Australian Journal of Basic and Applied Sciences, 8(19) Special 2014, Pages: 1-7

AENSI Journals

Australian Journal of Basic and Applied Sciences

ISSN:1991-8178

Journal home page: www.ajbasweb.com

Performance Evaluation of Three-Phase Inverter with Various Fuzzy Logic Controllers

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ARTICLE INFO

Article history:
Received 15 April 2014
Received in revised form 22 May 2014
Accepted 25 October 2014
Available online 10 November 2014

Keywords:
Fuzzy logic controller; Proportional integral; Inverter; Harmonic mitigation

ABSTRACT

This paper presents a performance evaluation for the three-phase inverter using various fuzzy logic controllers (FLC) and proportional integral (PI) controller. In FLC based inverters, selecting membership function (MF) and the number of the linguistic variable (LV) is critical in terms of its performance and efficiency. To find suitable MF and LV for FLC, a three-phase voltage source inverter is developed in MATLAB/Simulink and the effect of different MF and different LV were investigated. Simulation result shows that the two inputs of FLC with bell MF and seven LV (49 rule) give the best result. The best result obtained with regard to the system stability condition, minimum total harmonic distortion, minimum mean square error and minimum integral of time multiply absolute error.

To Cite This Article: A.M. Mutlag, H. Shareef and A. Mohamed., Performance Evaluation of Three-Phase Inverter with Various Fuzzy Logic Controllers. ***Aust. J. Basic & Appl. Sci.,*** *8(19): 1-7, 2014*

INTRODUCTION

The growing demand on the distributed generation (DG) such as photovoltaic (PV) and wind power has become the world attention due to the depletion of fossil fuel and environmental demands to reduce greenhouse gases and use clean electricity (Akorede, M.F., *et al*., 2012). However, the success of these DGs depends highly on the type of interface that is used to connect to the power grid. Voltage source inverter (VSI) is the most common type of interface whose performance relies on the controller it adopts (Ghani, Z.A., 2013).

Many control techniques were proposed in the literature to use with VSI. Traditionally, the proportional integral (PI) controller was utilized to control the inverter output. However, the PI controller requires a precise mathematical model of the system (Sanchis, P., *et al*., 2005; Selvaraj, J. and N. Rahim, 2009). Recently, Fuzzy Logic Controller (FLC) has been used in different applications such as VSI (Altin, N. and S. Ozdemir, 2013). The advantage of the FLC over PI controllers is that it does not need a detailed mathematical model of the system. However, the efficiency of the FLC depends highly on the Membership Function (MF) type and also on the Linguistic Variable (LV) number. There are many famous types of the MF such as triangular membership and bell membership (Ezoji, H., 2010; Nathenas, T. and G. Adamidis, 2012; Cheng, C.H., 2011). Nathenas *et al*. (2012) investigated the performance of a neutral point clamped (NPC) three-level voltage source inverter where the improvement of the control is achieved using a fuzzy logic controller. Ezoji *et al*. (2010) has used an asymmetrical voltage source inverter controlled with fuzzy logic method based on hysteresis controller to improve operation of Dynamic Voltage Restorer. Cheng (2011) has proposed a design method to improve the harmonic level of output voltage of a single phase inverter with an LC filter using fuzzy logic controller.

In this study, FLC with many types of MF and LV have been investigated to evaluate the performance of the VSI by calculating total harmonic distortion (THD) for the voltage, mean square error (MSE) and integral of time multiply absolute error (ITAE).

Simulation Model:

The main structure for the inverter system developed in MATLAB/Simulink is shown in Figure 1.

In order to control the inverter, the output three phase voltages (V_a, V_b and V_c) from the inverter are measured and converted to do reference frame using Park transformation (Tsengenes, G. and G. Adamidis, 2011) as explained in the Equation (1).

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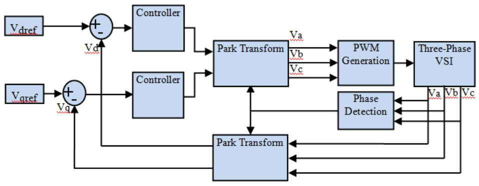

Fig. 1: The architecture of the voltage control strategy.

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} coswt & \cos\left(wt - \frac{2\pi}{3}\right) & \cos\left(wt + \frac{2\pi}{3}\right) \\ -sinwt & sin\left(wt - \frac{2\pi}{3}\right) & sin\left(wt + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \times \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (1)$$

Next V_d and V_q signals from Equation (1) are compared with the reference signals to get the error signals. The error signals are then fed to the controller to get the required V_d and V_q signals. Finally Park transformation is used to convert these signals to V_a, V_b and V_c and drive the pulse width modulation (PWM) signals as explained in the Equation (2) (Salam, Z., *et al*., 2006).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} coswt & -\text{sinwt} & 1 \\ \cos\left(wt - \frac{2\pi}{3}\right) & -sin\left(wt - \frac{2\pi}{3}\right) & 1 \\ \cos\left(wt + \frac{2\pi}{3}\right) & -sin\left(wt + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \times \begin{pmatrix} V_d \\ V_q \\ V_o \end{pmatrix} \quad (2)$$

Fuzzy Logic Controller:

The controllers that are used in this study are FLCs. The main structure of a FLC is shown in Figure 2. It consists of a fuzzifier, inference engine, knowledge base and defuzzifier (Elmas, C., 2009).

The types of MF used in fuzzifier part are triangular MF and bell MF. Figure 3 shows the types of the MF used in this study namely (a) triangular MF with five LV, (b) triangular MF with seven LV, (c) bell MF with five LV and (d) bell MF with seven LV.

The input for the FLC used in this study is either single input fuzzy logic controller (SIFLC) or two inputs fuzzy logic controller (TIFLC). The inference engine part uses different table and control rule depends on the number of inputs and the numbers of the LVs for FLC. Table 1 shows various control rules used in this study, namely (a) control rules for one input and five LV, (b) control rules for one input and seven LV, (c) control rules for two inputs and five LV and (d) control rules for two inputs and seven LV.

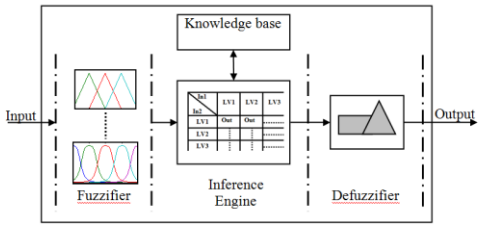

Fig. 2: Fuzzy Logic Controller architecture.

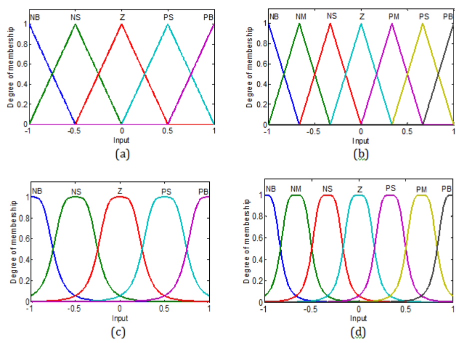

Fig. 3: The MF used in developed controllers: (a) Triangular MF with five LV, (b) Triangular MF with seven LV, (c) bell MF with five LV and (d) bell MF with seven LV.

Table 1: Control rules (a): control rules for one input and five LV.

In	NB	NS	Z	PS	PB
Out	NB	NS	Z	PS	PB

(b): control rules for one input and seven LV.

In	NB	NM	NS	Z	PS	PM	PB
Out	NB	NM	NS	Z	PS	PM	PB

(c): control rules for two inputs and five LV.

In1\In2	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

(d): control rules for two inputs and seven LV.

In1\In2	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

A comparison is made between the FLC which uses different MF and PI controller maintaining other inverter parameters and the connected load constant. The case studied simulated in this work is as follows:

Case 1: PI controller with Kp=15 and Ki=0.05
Case 2: PI controller with Kp=100 and Ki=1.5
Case 3: SIFLC with bell MF and five LV
Case 4: SIFLC with triangular MF and five LV
Case 5: SIFLC with bell MF and seven LV
Case 6: SIFLC with triangular MF and seven LV
Case 7: TIFLC with bell MF and five LV
Case 8: TIFLC with triangular MF and five LV
Case 9: TIFLC with bell MF and seven LV
Case 10: TIFLC with triangular MF and seven LV

In order to evaluate the performance of various inverter controllers in Cases 1 to 10, three indices namely Total Harmonic Distortion (THD), Mean Square Error (MSE), and Integral of Time multiply Absolute Error (ITAE) are used. These indices can be calculated using the following equations.

$$THD = \frac{1}{v_1}\sqrt{\sum_{i=1}^{\infty} v_i^2} \qquad (3)$$

Where v_i is the root mean square voltage of ith harmonic

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2 \qquad (4)$$

Where Y_i is the reference voltage value, and value $\hat{Y}_i$ is the measured voltage value.

$$\mathrm{ITAE} = \int_0^t t|e(t)|\,dt \qquad (5)$$

Where t is the time and $e(t)$ is the error value

RESULT AND DISCUSSION

In this study, a three-phase inverter is developed in MATLAB/Simulink. The simulation was performed for 0.1s and with sampling time of 2μs to evaluate the performance of the inverter. Figure 4 to 13 show the harmonic spectrum for cases 1 to 10. From these figures it can be observed that THD varies with the type of controller used in the inverter. In general, the THD value decreases with increasing the number of LV. Despite the benefits gained from the MF and increasing LV number, selecting the type of MF and LV number must be compensated due to the increased controller complexity.

Figure 14 shows THD summary of the ten cases studied, where the first four bars represent THD for SIFLC, the second four bars represent THD for TIFLC and the last two bars represent THD for PI controller.

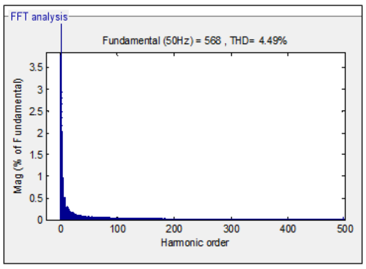

Fig. 4: THD for the inverter usingPI: Kp=15, Ki=0.05.

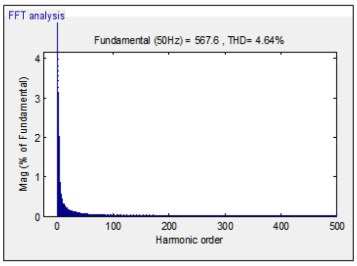

Fig. 5: THD for the inverter using PI: Kp=100, Ki=1.5.

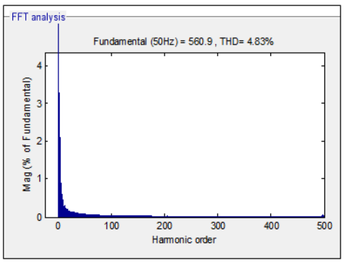

Fig. 6: THD for the inverter using SIFLC with bell MF and five LV.

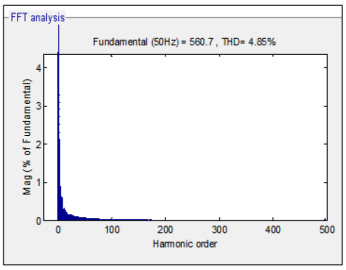

Fig. 7: THD for the inverter using SIFLC with triangular MF and five LV.

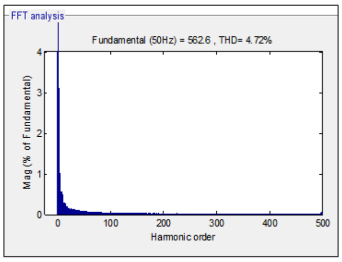

Fig. 8: THD for the inverter using SIFLC with bell MF and seven LV.

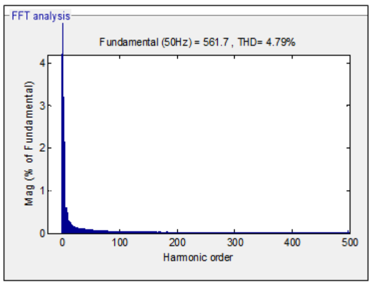

Fig. 9: THD for the inverter using SIFLC with triangular MF and seven LV.

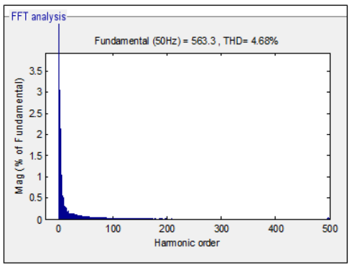

Fig. 10: THD for the inverter using TIFLC with bell MF and five LV.

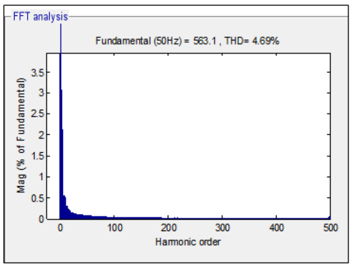

Fig. 11: THD for the inverter using TIFLC with triangular MF and five LV.

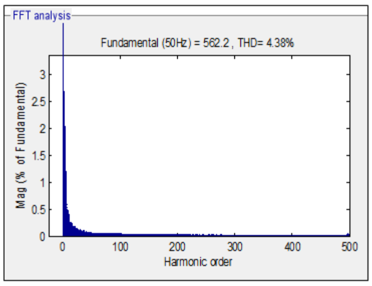

Fig. 12: THD for the inverter using TIFLC with bell MF and seven LV.

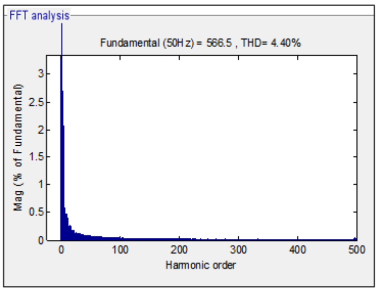

Fig. 13: THD for the inverter using TIFLC with triangular MF and seven LV.

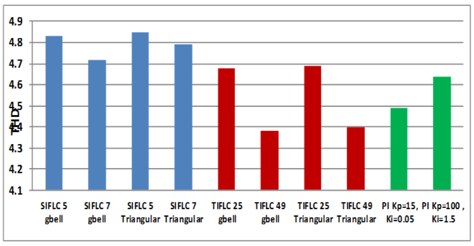

Fig. 14: The THD for the ten cases.

Similar to THD, MSE and ITAE, were evaluated for various cases as depicted in Figures 15 and 16. From these figures one can observe that MSE and ITAE is again affected by the type of controller. MSE and ITAE are inversely proportional to the quality of the signal. Decrease MSE and ITAE values mean increase the quality of the signal, therefore the controller design goal is always to decrease the MSE and ITAE values.

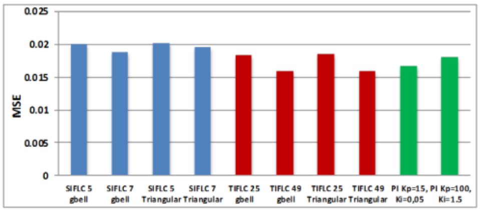

Fig. 15: The MSE for the ten cases.

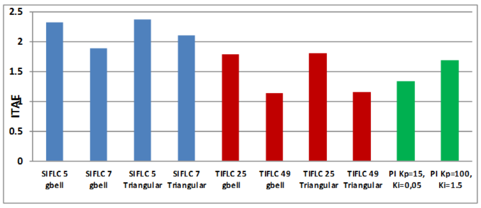

Fig. 16: The ITAE for the ten cases.

Table 2: Simulation results and values of the performance indices.

Parameters			THD	MSE	ITAE
SIFLC	bell	5 Rule	4.83	0.02009	2.31990
		7 Rule	4.72	0.01883	1.89862
	triangular	5 Rule	4.85	0.02026	2.36870
		7 Rule	4.79	0.01960	2.10138
TIFLC	bell	25 Rule	4.68	0.01838	1.78869
		49 Rule	4.38	0.01596	1.13631
	triangular	25 Rule	4.69	0.01852	1.81064
		49 Rule	4.4	0.01603	1.15904
PI		Kp=15 ki=0.05	4.49	0.01679	1.33751
		Kp=100 ki=1.5	4.64	0.01814	1.69793

Table 2 shows THD values and the other two performance indices namely MSE and ITAE which are calculated from the Equations (3) to (5). They are performed for FLCs with different MF and PI controller maintaining other inverter parameters. TIFLC with bell MF and seven LV were found to perform better than the other controller. It provides lowest THD value of 4.38%, MSE of 0.01596 and ITAE of 1.13631.

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Conclusion:

This paper exhibits a way to select the best MF with LV of FLC based inverter considering the performance of the three-phase inverter. In order to evaluate the performance of the three-phase inverter, ten cases were conducted, and THD, MSE and ITAE indices were measured. TIFLC with bell MF and seven LV was found to perform better than the other controller. It provides lowest THD value of 4.38%, MSE of 0.01596 and ITAE of 1.13631. Furthermore, TIFLC is found to be superior to the SIFLC and PI controller.

ACKNOWLEDGEMENT

The authors would like to thank the Universiti Kebangsaan Malaysia/ Faculty of Engineering and Built Environment/ Electrical, Electronic and System department.

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