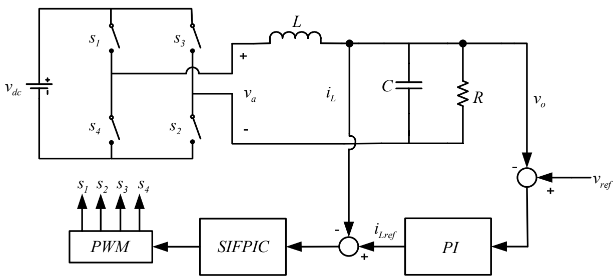


Fig. 4 Single-phase PWM dc-ac converter with feedback loops

Table 3 Circuit and Parameters values for the dc-ac converter system

Output Voltage	80V
Inductor filter (L)	250μH
Capacitor filter (C)	33μF
Switching frequency (f_s)	20kHz
Current Loop Sampling Time	25μs
Voltage Loop Sampling Time	50μs
Rated load (Resistor load)	20Ω

For the voltage loop regulator, the transfer function for a PI controller with a closed-loop bandwidth of 100 Hz and a phase-margin of 60° can be obtained as:

$$C(s) = \frac{0.415s + 28000}{s} \tag{15}$$

Then, by applying a bilinear transformation as defined in equation (3), with T_s = 50μs, its equivalent discrete transfer function $C(z)$ is calculated as:

$$C(z) = \frac{0.765z - 0.065}{z - 1} \tag{16}$$

From (16), m and n values for a discrete PI controller are obtained as 0.765 and -0.065, respectively.

For the inner current loop regulator, the transfer function for a PI controller with a closed-loop bandwidth of 1000 Hz and a phase-margin of 45° can be obtained as:

$$C(s) = \frac{0.114s + 8628}{s} \tag{17}$$

Applying a bilinear transformation and substituting T_s = 25μs, its equivalent $C(z)$ is found as:

$$C(z) = \frac{0.222z - 0.0063}{z - 1} \tag{18}$$

From (18), m and n can be obtained as 0.222 and -0.0063, respectively. Substituting these values into (10) and (14), the SIFPIC parameters that give equivalent performance as its PI controller for small input d are obtained as:

$$r = m + n = 0.222 - 0.0063 = 0.2157 \tag{19}$$

$$\lambda = \frac{m+n}{-n} = \frac{0.222 - 0.0063}{0.0063} = 34.24 \tag{20}$$

The range for small input d values is determined by applying small load perturbations to the converter system. The dynamic of the system is simulated using MATLAB. The input range for which the d values yield good performance is recorded to be $0 < |d| < 20$ units.

Beyond $|d| \geq 20$ units, the slope of the surface is tuned to a higher value to obtain better large-signal performance. The system is now subjected to large load disturbance and simulated with different slope values. For each slope value, its dynamic response is recorded and compared. Based on the simulated data it was found that the slope (k) that produces the best response is k = 3.1875 units. Using this information, the control surface for a SIFPIC can be constructed as in Fig. 5.

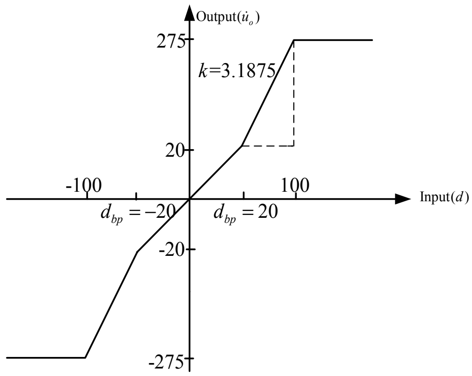


Fig. 5 Control surface for SIFPIC

5. Hardware Implementation

To verify the workability of the SIFPIC algorithm, a 500W prototype dc-ac converter is constructed. The control algorithm is implemented by a digital signal processor (DSP) DS1104 board using the dSPACE platform. MATLAB's Real Time Interface (RTI) tool is used to translate the Simulink blocks to *c*-codes and then download the codes onto the DSP board. Fig. 6 depicts the complete Simulink control block for the SIFPIC algorithm.

For comparison, an "equivalent" conventional Fuzzy PI Controller (CFPIC) is also designed and implemented. The two-input CFPIC is designed using Fuzzy Toolbox from MATLAB-Simulink. Before being fuzzified, the inputs (e and $\dot{e}$) are scaled by input scaling factor, k_e and $k_{\dot{e}}$. Using parameter λ value obtained from (20), the scaling factors can be computed as:

$$k_e = \lambda \Big/ \sqrt{1+\lambda^2} = 1 \tag{21}$$

$$k_{\dot{e}} = 1 \Big/ \sqrt{1+\lambda^2} = 0.029 \tag{22}$$

Both scaled inputs, now denoted as e_p and $\dot{e}_p$ are then fuzzified using membership functions arranged as depicted in Fig. 7 The resulting rule table is shown in Table 4.

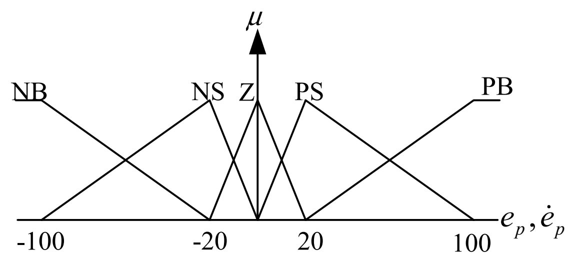


Fig. 7 Membership functions for input e_p and $\dot{e}_p$

Table 4 Rule table for CFPIC

$e_p \backslash \dot{e}_p$	NB	NS	Z	PS	PB
PB	0	211.25	275	275	275
PS	-211.25	0	20	83.75	275
Z	-275	-20	0	20	275
NS	-275	-83.75	-20	0	211.25
NB	-275	-275	275	-211.25	0

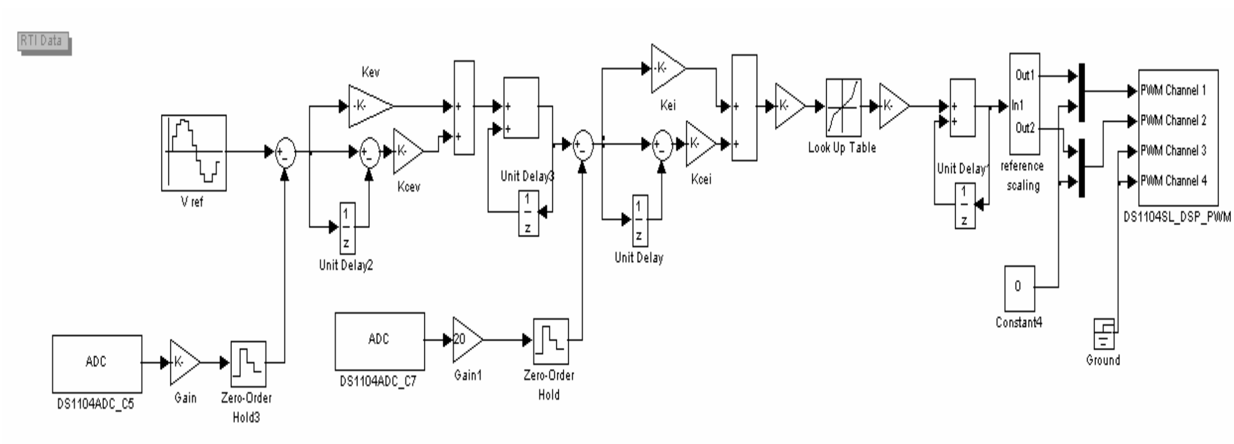
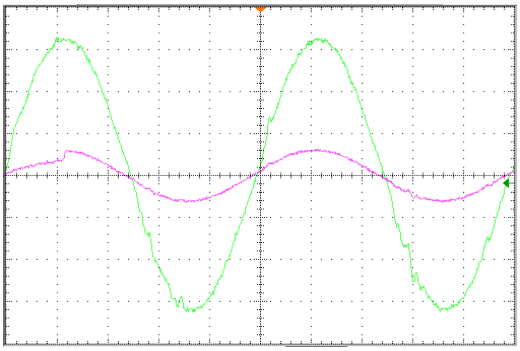


Fig. 6 Complete control block set for RTI-based implementation

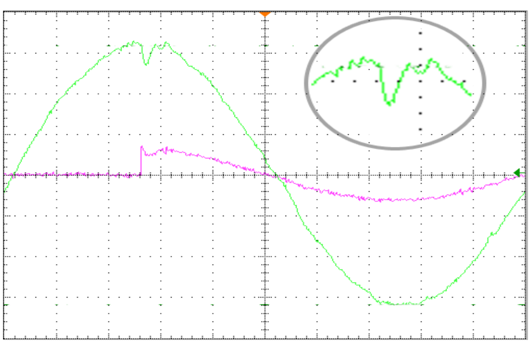
To show the effectiveness of SIFPIC when subjected to small-signal disturbance, i.e. a step load change from 25 Ω to 20 Ω is applied. Fig. 8 shows the result, which displays an excellent transient dynamic performance.



Vertical scale: output voltage 25V/div, output current 5A/div, Time scale 2ms/div

Fig. 8 Small-signal performance of SIFPIC

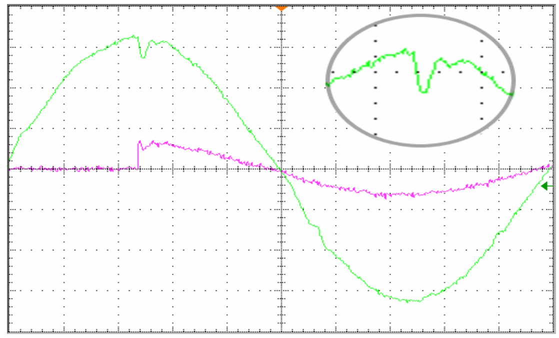
Fig. 9 shows the performance of the SIFPIC when the system is subjected to a large load disturbance (from no-load to 20 Ω). From the figure, it can be observed that the SIFPIC exhibits very fast transient performance, with very small overshoot and quick settling time. This fast response is attributed to a higher slope for the input d above $|d|$= 20 units, imposed on the SIFPIC control surface.



Vertical scale: output voltage 25V/div, output current 5A/div, Time scale 2ms/div

Fig. 9 Performance of the SIFPIC when subjected to sudden large load disturbance

Fig. 10 shows the large-signal performance of CFPIC. As can be observed from Fig. 8 and Fig. 10, the differences in the dynamics of a SIFPIC and a CFPIC are hardly noticeable.



Vertical scale: output voltage 25V/div, output current 5A/div, Time scale 2ms/div

Fig. 10 Performance of CFPIC when subjected to large load disturbance

Table 5 shows the computation time required to accomplish the calculation for the SIPFIC and the CFPIC. Clearly, the proposed SIFPIC is significantly faster than its conventional counterpart.

Table 5 Computation time comparison between the controllers

SIFPIC	11μs
CFPIC	25μs

6. Conclusions

This paper has described the concept, design and implementation of a Single Input Fuzzy PI Controller (SIFPIC) for PWM dc-ac converter regulation. The controller utilizes the signed distance method which greatly reduces the number of rules compared to a Conventional Fuzzy PI Controller (CFPIC) Moreover, its control surface can be approximated as a piecewise linear approximation which allows for simpler hardware implementation. To verify the idea, both a SIFPIC and a CFPIC are implemented and experiments performed using a low power dc-ac converter prototype. The results are compared and are found to be nearly identical. However, the SIFPIC requires less than the half computational time compared to the CFPIC.

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