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# Design of output filter for inverters using fuzzy logic

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ABSTRACT

This paper proposes a design method to improve the harmonic of output voltage of a single phase inverter with an L-C output filter using fuzzy logic controller (FLC). In practice, the harmonic characteristics of circuits are complicated and entangled. There are two kinds of harmonic sources that cause inverter output voltage waveform distortion: One is the PWM switching of inverter and the other is the nonlinear characteristics of the load. In general, PI feedback control by coefficient diagram method (CDM) is used to design the output voltage filter. The relation between the L-C value and the system time constant are described with the closed form and the filter values must be calculated repeatedly to satisfy the prescribed voltage total harmonic distortion (THD) of the system. Therefore, the MATLAB Fuzzy Logic Toolbox for the fuzzy logic control algorithm is proposed. The L-C value of the filter can be set to a fixed range in the nonlinear characteristic of the practical condition, to improve the harmonic of output voltage more effectively and to avoid repeated calculation.



## 1. Introduction

DC-to-AC converters are known as inverters. The function of an inverter is to change a DC input voltage to a symmetric AC output voltage of desired magnitude and frequency. The output voltage can be fixed or variable at a fixed or variable frequency. A variable output voltage can be obtained by varying the input DC voltage and maintaining the gain of the inverter constant. On the other hand, if the DC input voltage is fixed and is not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by pulse-width-modulation (PWM) control within the inverter. The inverter gain may be defined as the ratio of the AC output voltage to DC input voltage.

The output voltage waveforms of ideal inverters should be sinusoidal. However, the waveforms of practical inverters are nonsinusoidal and contain harmonics. For low- and medium-power applications, square-wave or quasi-square-wave voltages may be acceptable; for high-power applications, low distorted sinusoidal waveforms are required. With the availability of high-speed power semiconductor devices, the harmonic contents of output voltage can be minimized or reduced significantly by switching techniques or well designed output filter (Rashid, 2004). There are two kinds of harmonic sources that cause inverter output voltage waveform distortion: One is the PWM switching of inverter and the other is the nonlinear characteristics of the load. If any linear loads are connected to the inverter output side, then the output voltage harmonics due to the PWM switching can be eliminated by inserting the L-C filter between the inverter and the loads. The design of optimal values of the filter components has been well reported (Dewan and Ziogas, 1979; Ryu, Kim, Choi, & Choi, 2002). But, the configuration of the power circuit with L-C filter cannot meet the zero output impedance. Therefore, the capacitor voltage is usually collapsed in the case of sudden load change or under nonlinear load.

Most industrial processes have employed PID-family controllers for several decades due to their simplicity and their sufficiency in process control applications. It has been recently reported that more than 90% of the industrial controllers used nowadays are PI controllers. However, their parameters must be tuned for acceptable responses (Manabe, 1998; Pattanavijit, Nundrakwang, Benjarasuth, Ngamwiwit, & Komine, 2006). A design approach called the coefficient diagram method (CDM) has been proposed for assigning the parameters of controllers. It is an algebraic design algorithm utilizing polynomial form structure. In CDM, the closed-loop characteristic polynomial is designed based on stability index and equivalent time constant, which are used to determine stability and speed of the closed-loop response. Hence, the unknown parameters of the controllers resulting in over-damped response can be obtained accordingly (Cahyadi, Isarakorn, Benjanarasuth, Ngamwiwt, & Komine, 2004; Hamamci, Koksal, & Manabe, 2002; Kumpanya, Benjanarasuth, Ngamwiwit, & Komine, 2000). However, it is quite time consuming to assign the parameters of a controller especially for a higher-order plant.

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Fuzzy theory was initiated in 1965 by Zadeh who also developed the concept of state, which forms the basis of modern control theory. As the control methods evolved, Zadeh thought that classical control theory put too much emphasis on precision to handle complex systems in a practical manner. Fuzzy theory generated many debates and there are still ongoing discussions regarding its handling of complicated nonlinear systems. Since the fuzzy logic controller successfully controlled the simple dynamic plant in the laboratory, it was applied to the control of commercial mercantile products in Japan. Fuzzy logic based controllers have been attracting a great deal of attention in recent years. Applications of fuzzy controllers for power systems have been proposed (Cheng & Hsu, 1991; Hsu & Cheng, 1990; Hsu & Cheng, 1993) and attitude control of satellite using fuzzy controller has been presented (Cheng, Shu, & Cheng, 2009a). A few applications in power electronics for both DC-DC converters (Cheng, & Wu, 2009b; Elmas, Deperlioglu, & Sayan, 2009; Gupta, Boudreaux, Nelms, & Hung, 1997; Mattavelli, Rossetto, Spiazzi, & Tenti, 1997; So, Tse, & Lee, 1996) and inverters (Abdelkhalek et al., 2008; Bolat, 2006; Meah & Ula, 2008; Saad & Zellouma, 2009) have been reported. Thus, the fuzzy controller is proposed in this paper to design the output filter to obtain sinusoidal output voltage.

The organization of this paper is as follows: Section 2 derives the model of L-C filter for single phase inverter. Section 3 introduces the concept of coefficient diagram method. Section 4 discusses the derivation of fuzzy logic controller for the output filter of inverter. Section 5 will give a design example using this procedure, and simulation results. Conclusions are summarized in Section 6.

## 2. The model of L-C filter for single phase inverter

The circuit of single phase pulse width modulation voltage source inverter (PWM-VSI) is shown in Fig. 1. The switching circuit and L-C filter are included in the circuit. The equivalent block diagram for L-C filter is shown in Fig. 2. The transfer function of the open loop system is given by

$$V_c(s) = \frac{C\cdot RES\cdot s+1}{LC\cdot s^2 + C(R_f+RES)\cdot s+1}V_a(s) - \frac{L\cdot C\cdot RES\cdot s^2+(L+C\cdot R_f\cdot RES)\cdot s+R_f}{LC\cdot s^2+C\cdot(R_f+RES)\cdot s+1}i_o(s) \tag{1}$$

where $L$ is the inductance, $R_f$ is the resistance of the inductor, $C$ is the capacitance, and $RES$ is the resistance of the capacitor for the L-C filter.If the PI controller is used for feedback control, the transfer function of the closed loop system can be derived as (Ryu et al., 2002)

$$V_c(s) = \frac{K_i\cdot K_v\cdot(C\cdot RES\cdot s+1)\cdot V_{cd}^*(s) - s\cdot(C\cdot RES\cdot s+1)\cdot(L\cdot s+R_f)\cdot i_{od}(s)}{C\cdot L\cdot s^3 + C\cdot(R_f+RES+K_p)\cdot s^2+(1+C\cdot K_i+K_i\cdot K_v\cdot C\cdot RES)\cdot s+K_iK_v} \tag{2}$$

where $K_p$ and $K_i$ are the gains of PI controller, and $K_v$ is the gain used for compensation.

The characteristic equation of the closed loop system can be expressed as

$$P(s) = L\cdot C\cdot s^3 + C\cdot(R_f+RES+K_p)\cdot s^2 + (1+K_i\cdot C+K_i\cdot K_v\cdot C\cdot RES)\cdot s + K_iK_v \tag{3}$$

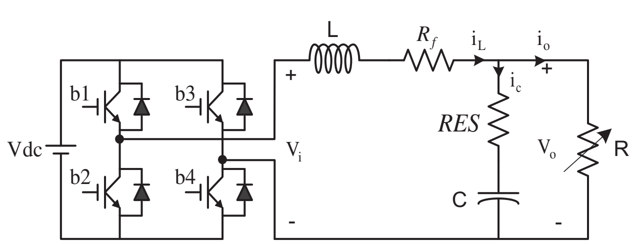


**Fig. 1.** Circuit of single phase PWM-VSI inverter.

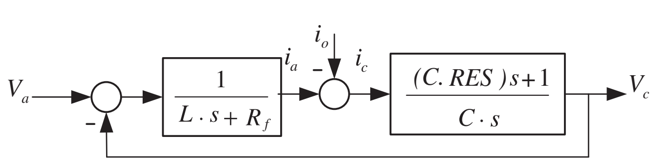


**Fig. 2.** Equivalent block diagram of L-C filter for single phase inverter.

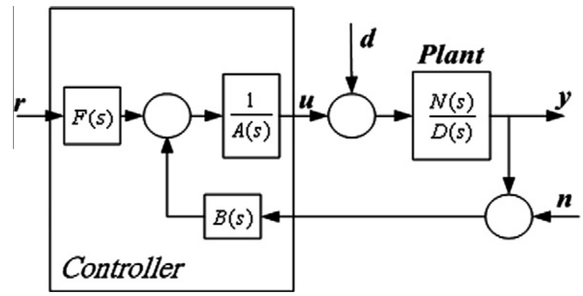


**Fig. 3.** CDM control system structure.

## 3. The concept of coefficient diagram method

### 3.1. Concept of CDM

The CDM structure is shown in Fig. 3. In CDM, the controllers are designed based on the stability index known as $\gamma_i$ and the equivalent time constant known as $\tau$ which are synthesized from the characteristic polynomial of the closed-loop transfer function.

$$P(s) = a_ns^n + a_{n-1}s^{n-1} + \cdots + a_1s + a_0 \tag{4}$$

From the characteristic polynomial $P(s)$ given in Eq. (4), the stability index $\gamma_i$ and the equivalent time constant $\tau$ are respectively described in general terms as the following equations.

$$\gamma_i = \frac{a_i^2}{a_{i-1}a_{i+1}}, \quad (i = 1,2,\ldots,n-1) \tag{5}$$

$$\tau = \frac{a_1}{a_0} \tag{6}$$

In order to meet the specifications, the equivalent time constant $\tau$ and the stability index $\gamma_i$ are normally chosen as

$$\tau = \frac{t_s}{2.5} - \frac{t_s}{3} \tag{7}$$

$$\gamma_i > 1.5\gamma_i^* \tag{8}$$

where $t_s$ is the specified settling time and $\gamma_i^*$ is the stability limit defined as

$$\gamma_i^* = \frac{1}{\gamma_{i+1}} + \frac{1}{\gamma_{i-1}}; \quad \gamma_0, \gamma_n = \infty \tag{9}$$

In general, the stability index is recommended as

$$\gamma_{n-1} = \cdots = \gamma_3 = \gamma_2 = 2, \quad \gamma_1 = 2.5 \tag{10}$$

which is also known as the standard stability index.Finally, the characteristic polynomial to be used to design the parameters of a controller is

$$P(s) = a_0\left[\left\{\sum_{i=2}^{n}\left(\prod_{j=1}^{i-1} 1/\gamma_{i-j}^{j}\right)(\tau s)^i\right\} + \tau s + 1\right] \tag{11}$$

where $a_n$, $a_{n-1}$, ..., $a_0$ are the coefficients of the desired characteristic polynomial.

### 3.2. Controller design

To design the PI controller, the concept of CDM and the rearranged CDM control system structure are respectively described in this section.

The characteristic equation for transfer function of filter is shown in Eq. (3). The characteristic equation for CDM control equation from Eq (11) can be rearranged as Eq. (12)

$$P(s) = \frac{a_0 \cdot \tau^3}{\gamma_2 \cdot \gamma_1^2} s^3 + \frac{a_0 \cdot \tau^2}{\gamma_1} s^2 + (a_0 \cdot \tau)s + a_0 \tag{12}$$

The parameters of PI controller can be expressed as follows from Eqns (3) and (12).

$$K_p = \frac{a_0 \cdot \tau^2}{C \cdot \gamma_1} - (R_f + RES) \tag{13}$$

$$K_i = \frac{a_0(\tau - C \cdot RES) - 1}{C} \tag{14}$$

$$K_v = \frac{a_0}{K_i} \tag{15}$$

## 4. Derivation of fuzzy logic controller for output filter of inverter

The design of fuzzy controller follows four steps:

Step 1: Defining the model functional and operational characteristics.

This step is essential to define exactly where the fuzzy subsystem fits into the total system architecture, which helps the designer to estimate the numbers and ranges of inputs and outputs that will be required.

Step 2: Designing the fuzzifier.

The fuzzifier performs the fuzzification interface defined as mapping from an observed input space to fuzzy sets in certain input universes of discourse. This strategy interprets a crisp value $x$ as a fuzzy set A with membership function $\mu_{A(x)}$ belonging to [0, 1]. To perform fuzzification, each variable in the fuzzy model is decomposed into a set of fuzzy regions which are given unique names, called labels such as "positive big", "positive small", "cool", "slow", ... etc. These labels are related to the physical states of the fuzzy variable.

Step 3: Designing the inference engine.

This step involves writing the rules with syntax like: IF <fuzzy proposition > THEN <fuzzy proposition>. The fuzzy proposition might be originally written in English, e.g. IF the output is much lower than the requirement and it is dropping moderately, THEN the input to the system shall be increased greatly. Thus, the statement of the rule will be: IF $e(t)$ is PB and $ce(t)$ is PM THEN $U_s(t)$ is PB. There are five methods to generate and justify fuzzy control rules. These methods are not mutually exclusive, and it seems likely that a combination of them may be necessary to construct an effective method for the derivation of fuzzy control rules. These methods are: 1. Expert experience and knowledge, 2. Modeling the operator's control actions, 3. Modeling the process, 4. Self-organization, and 5. Learning from numerical examples.

Step 4: Selecting a defuzzification method.

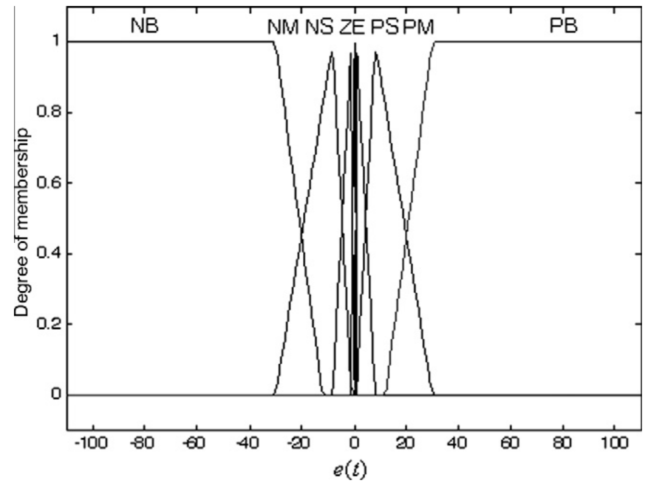


**Fig. 4.** Membership function of $e(t)$.

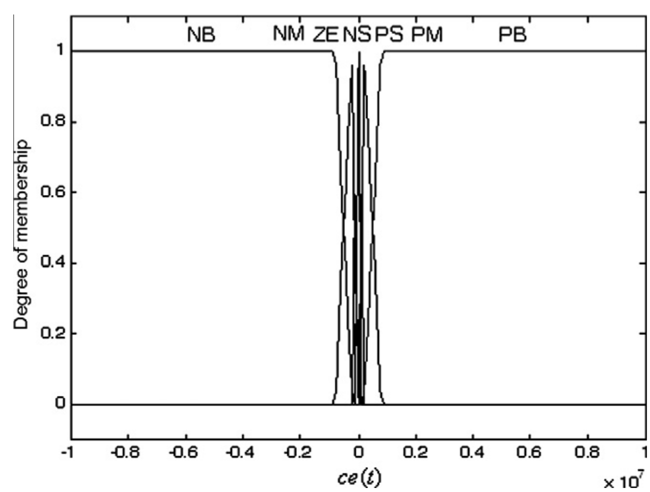


**Fig. 5.** Membership function of $ce(t)$.

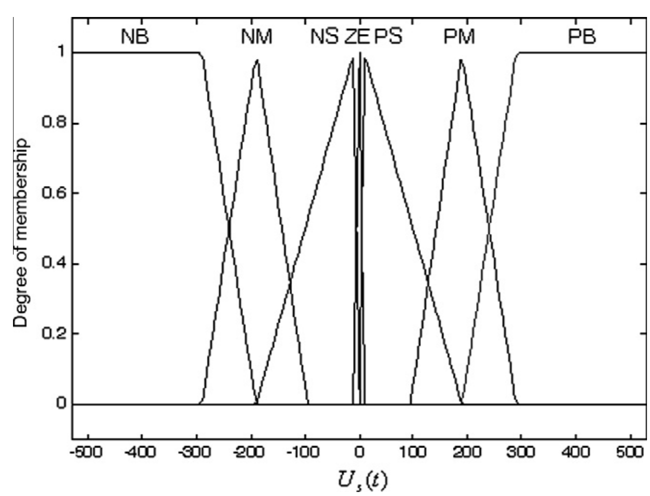


**Fig. 6.** Membership function of $U_s(t)$.

The last part of creating the FLC is the selection of the defuzzification interface. There are several ways to convert an output fuzzy set into a crisp variable, but the most commonly used strategies include: Max criterion, mean of maximum method (MOM), and

**Table 1**
Fuzzy rules for computation of $U_s(t)$.

| ce(t) | e(t) | | | | | | |
|---|---|---|---|---|---|---|---|
| | NB | NM | NS | ZE | PS | PM | PB |
| NB | NB | NB | NB | NB | NM | NS | ZE |
| NM | NB | NB | NB | NM | NS | ZE | PS |
| NS | NB | NB | NM | NS | ZE | PS | PM |
| ZE | NB | NM | NS | ZE | PS | PM | PB |
| PS | NM | NS | ZE | PS | PM | PB | PB |
| PM | NS | ZE | PS | PM | PB | PB | PB |
| PB | ZE | PS | PM | PB | PB | PB | PB |

center of area method (COA). The widely used COA strategy generates the center of gravity of the possibility distribution of a control action. The method considers both membership function value and its shape. In the case of two-inputs $(x_1, x_2)$ and one-output $(y)$,

$$y_{crisp} = \frac{\sum_{i=1}^{N} \mu_{(A_i \cap B_i)}(x_1, x_2).\overline{y_i}}{\sum_{i=1}^{N} \mu_{(A_i \cap B_i)}(x_1, x_2)}$$

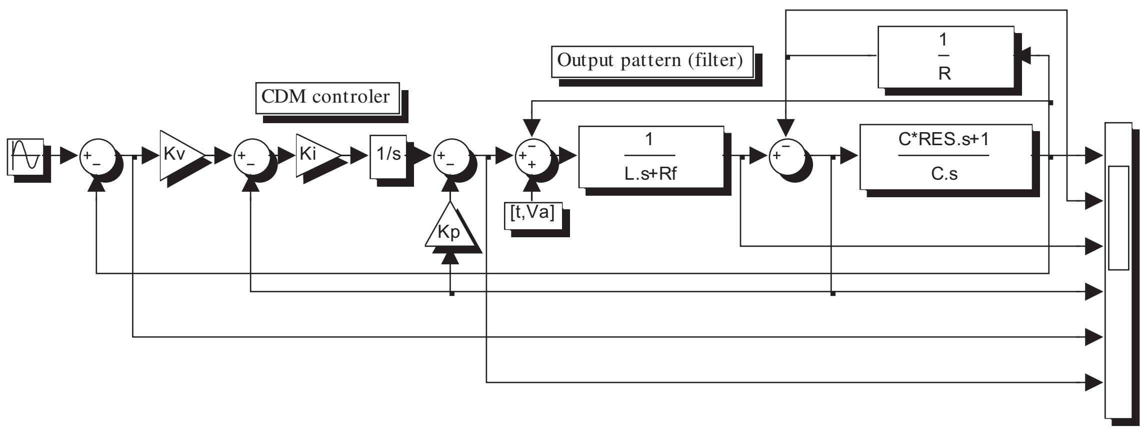


**Fig. 7.** Matlab-Simulink structure for CDM.

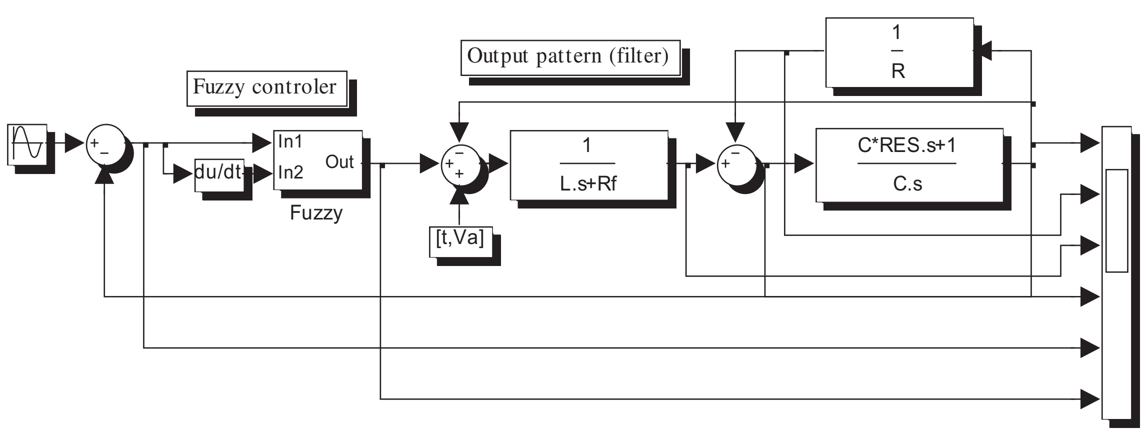


**Fig. 8.** Matlab-Simulink structure for FLC.

**Table 2**
Parameters for CDM control system.

| | | | |
|---|---|---|---|
| *Parameters of the converter* | | | |
| Output power | 800 W | Switching frequency | 9.54 KHz |
| Input voltage | 42–65 Vdc | Amplitude modulation index | 0.85 |
| Output voltage | 110 Vac/60 Hz | | |
| *Parameters of the filter* | | | |
| Mode I | | Cf = 25 $\mu F$; Lf = 4.22 $mH$; Rf = 0.05 Ω; RES = 0.02 Ω | |
| | | Ki = 1275453.125; Kv = 0.129243284; Kp = 105.43 | |
| | | Given specification of voltage THD | 3% |
| Mode II | | Cf = 25 $\mu F$; Lf = 2.53 $mH$; Rf = 0.05 Ω; RES = 0.02 Ω | |
| | | Ki = 748648.4375; Kv = 0.132008724; Kp = 63.18 | |
| | | Given specification of voltage THD | 5% |
| Mode III | | Cf = 25 $\mu F$; Lf = 1.26 $mH$; Rf = 0.05 Ω; RES = 0.02 Ω | |
| | | Ki = 352765.625; Kv = 0.139522523; Kp = 31.43 | |
| | | Given specification of voltage THD | 10% |

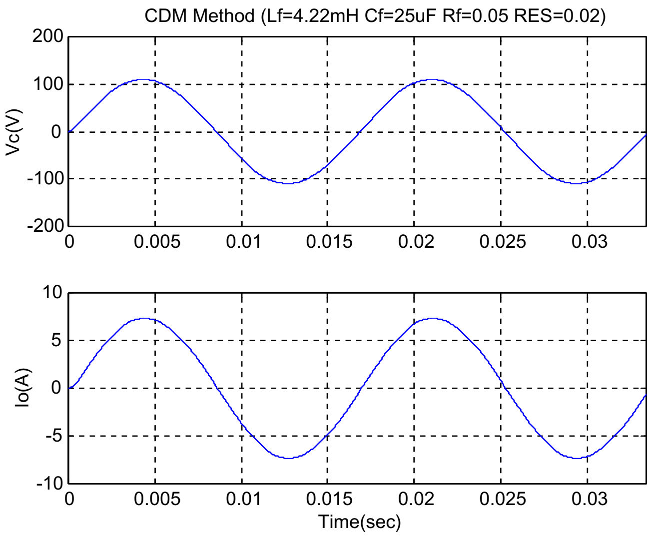


**Fig. 9.** Output voltage and current waveforms with L-C filter designed by CDM (Mode I).

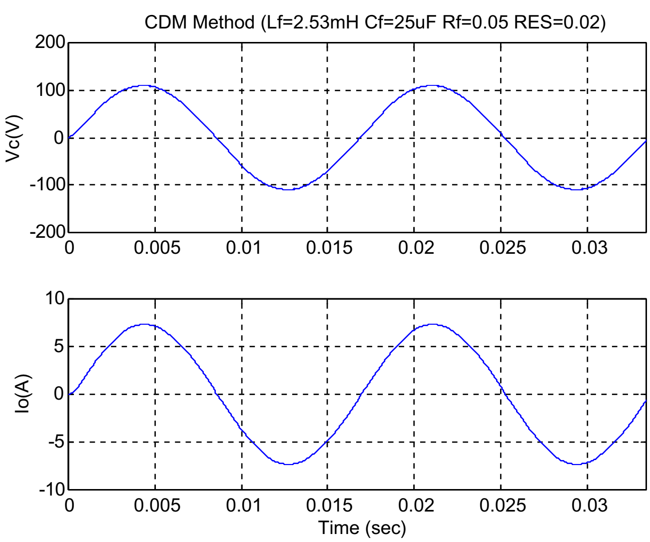


**Fig. 10.** Output voltage and current waveforms with L-C filter designed by CDM (Mode II).

where $N$ is the total number of fuzzy rules, $\overline{y_i}$ denotes the center value of the output set in the $y$ domain which is fired at the $ith$ fuzzy rule, and $\mu_{Ai}(\mu_{Bi})$ is the grade of membership at which $x_1$ and $x_2$ belong to the sets $A_i(B_i)$.

The FLC has two inputs, the voltage error $e(t)$ and the change in voltage error $ce(t)$, which are defined as:

$$e(t) = V_{ref}(t) - V_C(t) \tag{16}$$

$$ce(t) = e(t) - e(t-1) \tag{17}$$

where $V_C(t)$ is the output voltage of the L-C filter at time instant $t$, $V_{ref}(t)$ is the reference output voltage at time instant $t$.

The output of the fuzzy controller is the voltage used for compensation at time instant $t$, $U_s(t)$.

All MFs of the FLC inputs and the output are defined on the common normalized domain $[-1, 1]$, as shown in Figs. 4–6. The characters NB, NM, NS, Z, PS, PM, and PB stand for negative big, negative medium, negative small, zero, positive small, positive medium, and positive big, respectively. Here, triangular MFs are chosen for all fuzzy sets.

The rule base for computing the output $U_s(t)$ is shown in Table 1; this is an often used rule base designed with a two-dimensional phase plane. The control rules in Table 1 are built based on the characteristics of the step response. For example, if the output is falling far away from the setpoint, a large control signal that pulls the output toward the setpoint is expected, whereas a small control is required when the output is near and approaching the setpoint.

## 5. Simulation results

The proposed control scheme was modelled and simulated in MATLAB SIMULINK for both CDM and FLC. The simulation block for CDM is shown in Fig. 7 and the simulation block for FLC is shown in Fig. 8.

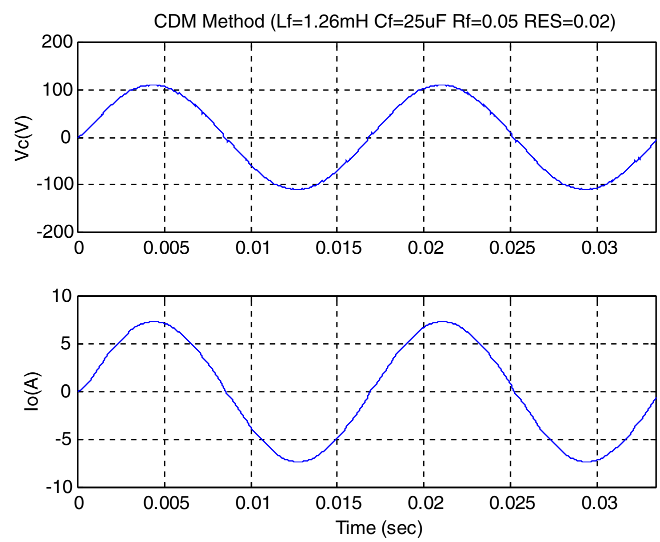


**Fig. 11.** Output voltage and current waveforms with L-C filter designed by CDM (Mode III).

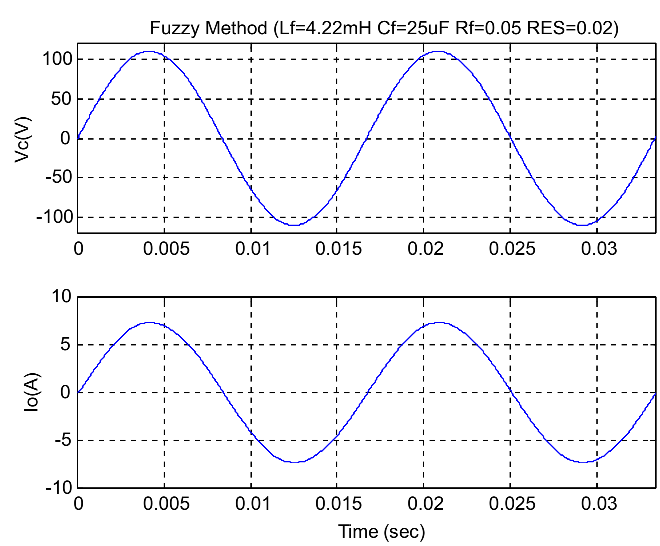


**Fig. 12.** Output voltage and current waveforms with L-C filter designed by FLC (Mode I).

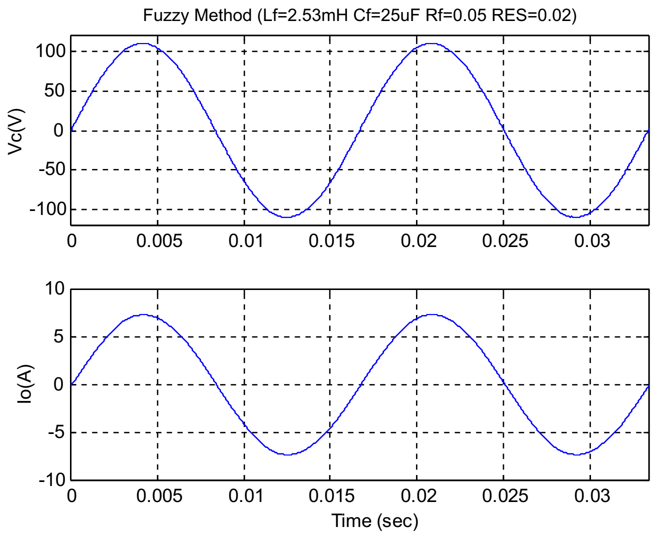


**Fig. 13.** Output voltage and current waveforms with L-C filter designed by FLC (Mode II).

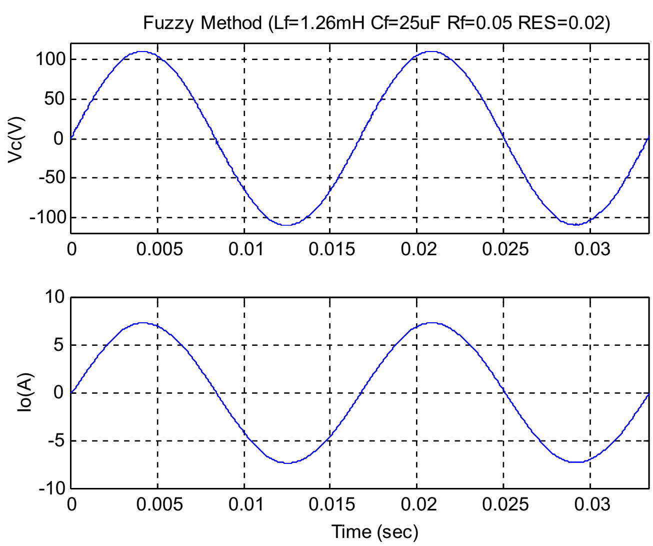


**Fig. 14.** Output voltage and current waveforms with L-C filter designed by FLC (Mode III).

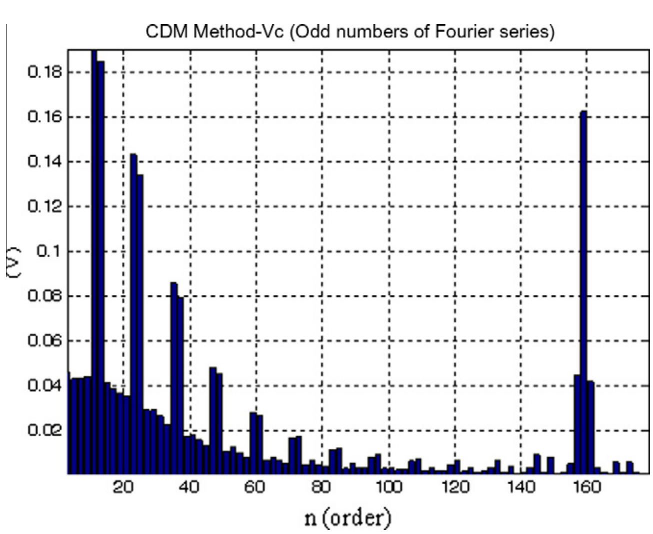


**Fig. 15.** Harmonic spectrum of output voltage for CDM (Mode I).

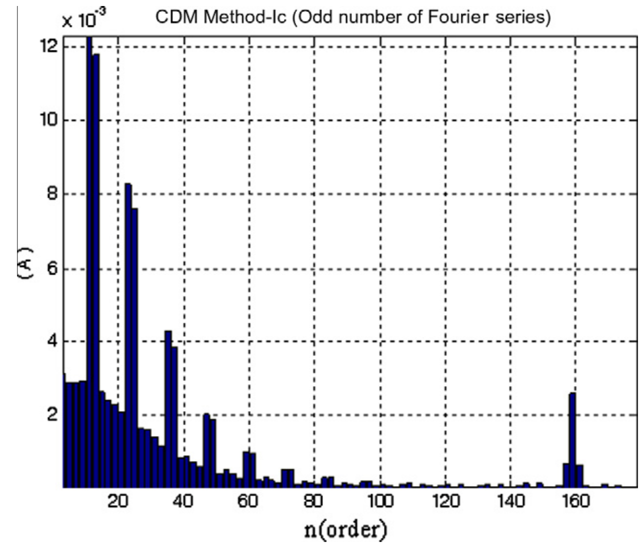


**Fig. 16.** Harmonic spectrum of output current for CDM (Mode I).

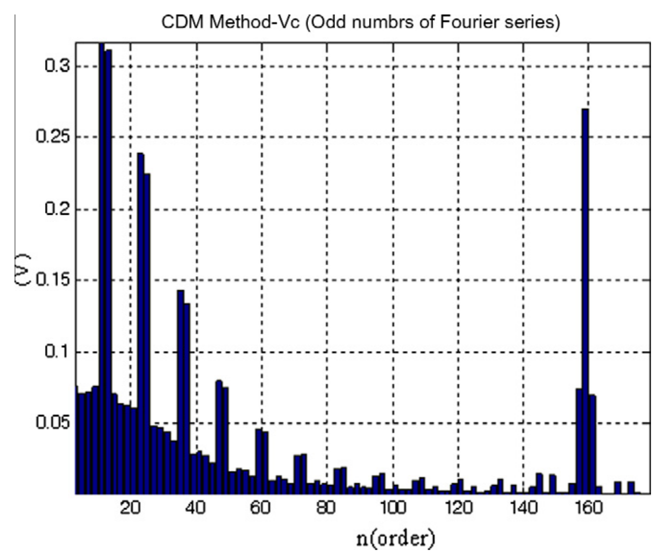


**Fig. 17.** Harmonic spectrum of output voltage for CDM (Mode II).

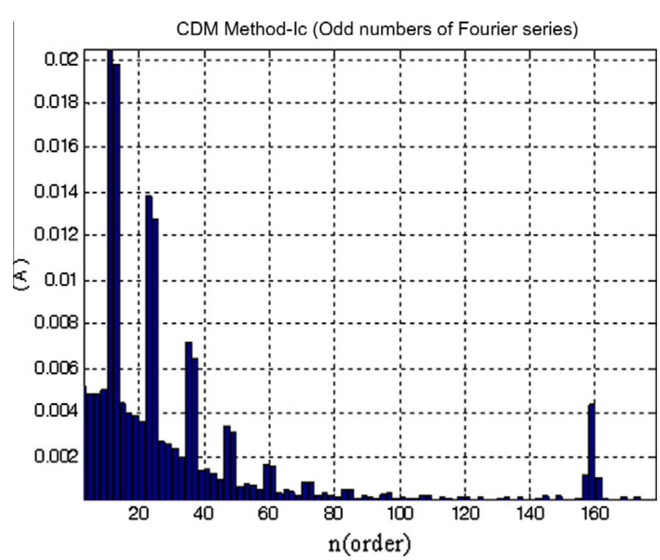


**Fig. 18.** Harmonic spectrum of output current for CDM (Mode II).

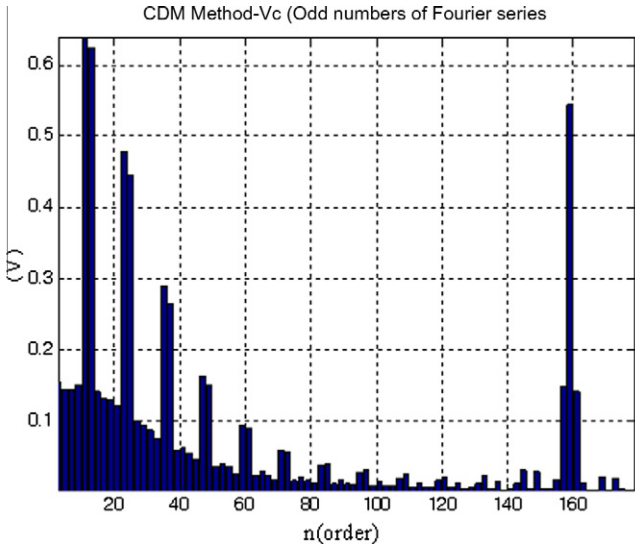


**Fig. 19.** Harmonic spectrum of output voltage for CDM (Mode III).

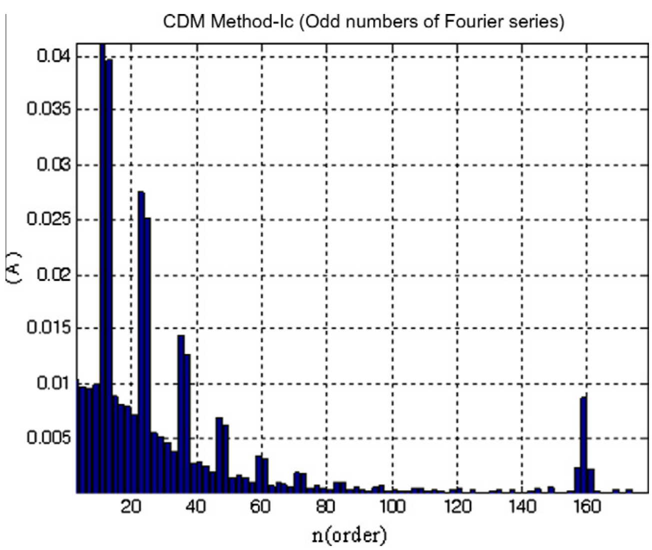


**Fig. 20.** Harmonic spectrum of output current for CDM (Mode III).

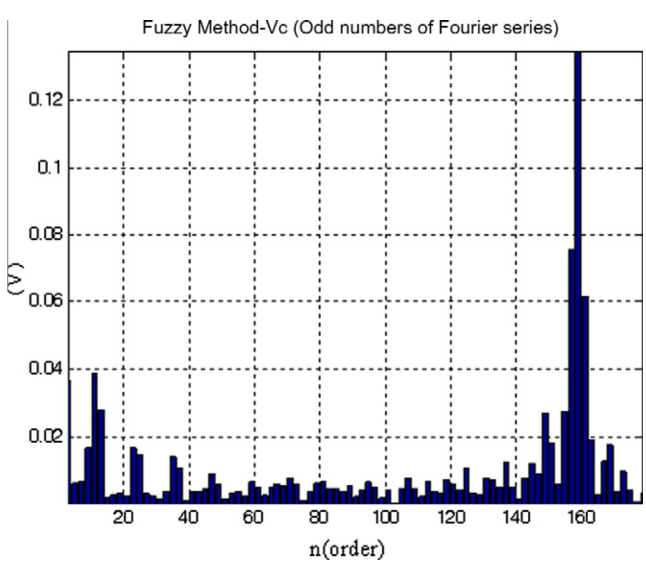


**Fig. 21.** Harmonic spectrum of output voltage for FLC (Mode I).

There are three possible scenarios in the simulation: (1) The given specification of voltage THD is 3% (Mode I). (2) The given specification of voltage THD is 5% (Mode II). (3) The given specification of voltage THD is 10% (Mode III). The parameters for CDM control system are shown in Table 2. The output voltage and current waveforms with L-C filter designed by CDM for three modes are shown in Figs. 9–11. In Figs. 12–14, the output voltage and current waveforms with L-C filter designed by FLC for three modes can be observed. The harmonic spectra of output voltage and output current designed by CDM are shown in Figs. 15–20. In Figs. 21–26, the harmonic spectra of output voltage and output current designed by FLC can be observed. The comparison of THD for output voltage of the filter by two methods for three modes is listed in Table 3. From the results, FLC is superior to CDM in filter design. The robust comparison between CDM and FLC is shown in Table 4. The $C_f$ of 25 $\mu F$ and $L_f$ of 0.1 mH are used in the first case. The THD of output voltage is 5.13% for CDM, but it is only 3.38% for FLC. The $C_f$ of 1 $\mu F$ and $L_f$ of 4.22 mH are used in the second case. The THD of output voltage is 67.41% for CDM, but it is only 3.33% for FLC. The FLC is more robust than CDM.

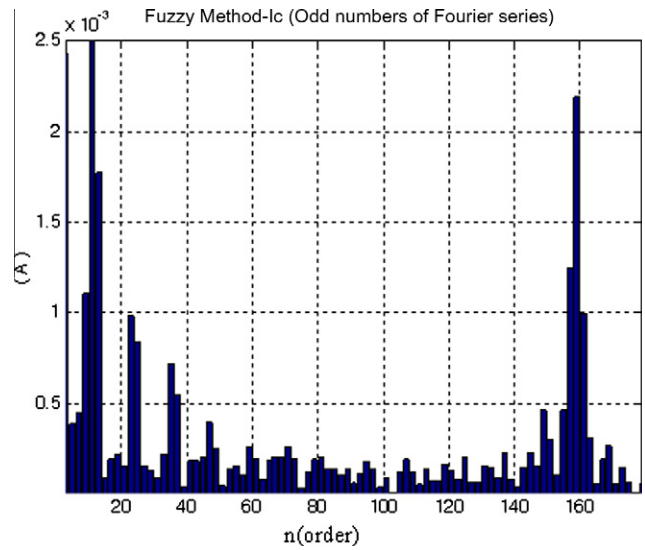


**Fig. 22.** Harmonic spectrum of output current for FLC (Mode I).

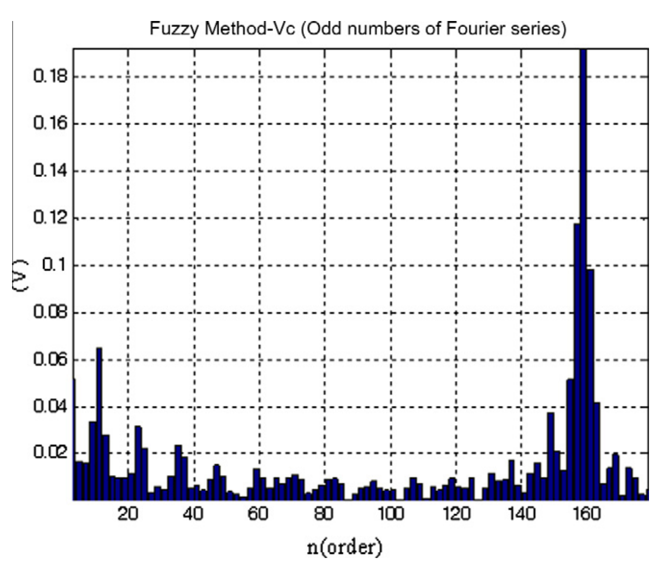


**Fig. 23.** Harmonic spectrum of output voltage for FLC (Mode II).

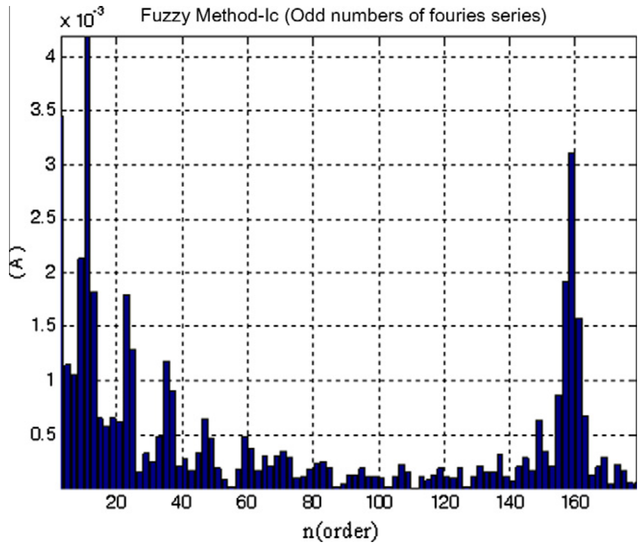


**Fig. 24.** Harmonic spectrum of output current for FLC (ModeII).

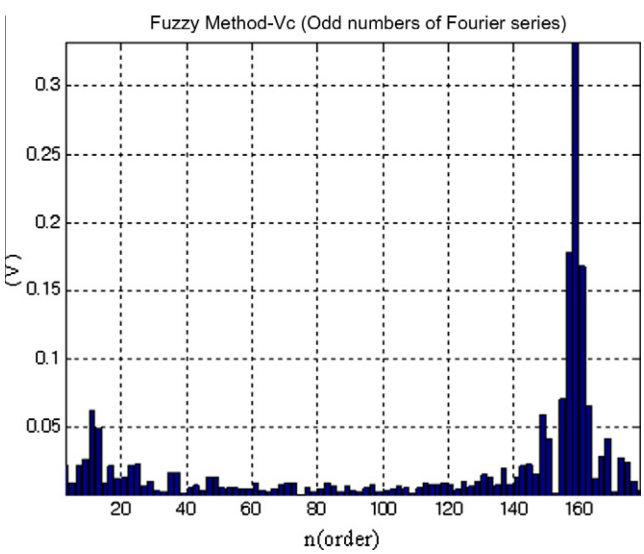


**Fig. 25.** Harmonic spectrum of output voltage for FLC (Mode III).

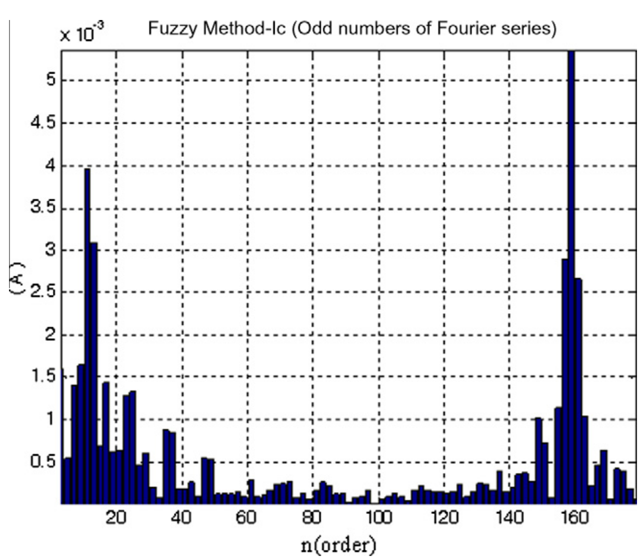


**Fig. 26.** Harmonic spectrum of output current for FLC (Mode III).

**Table 3**
THD for output voltage of the filter.

| | Mode I (%) | Mode II (%) | Mode III (%) |
|---|---|---|---|
| Given specification of voltage THD | 3 | 5 | 10 |
| THD for CDM | 4.04 | 6.75 | 13.5 |
| THD for FLC | 1.84 | 2.76 | 4.32 |

**Table 4**
Robust comparison between CDM and FLC.

| THD | Cf, Lf | |
|---|---|---|
| | Cf = 25 ($\mu F$)<br>Lf = 0.1 (mH) | Cf = 1 ($\mu F$)<br>Lf = 4.22 (mH) |
| CDM | 5.13% | 67.41% |
| FLC | 3.38% | 3.33% |

## 6. Conclusion

This paper proposes a filter design procedure for the single-phase inverter. By using the CDM, the filter values can be calculated from the closed form under the given system time constant. Therefore, the L-C filter value can be determined quickly through the systematic procedure without using any trial and error method. By using FLC, the voltage error and the rate of voltage error are inputs. From the fuzzy control rules the output of the voltage used for compensation is obtained. The filter for the circuit was simulated and the THD measured verified the reduction of harmonics to a very low level when FLC was employed.

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