DSP-Based Single Input PI-Fuzzy Controller for Inverter System

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***Abstract*—This paper presents a single input PI-Fuzzy controller (SIPI-FLC) for inverter system. The SIPI-FLC is based on the 'signed-distance' method which is capable of reducing multi-input fuzzy into a single input fuzzy system without degradation in performance. The SIPI-FLC exhibits a simpler structure, requires less tuning and has much fewer number of rules. It inherits the performance and stability of a linear PI controller for small-signal disturbances but has an improved performance when subjected to large-signal disturbances. To verify the viability of the proposed technique, a prototype inverter is constructed and the control algorithm is implemented. The results are then compared with the Conventional PI-FLC (CPI-FLC).**

I. INTRODUCTION

Power inverter is the most crucial component of many dc to ac conversion equipment such as the uninterruptable power supply, induction motor drive, induction heating etc. The main feature of a well-designed inverter is its ability to provide clean and stable ac voltage regardless of type of load connected to it. It must also have the ability to recover from transients caused by external disturbances as quickly as possible. However, with the proliferations of power converters connected as loads, the inverter is forced to provide non-linear currents. These highly distorted currents may cause deterioration in the quality of its output voltage. In addition, the high voltage and current switching of the inverter generates harmonics which can be harmful to sensitive equipments. Therefore, the challenge of an inverter design is to maintain high quality sinusoidal output voltage under any load conditions. The key to achieve this end is the appropriate design of its controller.

In practice, a large number of the controllers for the inverter are designed using the classical linear control theory. The most commonly used controller used is the linear proportional integral (PI) controller [1,2]. It is known to produce an excellent performance for load variation within a close neighborhood of the operating point. However, when subjected to large load variations, its performance could not be guaranteed.

Another approach in designing controllers for inverters is the non-model based types. Among the prominent non-model based controllers are Neural Network (NN), Sliding Mode Control (SMC) and Fuzzy Logic Control (FLC). They are obviously of great value for a system which is difficult to model mathematically. This may be due to system complexity, model inaccuracy and/or uncertainty. Most of the non-model based controllers are nonlinear in nature. They are known to be relatively immune to disturbances, robust and are capable of handling nonlinearities. Their design approaches are generally unrelated to the linear control theory and therefore are not bounded by limitations such as control bandwidth limit. They are reported to outperform their linear counterpart in large-signal performance [3].

FLC is a nonlinear linguistic based controller where the knowledge to design FLC is generally obtained from the system's operator experience. Compared to other nonlinear controllers, it requires simpler mathematics and exhibits excellent immunity to disturbances. It also offers a high degree of freedom in tuning its control parameters. This made it easily modified and can be tuned to approximate different kinds of linear or nonlinear controllers [4,5]. Despite these advantages, FLC suffers from lacks of standard design procedure; the design is basically heuristic in nature. The difficulty with heuristic approach is that it involves large number of rules and tuning parameters that must be considered in order to obtain the acceptable performance. Consequently, long design time cycle remains the challenge for FLC.

To alleviate some of these problems, several authors have proposed combinations of different controllers to achieve specific performance criteria. One approach is to integrate the linear PI control theory into FLC in its initial design stage [5]. In this stage, the FLC acts as linear PI controller for small-signal disturbance. Its large-signal performance is improved by tuning the rule table heuristically. The problem with heuristic approach is the difficulty to design the rule table so as to achieve optimum performance. Moreover, since the FLC is a conventional FLC type, typical FLC's processes such as fuzzification, inference and defuzzification are required. These processes make the calculation time for control action becomes longer, hence a large sampling interval. Thus, to achieve smaller sampling time, a faster processor is usually required.

To reduce the tuning complexity, a method called "signed-distance" can be applied to the FLC [6]. It results in a single input based FLC, referred to as Single Input PI-FLC (SIPI-FLC). It inherently reduces the complexity of tuning by reducing the number of inputs, rules and tuning parameters. Moreover, in SIPI-FLC, its control surface can be represented as a piecewise-linear approximation which eliminates the fuzzification, inference and defuzzification processes imposed in CPI-FLC. Thus, the implementation for SIPI-FLC can be realised using slower and inexpensive processors.

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This paper will describe the concept, design and implementation of the SIPI-FLC applied to an inverter system. Its performance is compared with conventional PI-FLC (CPI-FLC) based on the experimental results obtained by employing the dSPACE DS1104 DSP board using Matlab-Simulink Run Time Interface tool. From the results, it will be shown that SIPI-FLC performs similar to the discrete linear PI for small-signal disturbance and superior than the latter for large-signal disturbance. It is also shown that SIPI-FLC capable to perform equal to CPI-FLC.

II. THE SIGNED-DISTANCE METHOD

The "signed-distance" method was firstly proposed in [6]. Using this method, any multi-input FLC system can be reduced to a single-input FLC system without compromising the performance. This results in a simple structure, less number of rules and minimal tuning parameters. The method however can only be applied to an FLC with a rule table that exhibits a Toeplits structure as shown in Table I. Here, the diagonal line which consists of ZERO membership (LZ) is referred to as the main diagonal line. Since the output has a membership function arranged in diagonal direction, then any system's state ($\boldsymbol{e}, \dot{\boldsymbol{e}}$) positions can be represented as the absolute distance, *d*, perpendicular to any state points of LZ. The new input, distance can be expressed as in (1).

$$d = \frac{\dot{e} + \lambda e}{\sqrt{1+\lambda^2}} \tag{1}$$

where λ is the slope of the main diagonal line.

TABLE I.
RULE TABLE WITH TOPELITS STRUCTURE

E\CE	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 L_{PS}
NB	NB	NB	NB	NS L_{NS}	Z L_Z

Thus, a new reduced rule table can be shown as in Table II. The new input variable is the distance with five fuzzy input sets, which are LNB, LNS, LZ, LPS and LPB which represent the diagonal line from Table I while the output membership is similar to the original output membership in Table I.

TABLE II.
RULE TABLE WITH TOPELITS STRUCTURE

d	LNB	LNS	Z	LPS	LPB
$\dot{u}$	NB	NS	Z	PS	PB

The rule table of the proposed controller or hereafter referred to as control surface is a single-dimension input-output mapping which can be either linear or nonlinear. Based on the investigation on the input-output fuzzy sets and control surfaces, it is shown that the control surface for a single input system can be approximated using a simple look-up table [7,8].

III. DERIVATION OF DISCRETE LINEAR PI AND THE PROPOSED SIPI-FLC

Consider the transfer function of continuous liner PI controller as expressed in (2). A bilinear transformation, given in (3) is adopted to transform the transfer function into the equivalent discrete form transfer function as in (4), where the parameters *m* and *n* are defined by (5a) and (5b).

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

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

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

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

$$n = K_i \left[\frac{T_s}{2} - \frac{K_p}{K_i} \right] \tag{5b}$$

The transfer function of *C(z)* can be expressed as a difference equation as in (6).

$$\dot{u}(k) = (m+n)[e(k) + \frac{(-n)}{(m+n)} \dot{e}(k)] \tag{6}$$

Equation (6) is the mathematical equation of the discrete linear PI controller. The discrete linear PI controller block diagram representation is as illustrated in Figure 1.

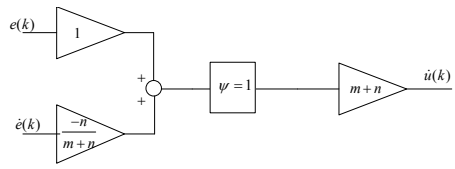

Figure 1. Discrete linear PI controller block diagram

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A. Similarities between discrete linear PI controller and SIPI-FLC

In this section, the structure similarities between these two controllers are investigated. From the similarities, the SIPI-FLC can then be designed to be equal to its discrete linear PI controller in terms of performance and stability. The SIPI-FLC block diagram is as shown in Figure 2. As in the figure, the new input "*distance (d)*" is the input to the approximated control surface (ψ). By setting the surface to be linear with unity gain, and comparing the PI-SIFLC structure with discrete linear PI controller, the similarities between these controllers can be seen.

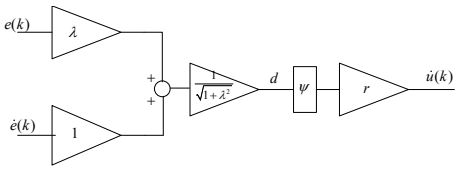

Figure 2. The proposed SIPI-FLC block diagram

Hence, to make the proposed controller performs equally to the linear PI controller; the following conditions should be followed. The distance equation (1) can be rewritten as,

$$d = \frac{\dot{e} + \lambda e}{\sqrt{1+\lambda^2}} \Rightarrow \frac{\dot{e}}{\sqrt{1+\lambda^2}} + \frac{\lambda e}{\sqrt{1+\lambda^2}} \qquad (7)$$

By comparing the term *–n/(m+n)* of Figure 1 and the first term of (7), λ can be obtained as,

$$\frac{1}{\sqrt{1+\lambda^2}} = \frac{-n}{m+n} \Rightarrow \lambda = \sqrt{\left(\frac{m+n}{-n}\right)^2 - 1} \qquad (8)$$

To further simplify (8), the term *(m+n)/(-n)* can be further expressed in terms of K_p, K_i and T_s as given by (9).

$$\frac{m+n}{-n} = \frac{T_s}{\frac{K_i T_s - 2K_p}{2K_i}} \Rightarrow \frac{2K_i T_s}{K_i T_s - 2K_p} \qquad (9)$$

From (9), since K_i is always much larger than K_p in a typical inverter control system, then $m+n>n$, which means $\frac{m+n}{-n}$ >>1 will always be valid. Then, λ and r can be defined by (10a) and (10b).

$$\lambda \approx \frac{m+n}{-n} \qquad (10a)$$

$$r = m+n \qquad (10b)$$

By setting λ and r to values obtained using (10a) and (10b), the performance of the SIPI-FLC will be assured to be equal to the discrete linear PI. It is commonly known however that the performance of a PI controller is limited only for disturbance variations that are within the neighbourhood of an operating point. Its performance degrades for disturbance variations that are outside of the neigbourhood. Since the same PI control design is imposed on the SIPI-FLC, the controller is expected to suffer the same problem when λ and r are set to values obtained using (10a) and (10b). However, since the SIPI-FLC is an FLC-based structure, it can be further tuned so that its large-signal performance is improved without compromising its small-signal performance and stability. The improvement can be done by increasing the gain of the control surface outside of the neighbourhood to values higher than unity. By increasing the gain, it is expected that the transient can be made faster. While within the neighbourhood, the gain is fixed at unity (assuring the PI controller performance for small-signal disturbances). It should be noted that, the value of the neighbourhood boundary is not fixed and depends on the robustness of the PI controller design.

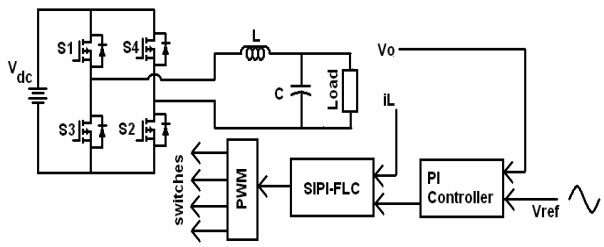

Figure 3. Complete controlled inverter system

TABLE III.
PARAMETER USED IN SIMULATION

Parameter	Values
DC Input Voltage	100V
Inductor filter	250uH
Capacitor filter	33uF
Rated resisitor load	20 Ohm
Reference Voltage Output	80V
Voltage loop sampling frequency	10K Hz
Current loop sampling frequency	20K Hz
Switching frequency	20K Hz

IV. DESCRIPTION OF INVERTER SYSTEM

The inverter used in this work is a typical inverter system which consisted of an H-bridge inverter with LC filter as shown in Figure 3. In this paper, the inductor current and output voltage are sensed as feedback variables and are arranged in cascaded structure. The outer voltage loop is regulated using a discrete linear PI controller while SIPI-FLC is used for the inner inductor current loop. Table III summarises the parameters of the system that are used in the simulation.

For comparison purposes, a discrete linear PI controller has also been designed. The transfer functions

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of discrete linear PI controllers for both voltage and current loops are as expressed by (11a) and (11b). The parameters of the SIPI-FLC for each loop that ensure identical performance to its linear PI counterpart based on (10a) and (10b) are given by (12a) and (12b).

$$C(z)_v = \frac{0.165z + 0.065}{z - 1} \tag{11a}$$

$$C(z)_i = \frac{0.03465z - 0.02835}{z - 1} \tag{11b}$$

$$\lambda_v = -3.538 \ , \ \ r_v = 0.23 \tag{12a}$$

$$\lambda_i = 0.222 \ , \ \ r_i = 0.063 \tag{12b}$$

In order to determine the neigbourhood boundary, several simulations on the inverter system when subjected to small load disturbances are carried out. From the simulations, it is found that SIPI-FLC gives a matching small-signal performance of linear PI controller when the neighbourhood bound is set at |d| = 20 units. Therefore, the surface's gain within the boundary is set to unity. To obtain an improved large signal performance, the gain beyond the boundary is increased. By examining the transient response in large-signal disturbances, the gain has been set to 3.1875 units.

V. Approximation Verification between the SIPI-FLC and CPI-FLC

To verify the approximation, a conventional PI-Fuzzy Logic Controller (CPI-FLC) has been designed. The inputs of the CPI-FLC are the error (with the scaling factor of 1), and the change of error (with the scaling factor of $-n/(m+n)$). The input range of d (-100 to 100) is divided into five sets as shown in Figure 4 for both inputs. Table IV is the generated rule table.

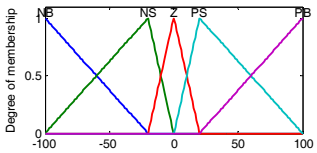

Figure 4. Membership function for both input of CPI-FLC controller

TABLE IV
RULE TABLE WITH TOPELITS STRUCTURE

e / ce	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

VI. Hardware Implementation

To validate the simulation results conducted using MATLAB-SIMULINK, a hardware prototype has been constructed. Similar parameters used in the simulation are adopted in realising the hardware. For flexible and rapid prototyping design approach, a dSPACE platform is used. It comes with its own software for integration with Simulink, called Real-Time Interface (RTI) and a separate program called ControlDesk. ControlDesk is used for real-time monitoring where minor modifications of the proposed controller could be possibly done. A dSPACE DS1104 DSP board is employed to implement the SIPI-FLC and the PWM signal generator.

To implement the proposed controller in dSPACE, the Simulink blocks that are used in the simulation are firstly modified. The modification is done by replacing the physical model such as the inverter and a self-defined PWM generator used in the off-line simulation with the RTI input/output blocks. These include the insertion of dSPACE compatible PWM blocks and the ADCs as shown in the Figure 5.

The RTI converts the Simulink block-set to a C- code that runs on the DSP DS1104 processor. While the experiment is in running mode, the dSPACE provides a mechanism that allows the user to change the controller parameters online via ControlDesk.

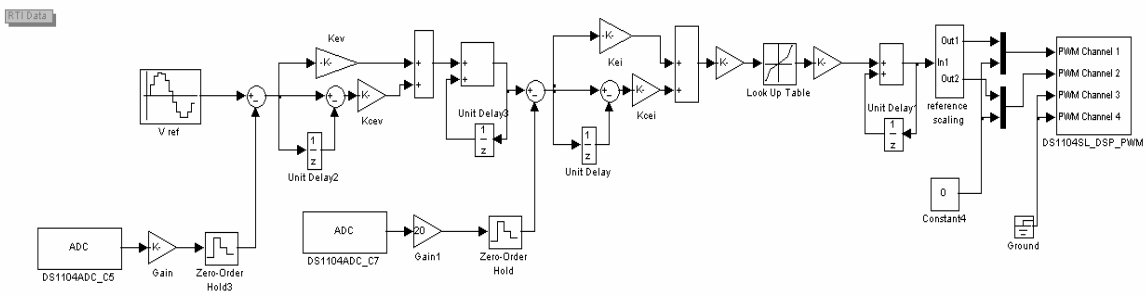

Figure 5. SIPI-FLC's Simulink-RTI Compatible blockset

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VII. RESULTS

A. Small-signal Pertubation

To show the effectiveness of the proposed SIPI-FLC in handling small-signal disturbances, a sudden small load disturbance (from 25 Ω to 20 Ω) is imposed to the system. To compare its performance with the discrete linear PI controller, the same disturbance is injected to the latter. Figure 6(a) and 6(b) show the hardware results for both controllers. As can be expected, the SIPI-FLC performs similarly to the discrete linear PI controller.

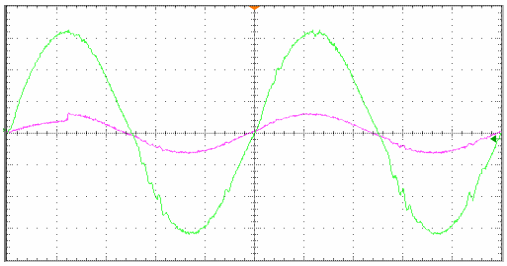

Figure 6(a). Hardware output voltage for the SIPI-FLC when subjected to a small load disturbance

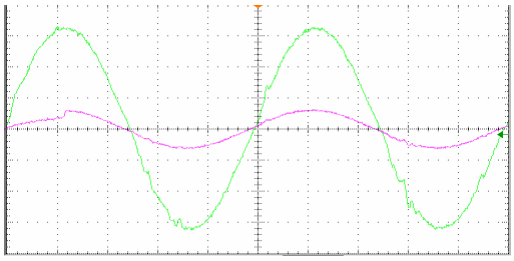

Figure 6 (b). Hardware output voltage for the discrete linear PI controller when subjected to a small load disturbance

B. Large-signal Disturbance

The superiority of the SIPI-FLC over its discrete linear PI controller can be judged by evaluating its performance under large signal disturbance. Figure 7(a) and 7(b), show the practical performance of the discrete linear PI controller and the SIPI-FLC, respectively when a large load disturbance (from no-load to 20 Ω) is imposed. From the figures, it can be observed that the SIPI-FLC exhibits better transient performance compared the discrete linear PI controller.

C. SIPI-FLC and CPI-FLC

In this section, performance of the SIPI-FLC under large disturbances is compared with the CPI-FLC. Figure 8 shows the hardware result for CPI-FLC when subjected to large load disturbance. As can be observed from the Figure 7(b) and Figure 8, the SIPI-FLC yields a comparable performance with its conventional counterpart. The differences in their dynamics are hardly noticeable. Thus it can be concluded that SIPI-FLC provides similar performance to the CPI-FLC but with reduced number of rules, simpler structure and smaller sampling interval. The minimum calculation step-size for both SIPI-FLC and CPI-FLC are measured at 11us and 25us, respectively. Table V numerically summarises the dynamic performance of the discrete linear PI, the SIPI-FLC and the CPI-FLC. As shown in the table, it is clear that both PI-Fuzzy controllers outperformed the discrete linear PI controller in terms of shorter rising time and faster settling time.

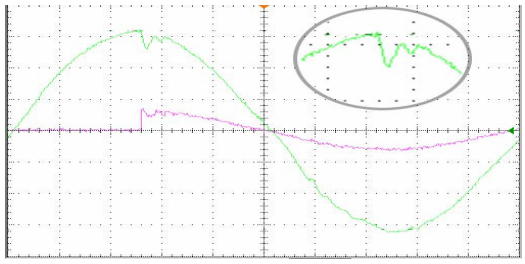

Figure 7 (a). Hardware output voltage of discrete linear PI controller for large load disturbance

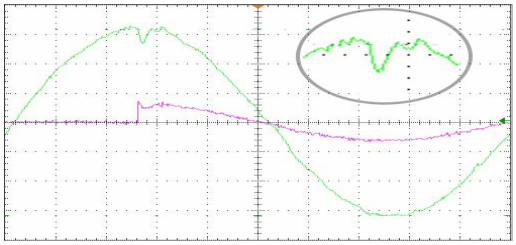

Figure 7(b). Hardware output voltage of SIPI-FLC for large load disturbance

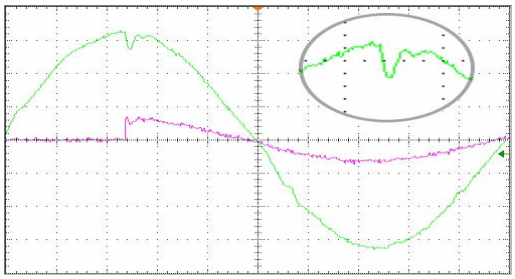

Figure 8. Hardware output voltage of CPI-FLC for large load disturbance

TABLE IV.
PERFORMANCE COMPARISON BETWEEN CONTROLLERS

Performance Index	Rising time (ms)	Settling time (ms)
Discrete Linear PI	1.00	1.20
SIPI-FLC	0.40	0.50
CPI-FLC	0.40	0.45

D. Inductive Load and Rectifier Load

Figure 9 shows the hardware result for the SIPI-FLC in inductive load condition. For this test, a resistor with the value of 20 ohm and an inductor of 92.5mH is connected in series. As expected, a clean sinusoidal output voltage with a power factor of 0.85 is obtained.

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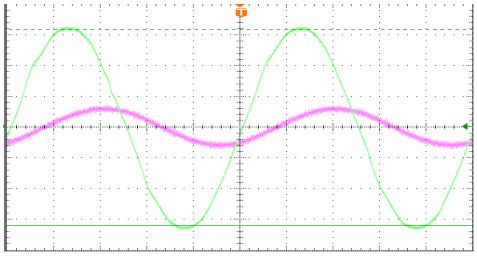

Figure 9. Hardware output voltage of SIPI-FLC for inductive load

To quantify the performance of the inverter with non-linear load, a single-phase full-bridge uncontrolled rectifier with capacitor filter is used. This type of load can be considered amongst the severest steady state test possible. The filter capacitor is 470 µF, with the load resistor set at 100 Ω. Figure 10 shows the corresponding hardware result. As can be observed, the result is consistent with the theoretical prediction. The output voltage THD for the SIPI-FLC measured using Voltech PM100 Power Analyser is 3.6%.

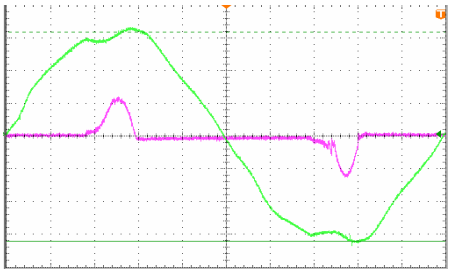

Figure 10. Hardware output voltage of SIPI-FLC for rectifier load

VIII. Conclusion

In this paper a DSP-based Single Input PI-Fuzzy Logic Controller (SIPI-FLC) for inverter systems has been proposed. The controller is an application of the "signed-distance" method which is capable of reducing the multi-input FLC system into a single-input FLC system. This results to a significant reduction in the number of rules, tuning parameters and simpler FLC structure as compared to conventional PI-FLC (CPI-FLC). Thus, less complex heuristic tuning is expected. SIPI-FLC can also be implemented using slower and inexpensive processors. A dSPACE-RTI platform with DS1104 DSP board is used to implement the controller. Based on the hardware results, it is shown that the design of SIPI-FLC has a small-signal performance similar to linear PI controller while its large-signal performance matches the CPI-FLC.

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