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A New Optimum Design for a Single Input Fuzzy Controller Applied to DC to AC Converters

Shahrin Md. Ayob†, Zainal Salam*, and Naziha Ahmad Azli*

†* Power Electronics and Drives Research Group, Universiti Teknologi Malaysia, Johor, Malaysia

Abstract

In this paper, the design of an optimum single input Fuzzy controller for application in dc to ac converters is presented. Contrary to conventional Fuzzy controllers, the proposed controller has a smaller number of rules and tuning parameters but is capable of performing identically to a conventional controller. These benefits lead to a simpler controller design. The controller is designed as a PI controller for small-signal disturbances. However, for optimum large-signal performance, heuristic tuning is used. The tuning is less complicated and hence optimum large-signal performance is achievable. The system is simulated and a hardware prototype was developed for comparison purposes.

Key Words: DC-AC converters, Fuzzy logic controller, Optimum design, Piecewise linear control surface

I. INTRODUCTION

Dc to ac converters are the most crucial component for power conversion systems such as uninterruptible power supplies (UPS), photovoltaic (PV) power conditioners, adjustable speed drives, induction heaters etc. The main feature of a well designed dc to ac converter is its ability to provide a clean and stable ac output voltage regardless of the type of loads connected to it. Moreover, in certain high performance applications, it must also be able to recover from transients caused by external disturbances as quickly as possible. However, with the proliferations of power electronics converters connected as loads, a dc to ac converter is forced to provide non-linear currents. These highly distorted currents cause deterioration in the quality of its output voltage. There are numerous reported cases in which the severity of the distortion results in system failure [1], [3], [6]. In addition, the high voltage and current switching of a dc to ac converter generates harmonics, which can be harmful to sensitive equipment. It has always been a challenge for dc to ac converter designers to maintain a high quality sinusoidal voltage output under any load conditions. The key is to employ an appropriate closed-loop controller.

Over the years, a large number of dc to ac converter systems have been designed based on linear controllers [2]–[4]. One classic example is the Proportional-Integral (PI) controller. The linear controller is a model-based approach whereby a mathematical model of the dc to ac converter is first derived in a frequency domain. The model is then subjected to a small-signal perturbation around an operating point and the resulting small-signal model is linearized. Then the controller is designed based on the stability requirement to compensate for the disturbance. It is known that PI controllers exhibit excellent small-signal transient response, i.e. disturbances that vary in close proximity to the operating point [2]. However, the performance deteriorates when the system is subjected to large-signal disturbances and uncertainties [1], [5].

An alternative approach to the control of a dc to ac converter is by using non-model based controllers such as a Fuzzy Logic Controller (FLC) [7]. The controller operates based on linguistic rules, obtained through an expert's knowledge of system performance and response [1], [8]. The FLC is simple to implement and offers high degree of freedom in tuning its control parameters. However, its main drawback is the lack of a standard design procedure and consequently most FLC systems are designed in a heuristic manner [7]. Lengthy design time, difficulty in tuning and inconsistency in obtaining optimum performance are the major problems relevant to FLC [10].

The tuning complexities of a conventional FLC depend on the decided number of rules and their input variables [10]. Clearly, fewer FLC rules are preferable as it shortens the computation time. However, a reduced number of rules come at the expense of controller performance [11], [12]. Recently, Choi et al. [13] have developed a signed distance method that effectively reduces a multi-input FLC system to a single-input FLC system. This implies that the number of rules is now solely determined by the number of its membership functions. This reduction results in significantly fewer tuning parameters and rule inferences. However, this method has not been applied to the control of a practical dc to ac converter.

This paper proposes the optimum design for a single input Fuzzy controller. It is possible to achieve optimum performance due to the smaller number of rules and tuning

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† Corresponding Author: shahrin@fke.utm.my
Tel: +607-5535331, Fax: +607-5566272
* Power Elect. & Drives Research, Uni. Tek. Malaysia, Malaysia

parameters. For stable and optimum small-signal performance, the controller is designed to be identical to a PI controller. For optimum large-signal performance, two parameters are tuned heuristically. The effects of the parameters are studied and analyzed for optimum performance. To validate the viability of the design, the controller is applied to a dc to ac converter. The system is simulated and a hardware prototype is constructed. It was shown that for both the simulation and hardware results, the performance is identical.

II. THE PROPOSED CONTROLLER

The control performance of a FLC is highly dependent on the number of rules that need to be inferred. In general, the more rules being applied to a FLC, the higher the accuracy of the control action. However, a large set of rules requires more computation time. Consequently, FLC implementation demands a fast, high performance processor. To alleviate the problem, a simple yet efficient FLC is proposed in this paper. It is a single input Fuzzy controller, where its sole input is derived from a technique known as the signed distance method [13].

A. The signed distance method

Typically, a dc to ac converter that employs a FLC has two controlled inputs, namely the error (e) and the change of the error ($\dot{e}$). Its rule table can be established on the two-dimensional space of the phase-plane (e, $\dot{e}$) as shown in Table I. It is common for the rule table to have the same output membership in a diagonal direction. In addition, each point on a particular diagonal line has a magnitude that is proportional to the distance from its main diagonal line L_Z. This is known as the Toeplits structure. The Toeplits property is true for all FLC types which use an error and its derivative terms, namely $\dot{e}, \ddot{e}, \ldots$ and $e^{(n-1)}$ as input variables [13].

By observing the consistent patterns of the output memberships in Table I, there is an opportunity to simplify the table considerably. Instead of using two-variable input sets (e, $\dot{e}$), it is possible to obtain the corresponding output, $\dot{u}_o$ using a single input variable only.

TABLE I
RULE TABLE WITH TOEPLITS STRUCTURE

$\dot{e}\backslash e$	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}

The significance of this reduction was first realized by Choi *et al.* and is known as the Signed distance method. This method simplifies the number of inputs into a single input variable known as distance, *d*. The 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 and can be defined as:

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

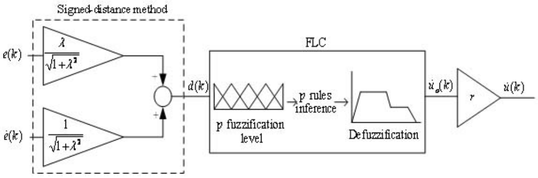


Fig. 1. The Single Input Fuzzy control structure.

In equation (1), λ is defined as the slope of the main diagonal line, L_Z. The derivation of the distance input variable results in a one-dimension rule table, as opposed to the two-dimension table required by a conventional two-input FLC. The reduced rule table is depicted in Table II, where L_{NB}, L_{NS}, L_Z, L_{PS} and L_{PB} are the diagonal lines from Table 1. The diagonal lines represent the new inputs of this rule table, while NB, NS, Z, PS and PB represent the outputs of the corresponding diagonal lines. As can be deduced, the control action of the FLC is now solely determined by *d*. It is therefore appropriate to called it a Single Input Fuzzy controller.

TABLE II
A NEW REDUCED RULE TABLE

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

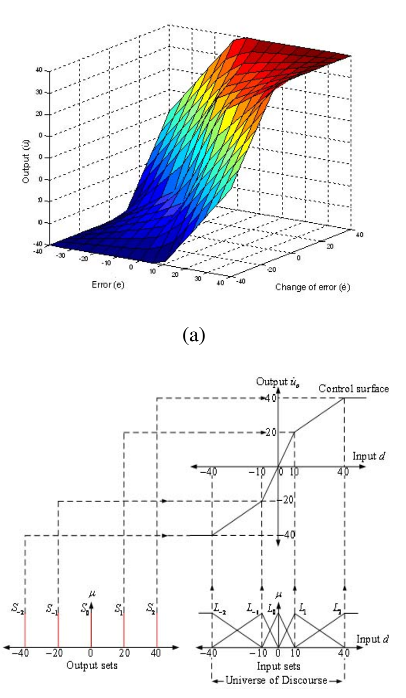
The overall structure of the proposed controller derived from the Signed distance method can be depicted as a block diagram in Fig. 1(a). The input to the FLC block is the distance variable *d*, while the output from the FLC block is the change in the control output, $\dot{u}_o$. The final output of the FLC is obtained by multiplying $\dot{u}_o(k)$ with the output scaling factor, denoted as *r*. The output equation can be written as:

$$\dot{u}(k) = \dot{u}_o(k) r. \tag{2}$$

B. Fuzzy control surface as single-dimension piecewise linear approximation

The main benefit of the Signed distance method is a significant reduction in the number of rules, which in turn lessens the computation burden. Another advantage is the ability to reduce the control surface from multi to two-dimensions. The reduction from a multi-input single-output (MISO) to single-input single-output (SISO) method allows a piecewise linear approximation to take place. By having an input and output that relate to each other in a piecewise linear fashion, it is not necessary to delve into the complexity of constructing a conventional FLC control surface that involves numerous processes such as fuzzification, rule inferences and defuzzification. In order to realize this approximation, several conditions must be met [14]:

1) The input membership functions must use a triangular shape.



(a)

(b)

Fig. 2. (a) Original control surface of the conventional Fuzzy controller (b) Piecewise linear control surface of the proposed controller.

2) The output membership functions must use a singleton shape.
3) The defuzzification process must use the Centre of Gravity (CoG) method.

By following the above-mentioned conditions, it can be assured that the control surface will be a piecewise linear approximation. Fig. 2(a) shows the control surface for a conventional Fuzzy controller while Fig. 2(b) shows a piecewise linear control surface. As can be seen from both figures, the shape of the control surface is determined by the peak locations of the input and output membership functions. Thus, different control surfaces to meet the desired control performance can be simply obtained by changing the peak locations. Based on this, the structure of the proposed controller can be further simplified as shown in Fig. 3.

III. DESIGN FOR OPTIMUM SMALL-SIGNAL PERFORMANCE

The linear control design technique can be applied to design the small-signal performance provided there is similarity in the control structures between the single input Fuzzy controller and a PI controller. Fig. 4 shows the block diagram of a discrete PI controller, where parameters *m* and *n* are given by:

$$m = K_i\left(\frac{K_p}{K_i} + \frac{T_s}{2}\right) \tag{3a}$$

$$n = K_i\left(\frac{T_s}{2} - \frac{K_p}{K_i}\right). \tag{3b}$$

By comparing Figs. 3 and 4, it is obvious that structure-wise, the proposed controller is similar to a discrete PI controller if the control surface ψ of the former is set to unity. Therefore, it can be concluded that using the same controller structure, a discrete PI controller is interchangeable with the proposed controller. This will allow PI controller design techniques to be applied to the design of the proposed controller. The integration of the PI controller design into a FLC, results in the proposed controller having excellent small-signal performance. Moreover, its performance and stability can be conclusively evaluated using established methods such as bandwidth and phase margin analysis. From the figures, λ and r can be derived as:

$$r = m + n \tag{4}$$

$$\lambda = \frac{m+n}{-n}. \tag{5}$$

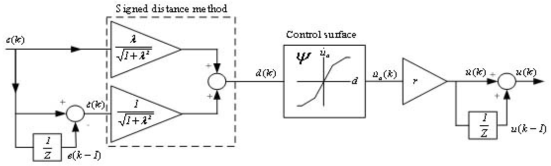


Fig. 3. Block diagram of the simplified proposed controller.

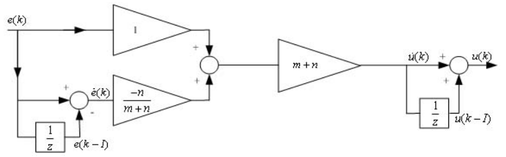


Fig. 4. Discrete PI control structure.

Thus, for small values of *d*, the proposed controller becomes a PI controller provided that the control surface is at unity for small input values of *d* and the parameters for λ and r are selected as (4) and (5), respectively.

IV. DESIGN FOR OPTIMUM LARGE-SIGNAL PERFORMANCE

In contrast to small-signal operation, the design of the proposed controller for large-signal disturbances does not involve analytical formulation. Rather it will be carried out using the heuristic manner with prior knowledge of the desired large-signal response. The tuning involves an adjustment of the shape of the piecewise linear control surface. Fig. 5 shows the piecewise linear control surface used for the proposed controller. It is made up of two piecewise linear regions with different slope values, denoted as the small-signal slope (α_{ss}) and large-signal slope (α_{ls}). The former is the slope for the $d \leq d_{bp}$ input region while α_{ls} is the slope for the $d > d_{bp}$ input region. For the latter slope, its value is set to be much higher than unity. By doing so, a higher rate of change for the control output $\dot{u}_o$ is obtained, which results in a faster rising time during the transient.

For the region with slope α_{ss}, its value is fixed at unity. This is to allow the proposed controller to change its properties to those of a PI controller. Having the controller operates as a PI controller ensures zero steady-state errors and stability of the system when subjected to small-signal disturbances. Moreover, the acceleration caused by α_{ls} can be reduced

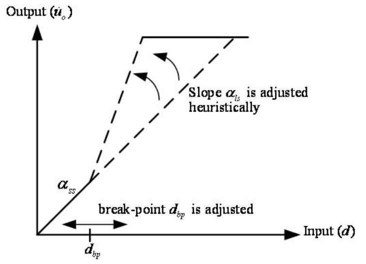


Fig. 5. Control surface used for the proposed controller.

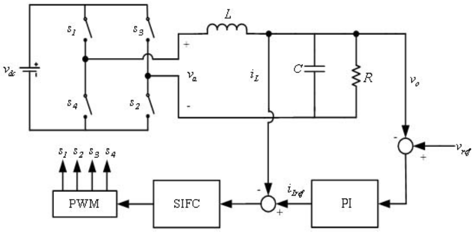


Fig. 6. A dc to ac converter with feedback loops.

when the distance input d gets smaller since α_{ss} has a unity slope value. This helps in minimizing the overshoot during the transient that is normally associated with a faster rising time.

Since the slope α_{ss} value is fixed, d_{bp} and α_{ls} are the only parameters that determine the large-signal performance of the controller. However, the combinational effects of these two parameters on the transient are difficult to analyze mathematically. Moreover, no guidelines can be used to optimize their values. Inevitably, the heuristic tuning approach based on simulations is considered the best approach. Performance indices such as overshoot, rising time and settling time are simulated to determine the optimum combination of d_{bp} and α_{ls}.

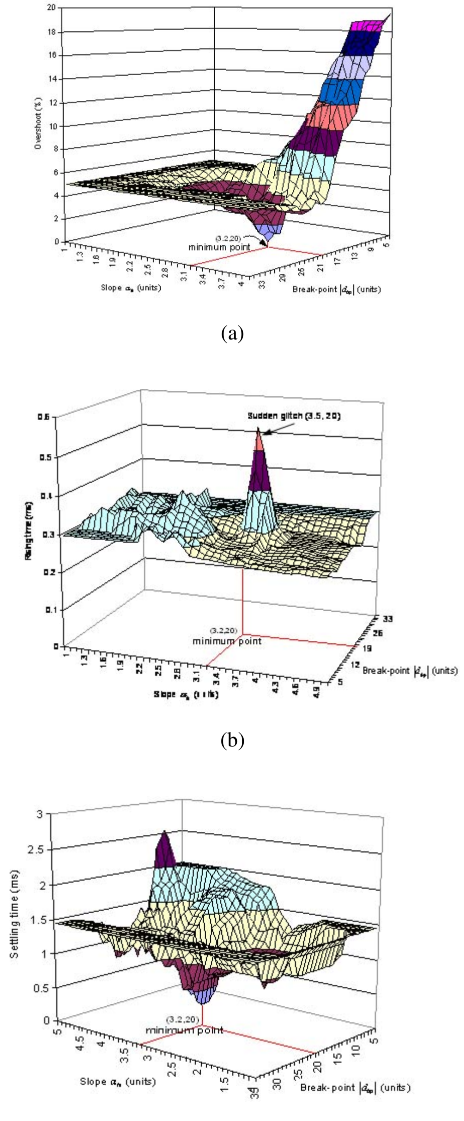
V. SYSTEM DESCRIPTION AND DESIGN EXAMPLE

The proposed controller is employed to regulate the output voltage of a single-phase dc to ac converter. Fig. 6 shows a dc to ac converter utilizing two feedback control loops. Two system variables namely, the output voltage v_o and the inductor current i_L are selected as the feedback signals.

The loops are arranged in a cascaded fashion. The inductor current is used to regulate the inner loop while the output voltage is used to regulate the outer loop. The inner loop is regulated using the proposed controller and the outer loop is regulated with a PI controller. Table III summarized the parameters values used in this dc to ac converter system.

TABLE III
SYSTEM PARAMETERS VALUES

Input voltage (v_{dc})	100 V
Output Voltage (v_o)	57 V_{rms}
Inductor filter (L)	250μ H
Capacitor filter (C)	33μ F
Switching frequency (f_s)	20k Hz
Current Loop Sampling Time (T_{s1})	25μ s
Voltage Loop Sampling Time (T_{s2})	50μ s
Rated load (Resistor load)	20 Ω



(a)

(b)

(c)

Fig. 7. Transient response for different d_{bp} and α_{ls}
(a) Overshoot (b) Rising time and (c) Settling time.

A. Design example for optimum small-signal performance

The proposed controller is designed as a discrete PI controller for the $d < d_{bp}$ input region. Therefore, the linear control design procedure for a double-loop configuration can be adopted. General guidelines for designing a PI controller are followed as in [15]. Using Sisotool, the transfer function of the current loop compensator $C(s)_i$, for a bandwidth of 1K Hz and a phase margin of 45° is obtained as:

$$C(z)_1 = \frac{0.222z - 0.0063}{z - 1}. \tag{6}$$

From (6), m_i is 0.222 and n_i is -0.0063. By substituting m_i and n_i into (4) and (5), the values of λ_i and r_i for the proposed controller can be obtained as:

$$\lambda_i = 34.24 \text{ and } r_i = 0.2157\ . \tag{7}$$

For the outer loop, a similar approach is used. From Sisotool, the transfer function of the PI compensator for the

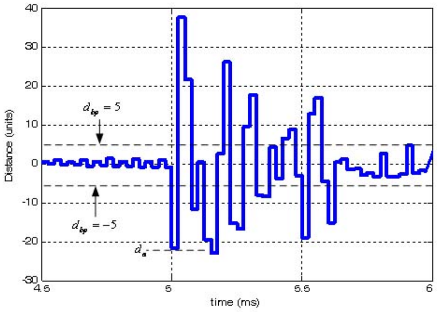


Fig. 8. Distance input produced by $|d_{bp}| = 5$ and $\alpha_{ls} = 3.2$.

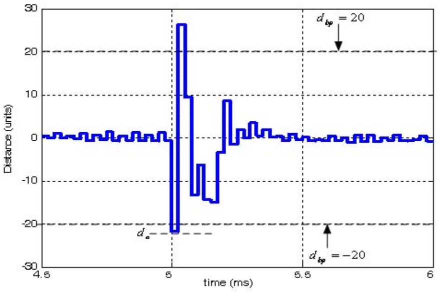


Fig. 9. Distance input produced by $|d_{bp}| = 20$ and $\alpha_{ls} = 3.2$.

outer voltage loop, $C(s)_v$ with a bandwidth of 100 Hz and a phase margin of 60° is obtained as:

$$C(z)_2 = \frac{0.765z - 0.065}{z - 1}. \tag{8}$$

B. Design example for optimum large-signal performance

For large-signal design, the control surface ψ is heuristically adjusted. Two parameters are tuned; the break-point value d_{bp} and the slope α_{ls}. To determine the optimum d_{bp} and slope α_{ls} values, a dc to ac converter system with a large step load change is simulated. The response is analyzed using performance indices such as overshoot percentage, rising and settling times. These are the common indices used to evaluate controllers, defined by the second order step response.

The controller can be categorized as good if it exhibits a small overshoot as well as a fast rising and settling time during the transient. Figs. 7(a), (b) and (c) show the overshoot, rising and settling time plots for different $|d_{bp}|$ and α_{ls} values, respectively. They are plotted on a three dimensional axis to identify the trend of the performance indices with varying $|d_{bp}|$ and α_{ls} values.

It should be noted that when the slope α_{ls} is unity, the controller acts as a PI controller. Therefore, for all values of $|d_{bp}|$ with a slope $\alpha_{ls} = 1$, the controller should demonstrate a PI-type performance. This fact is clearly indicated by the plots; the controller constantly produces an overshoot of 5% with a rising time of 0.3ms and a settling time of 1.45ms for all values of $|d_{bp}|$. The variation of $|d_{bp}|$ has no effect on the transient.

From the plots, it can be seen that the large-signal response is very non-linear. Moreover, the response is quite unpredictable. However, it can be noticed that the overall performance is improved when the $|d_{bp}|$ values are placed within the 19 to 24 range for all of the values of α_{ls}. In this range, the response has the lowest overshoot, the fastest rising and the shortest settling time. The optimum response value is obtained when α_{ls} is 3.2 units.

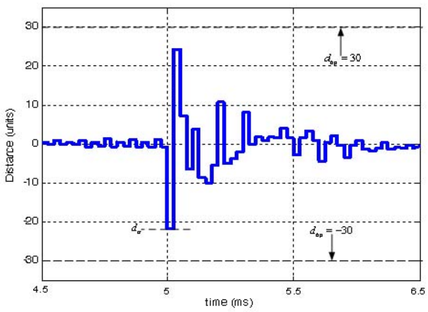


Fig. 10. Distance input produced by $|d_{bp}| = 30$ and $\alpha_{ls} = 3.2$.

VI. QUALITATIVE ANALYSIS OF THE PLOTS

The optimum transient is obtained when $|d_{bp}| = 20$ and $\alpha_{ls} = 3.2$. Under these conditions the rising time is found to be 0.26ms with a small overshoot percentage of 0.25% and a settling time of 0.275ms. In this section, a qualitative analysis is carried out to explain the internal working mechanism, which dictates the controller behavior. For ease of analysis, d_{bp} is grouped under three sections namely, small $|d_{bp}|$ (5 to 18), medium $|d_{bp}|$ (19 to 27) and large $|d_{bp}|$ (28 to 35). For all α_{ls}, the value is set to 3.2 units.

A. Case I: For $5 \leq |d_{bp}| \leq 18$

Fig. 8 shows the d values produced by a small value of d_{bp}, $|d_{bp}| = 5$. The variable d_a is defined as the first d value that is produced by the controller when a disturbance is initially subjected at 5ms. For this simulation, $d_a = -22$ units. It is important to note that a faster rising time is obtained when the rate of change in $\dot{u}_o$ for d_a is increased. This can be done by selecting a $|d_{bp}| < |d_a|$ and by increasing the value of α_{ls} so that it is higher than unity. However, increasing $\dot{u}_o$ will naturally increase the overshoot. Nevertheless, the overshoot can be minimized by quickly reducing the rate of change in $\dot{u}_o$ by forcing d to re-enter and to remain within the α_{ss} region. This can only be achieved when the value of $|d_{bp}|$ is high. However, it is also important to note that in order to maintain a fast rising time response, $|d_{bp}|$ must not exceed the $|d_a|$ value.

Based on the above fact, it can be concluded that the only way for the controller to obtain an optimum response, i.e. a fast rising time with a small overshoot, is by placing $|d_{bp}|$ slightly lower than the $|d_a|$ value. Consequently, for this case, a fast rising time is obtained at the expense of a high overshoot and a lengthy settling time. This is inevitable due to the fact that $|d_{dp}| << |d_a|$.

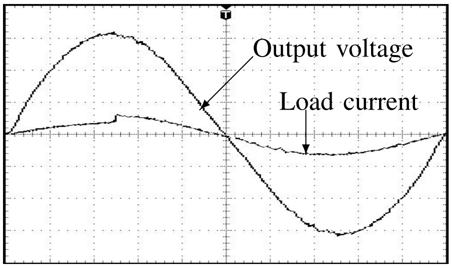


Fig. 11. Response of the proposed controller for small step load disturbance.

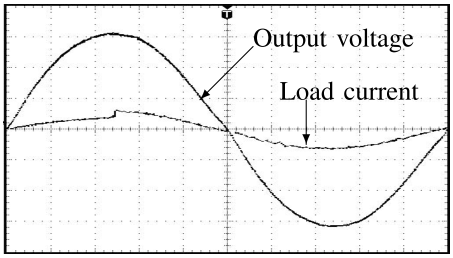


Fig. 12. Response of PI controller for small load disturbance.

B. Case 2: For $19 \leq |d_{bp}| \leq 27$

A better transient response is obtained when d_{bp} is within this range. In fact, the optimum transient response is achieved when $|d_{bp}| = 20$ and $\alpha_{ls} = 3.2$ units. Fig. 9 depicts the d values produced at these values. It is clear that the optimum response is achieved due to the fact that $|d_{bp}|$ was placed slightly lower than $|d_a|$. Thus, a fast rising time with a small overshoot and settling time is obtained.

C. Case 3: For $28 \leq |d_{bp}| \leq 35$

Fig. 10 shows the d values produced when $|d_{bp}| = 30$. It is obvious that for this range, no improvement in rising time response is expected. This is due to the fact that $|d_{bp}| >> |d_a|$. It is also important to note that all of the d values are within the α_{ss} region. Hence, this causes the controller to produce a PI-type transient performance.

VII. HARDWARE IMPLEMENTATION AND RESULTS

A 160W PWM dc/ac converter prototype is constructed. A dSPACE DS1104 digital signal processing (DSP) is employed as the PWM and control signals generator. To validate the performance of the proposed controller, the dc to ac converter is subjected to both small-signal and large-signal disturbances. For comparison purposes, simulation and experiment results for a PI controller are also presented.

A. Results for a small-signal disturbance

The inverter model is subjected to a small step load change i.e. from 25Ω to 20Ω, at 5ms. The results of the experiment are depicted in Figs. 11 and 12 for a PI and the proposed controller, respectively. As can be seen from the results, the performances of the PI and the proposed controller are indistinguishable. Both controllers are capable of compensating for the disturbance and recovering it to its sinusoidal reference value.

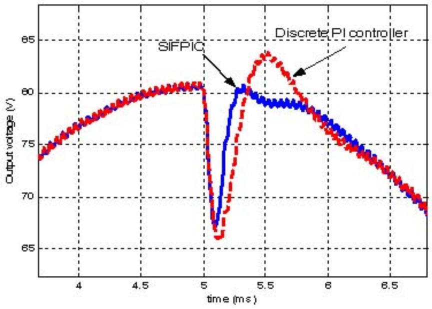


Fig. 13. Comparison between the proposed controller and PI controller.

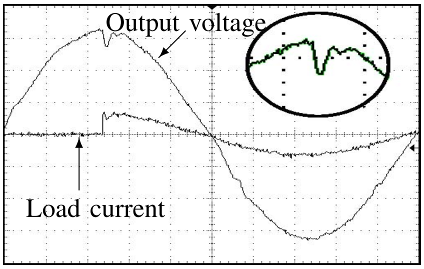


Fig. 14. Transient performance of the proposed controller when subjected to large step load disturbance.

B. Results for a large-signal disturbance

The dc to ac converter is simulated under a large load disturbance (a load step change from 0 Ω to 20 Ω). For comparison purposes, a discrete PI controller is also simulated under the same conditions. The output voltage transient responses of both controllers are graphically shown in Fig. 13.

As can be seen from the figure, the proposed controller yields a better transient performance than its linear counterpart. It should be noted that, the large-signal transient response of Fig. 13 is achieved without compromising the small-signal performance of the proposed controller. Fig. 14 depicts the experiment result under a similar load disturbance. As can be seen, the results are identical to the simulation.

VIII. CONCLUSION

In this paper, the optimum design of a single input Fuzzy controller for dc to ac converters is presented. The controller yields a simpler structure and less tuning parameters. This allows for a simpler tuning design and hence optimized performance. The design involves a PI control design technique to compensate for small-signal disturbances while the heuristic approach is used for large-signal disturbances. Two parameters have been studied and their effects in achieving optimum large-signal performance are analyzed.

REFERENCES

[1] T. G. Habetler, and R. G. Harley, "Power electronic converter and system control," *Proceeding of the IEEE*, Vol. 89, No. 6, pp. 913-925, Jun. 2001.

[2] T. Hagglund, and K. J. Astrom, “Revisiting the ziegler-nichols tuning rules for PI control,” *Asian Journal of Control*, Vol. 4, No. 4, pp. 364-380, Dec. 2002.

[3] P. Sanchis, A. Ursaea, E. Gubia, and L. Marroyo, “Boost DC-AC inverter: a new control strategy,” *IEEE Transaction on Power Electronics*, Vol. 20, No. 2, pp. 343-353, Mar. 2005.

[4] J. Selvaraj, and N. A. Rahim, “Multilevel inverter for grid-connected PV system employing digital PI controller,” *IEEE Transaction on Industrial Electronics*, Vol. 56, No. 1, pp. 149-158, Jan. 2009.

[5] F. Celani, M. Macellari, A. Schiaratura, and L. Schirone, “Digital control for power inverter,” *Proceeding of Control and Applications*, Vol. 65, No. 1, pp. 92-107, Jul. 2009.

[6] D. Biel, F. Guinjoan, E. Fossas, and J. Chavarria, “Sliding-mode control design of a boost-buck switching converter for AC signal generation,” *IEEE Transaction on Circuits and Systems*, Vol. 51, No. 8, pp. 1539-1551, Aug. 2004.

[7] C.-H. Lee and C. -C. Teng, “Fine tuning of membership functions for fuzzy neural systems,” *Asian Journal of Control*, Vol. 3, No. 3, pp. 216-225, Sep. 2001.

[8] Y.–K. Chen, C.–H. Yang, and Y. –W. Wu, “Robust fuzzy controlled photovoltaic power inverter with taguchi method,” *IEEE Transaction on Aerospace and Electronic Systems*, Vol. 38, No. 3, pp. 940-954, Jul. 2002.

[9] T.-F. Wu, C.-H. Chang, and Y.-H. Chen, “A fuzzy logic controlled single-stage converter for PV-powered lighting system applications,” *IEEE Transaction on Industrial Electronics*, Vol. 47, No. 2, pp. 287-296, Apr. 2000.

[10] K. Viswanathan, R. Oruganti, and D. Srinivasan, “Nonlinear function controller: a simple alternative to fuzzy logic controller for a power electronic converter,” *IEEE Transaction on Industrial Electronics*, Vol. 52, No. 5, pp. 1439-1448, Oct. 2005.

[11] G.-C. Hwang, and S.-C. Lin, “A stability approach to fuzzy control design for nonlinear systems,” *Fuzzy Sets and Systems*, Vol. 48, No. 3, pp. 279-287, Jun. 1992.

[12] M. Dotoli, “Fuzzy sliding mode control with piecewise linear switching manifold,” *Asian Journal of Control*. Vol. 5, No. 4, pp. 528-542, Dec. 2003.

[13] B. J. Choi, S. W. Kwak, and B. K. Kim, “Design and stability analysis of single-input fuzzy logic controller,” *IEEE Transaction on Systems, Man and Cybernetics-Part B: Cybernetics*, Vol. 30, No. 2, pp. 303-309, Apr. 2000.

[14] S. M. Ayob, “Single input fuzzy proportional integral controller for inverter regulation,” *PhD Thesis, Universiti Teknologi Malaysia*, 2009.

[15] N. Mohan, *Electric Drive: An Integrative Approach*, Minnesota: John Wiley, 2001.

Shahrin Md. Ayob was born in Kuala Lumpur, Malaysia in 1979. He obtained his Bachelor’s degree in Electrical Engineering (B.E.E), his Master degree (M.E.E) and his PhD from the Universiti Teknologi Malaysia in 2000, 2003 and 2009, respectively. His current research interest is in the application of artificial intelligence to power converters and electric vehicles.

Zainal Salam was born in Seremban, Malaysia in 1963. He obtained his B.Sc., M.E.E. and PhD from the University of California, the Universiti Teknologi Malaysia, Kuala Lumpur, and the University of Birmingham, UK, in 1985, 1989 and 1997, respectively. He has been a lecturer at the Universiti Teknologi Malaysia for over 20 years. His research interests include all areas of power electronics, renewable energy, power electronics and machine control. He is currently a director of the Inverter Quality Control Center (IQCC), Universiti Teknologi Malaysia.

Naziha Ahmad Azli was born in Perak, Malaysia in 1965. She received her B.Sc. in Electrical Engineering from the University of Miami, Florida, USA and her M. E. E. and Ph. D. from the Universiti Teknologi Malaysia in 1986, 1992 and 2002 respectively. She is now a Senior Lecturer at the Universiti Teknologi Malaysia (UTM) where she has been affiliated since 1988. She currently teaches power electronics at both the undergraduate and post-graduate level. Her research interests include power quality, renewable/alternate energy and intelligence systems as applied to power electronics converters.