Design and implementation of a novel AC-AC current source converter using DSP

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This paper proposes a novel current source converter for AC systems that provides an inherent protection against power quality problems. The power circuit topology and control scheme of the proposed converter are presented offering several advantages such as reduced number of switching devices and increased efficiency. The control strategy is built using pulse width modulation technique accompanied by two different control methods, PI control and fuzzy logic based control, to select the most effective one. The simulation results of the proposed converter are presented based on MATLAB/SIMULINK tools. In order to validate the converter operation, a laboratory prototype based on TMS320C31 digital signal processor has been designed and constructed. Experimental results for different cases are presented. Also, the reliability of the proposed converter against different power quality problems is investigated on the basis of simulation and experimental work.

مغيرات القدرة الإستاتيكية تلعب دور حيوي وهام في نظم القوى الكهربية الحديثة حيث أنها المسئولة عن إمداد الحمل بجهود أو تيارات متغيرة طبقا لمتطلباته. بناءا على ذلك يقترح هذا البحث مغير مصدر تيار لأنظمة التيار المتردد قادر على إمداد الحمل بتيار ثابت تحت الظروف المختلفة من مشاكل جودة القدرة. يتميز المغير المقترح في تركيبه بأنه يتطلب فقط مفتاحين إلكترونيين في حالة الأنظمة أحادية الوجه وهذا يقلل من مفاقيد الفتح والغلق وبالتالي يزيد من الكفاءة. يتميز أيضا المغير المقترح بأنه لا يسبب حدوث توافقيات داخل الشبكة كما هو الحال في مغيرات القدرة السابقة. مخطط التحكم المستخدم في هذا المغير تم بنائه من خلال تقنية تعديل عرض النبضة وقد تم المقارنة بين طريقتين للتحكم لاختيار الطريقة الأفضل، الطريقة الأولى هي التحكم التناسبي التكاملي والطريقة الثانية هي التحكم باستخدام المنطق الغيمي. وقد تم بناء مغير التيار المقترح عن طريق برنامج المحاكاة MATLAB/SIMULINK. تم إنشاء نموذج عملي مبني على معالج إشارات رقمي من النوع TMS320C31 وتم أخذ النتائج العملية للحالات المختلفة لإثبات صحة نتائج المحاكاة . أيضا تم اختبار أداء المغير المقترح في حالة وجود المشاكل المختلفة لجودة القدرة مثل انخفاض أو ازدياد الجهد، انقطاع الخدمة لفترة قصيرة، والتوافقيات مع عرض النتائج الخاصة بذلك.

Keywords: Current source converter, Power quality problems, Digital signal processing, Fuzzy logic based control

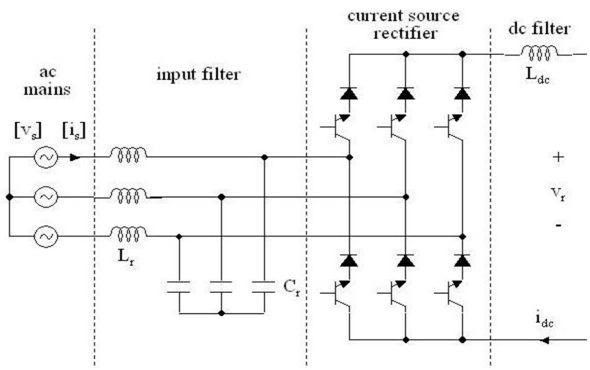
1. Introduction

Electrical energy is primarily distributed as ac voltage at constant amplitude and constant frequency. However, most of the electrical loads may demand different requirements. For instance, in a modern adjustable speed drive, induction machines require a variable ac voltage and variable frequency supply as the speed requirements vary. Therefore, to interface a load to the ac mains, a power conversion system is required. Today, electrical power conversion is basically achieved by means of static power converters. These static power converters can be used in many applications such as motor drives, power supplies, and active power filters.

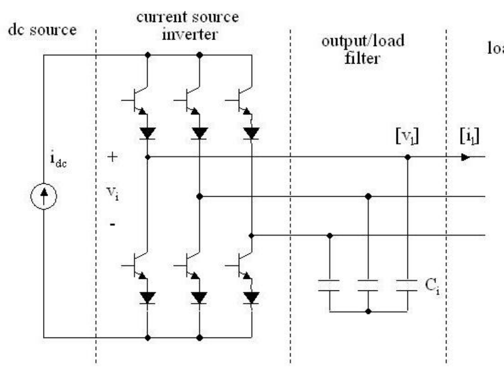
There are different topologies for ac/ac energy transfer. The Voltage Source Converter (VSC) is the most common power converter, extensively used in ac drive systems, ac uninterruptible power supplies, and active power filters [1]. It is simple, robust, and easy to control. Wide ranges of the frequency and magnitude of fundamental output voltage are attainable. However, VSCs, typically based on fast-switching, are not free of certain drawbacks as evidenced by a slate of publications. These include substantial switching losses, radiated electromagnetic interference, high dv/dt in the output voltage, and no current limiting capability in case of failure.

As a partial remedy, the Current Source Converter (CSC) is used, which is typically a current source inverter supplied from controlled rectifier with closed loop current control as shown from the schematic diagram of three-phase arrangement in fig. 1. The power circuit of the CSC is simpler and more robust than that of the VSC as a result of the absence of freewheeling diodes. Besides CSC provides an inherent protection from short-circuit currents due to the large dc-link inductance and current control in the rectifier and also provides the advantages of low dv/dt in the output voltage due to the output filter capacitor. However, CSCs have their weaknesses too, such as the increased size and cost, reduced efficiency resulting from higher conduction losses, greater complexity of the control algorithm, and susceptibility to resonance between the output capacitors and load inductances [2].

No wonder that alternative topologies of converters, such as the multilevel converters [3-4] or hybrid converters [5] have excited a vivid interest of researchers. Multilevel converters are particularly attractive in high power applications where power converters with high voltage, high current, and considerably reduced harmonics are required. On the other side, The principle of operation of the hybrid converter is different where the primary converter produces rectangular current pulses and provides most of the energy to the load and the secondary converter supplies the harmonic power required for making the load current waveforms sinusoidal. Despite the advantages of these topologies, they are costly and their structure and control are complicated.



(a)



(b)

Fig. 1. Three-phase current-source converter topology (a) current-source rectifier (b) current-source inverter.

Recently, the matrix converter was proposed as a final solution to these problems [6]. The matrix converter uses bi-directional fully controlled switches for direct conversion from ac to ac. It is a single-stage converter that requires only nine switches for three-phase to three-phase conversion. In respect to advantages compared with a traditional converter, it has full four-quadrant operation, input power factor control, and no dc-link. However, because of no energy storage, the power at the input can also be seen at the output. Grid disturbances affect the output immediately, and it is important to select a proper protection strategy [7].

To overcome the problems associated with different converter topologies, this paper proposes a novel current source converter for ac power applications. First of all, the power circuit topology of the proposed converter is presented. Next, the principle of operation and detailed description of the control scheme are illustrated. Finally, the reliability of the proposed converter against different power quality problems is studied.

2. Power circuit topology

The proposed converter is formed by several discrete components in series and parallel connection as shown in fig. 2.

The input inductor L_i and output inductor L_o are in the range of 0.5 – 0.75 H while the input and output resistors are equal at 18 KΩ approximately. These values are derived from the regulated line filter proposed in [8] with some modifications and enhancements to be suitable for the application as a current source converter. The combination of intermediate inductors, L_1, L_2 and L_3, constitutes the controlled inductor L_C.

Likewise, the output capacitors, C_1 and C_2, constitute the controlled capacitor C. The values of L_1, L_2, L_3, C_1 and C_2 are susceptible to change according to the output current required. The two switches S_1 and S_2 are bi-directional switches of the MOSFET type and the gating signal is derived from the control circuit.

On the output terminals a current transducer is used to extract the current signal. This signal is then provided to the control circuit to be processed giving the desired control action.

3. Principle of operation

The two-port network concept is used to analyze the operation of the proposed converter. The ratio of interest in this study is the input voltage, (V_i), divided by the output current (I_o) when the input current (I_i), is equal to zero, which represents the open-circuit reverse-transfer impedance, Z_{12}, [9] as given from the following equation:

$$Z_{12} = \frac{V_i}{I_o}\Big|_{I_i=0} . \quad (1)$$

For the sake of simplicity, the input and output parallel resistors, R_i and R_o, have been neglected without significant effect on the final result because their values are large compared to the parallel inductors. The relation between the output current, I_o, the capacitor current, I_c, the intermediate inductor current, I_{Lc}, and the output inductor current I_{Lo} is defined in

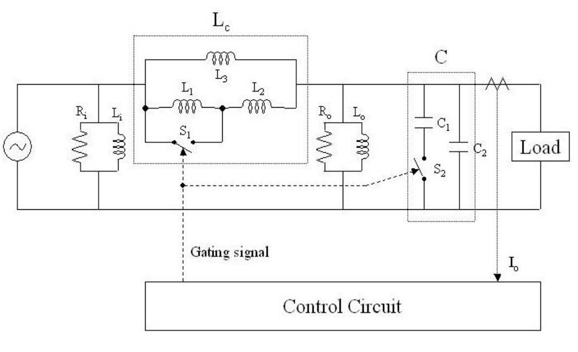


Fig. 2. Power circuit design of the proposed converter.

the S-domain as follow:

$$I_o(s) = I_c(s) + I_{Lc}(s) + I_{Lo}(s) . \quad (2)$$

Where:

$$I_c(s) = sCV_o(s) . \quad (3)$$

$$I_{Lc}(s) = \frac{V_o(s)\text{-}V_i(s)}{sL_c} . \quad (4)$$

$$I_{Lo}(s) = \frac{V_o(s)}{sL_o} . \quad (5)$$

On the other hand, when the input current I_i is equal to zero, the current I_{Lc} will be equal to the input inductor current I_{Li} as follows:

$$I_{Lc}(s) = I_{Li}(s) = \frac{V_i(s)}{sL_i} . \quad (6)$$

Solving eqs. (4 and 6) for the output voltage yields:

$$V_o(s) = V_i(s)\left[\frac{L_c}{L_i} + 1\right] . \quad (7)$$

Substituting eqs. (2 and 7 into 1) gives Z_{12} in the following form:

$$Z_{12} = \frac{V_i(s)}{I_o(s)} = \frac{sL_iL_o}{(L_c + L_i)CL_o s^2 + L_c + L_i + L_o} . \quad (8)$$

It can be assumed that L_i = L_o = L and L_c is much smaller than L_i or L_o. Then, eq. (8) can be rewritten as follows:

$$\frac{V_i(s)}{I_o(s)} = \frac{sL}{s^2CL + 2} . \quad (9)$$

From eq. (9), it can be concluded that the output current is in direct proportion to only the capacitance C where L is constant. Thus, this current can be kept constant by the appropriate control of the capacitance value.

4. Control scheme

In the proposed converter, two different control methods are compared to choose the superior one. These methods are PI control and fuzzy logic based control.

4.1. PI control

The PI controller is common in control systems. In PI controller, the integral of the error as well as the error itself is used for control. This type of controller is a first order system and its transfer function is given as follows:

$$G(s) = K_P + \frac{K_I}{s} . \tag{10}$$

Where K_P and K_I are the controller parameters. The objective of using PI controller is to combine transient response characteristics of proportional control with the zero steady state error characteristic of integral control. Proper controller design requires tuning the parameters K_P and K_I to give the desired control action. In the present study, K_P and K_I are adjusted at 50 and 300 respectively.

4.2. Fuzzy logic based control

The design of Fuzzy Logic based Control (FLC) used in this work is shown in fig. 3. The total fuzzy inference system is a mechanism that relates the inputs to a specific output or set of outputs. First, the inputs are categorized linguistically (fuzzification), then the linguistic inputs are related to outputs through fuzzy rules and, finally, all the different outputs are combined to produce a single output (defuzzification).

The main purpose of the fuzzification layer is to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. Fuzzification of the input results in a fuzzy vector where each component of this vector represents the degree of membership of the linguistic variables into a specific fuzzy variable's category. The number of components of the fuzzy vector is equal to the number of fuzzy variables used to categorize specific linguistic variables. Then, the fuzzy inference engine uses the fuzzy vectors to evaluate the fuzzy rules and produce an output for each rule. There are three different shapes of membership functions, triangular, trapezoidal and Gaussian. In this study the Gaussian shape is used for the input membership functions with three linguistic variables as shown in fig. 4. Gaussian membership function has the advantage of being smooth and nonzero at all points. The fuzzy inference engine often has multiple rules, each with possibly a different output, according to the output membership functions which are organized as shown in fig. 5.

Defuzzification refers to the method employed to combine these many outputs into a single output. There are a number of methods used for defuzzification. The most common defuzzification method is the centroid calculation, which returns the center of area under the curve, and this method is the one employed in this study.

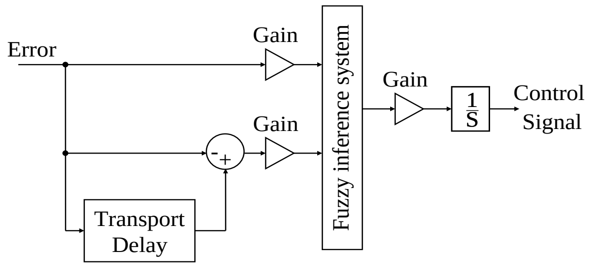


Fig. 3. Fuzzy controller design.

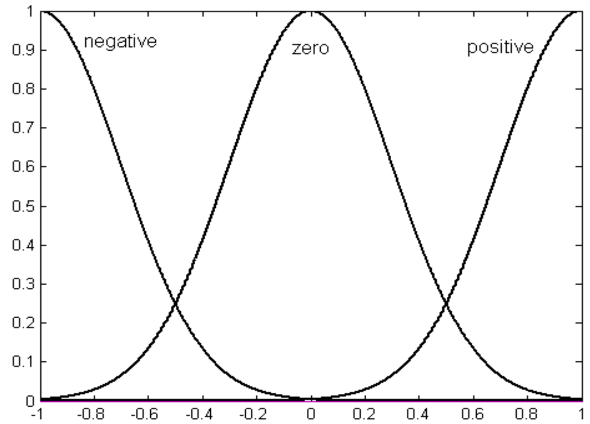


Fig. 4. Input membership functions.

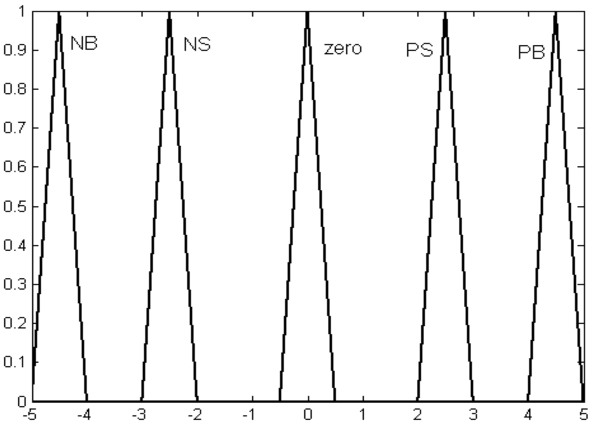


Fig. 5. Output membership functions.

5. Simulation results

The performance of the proposed converter as a current source converter is assessed by a computer simulation that uses MATLAB/SIMULINK. Different simulation tasks are carried out to examine the performance of the converter. The first task is dedicated to the evaluation of the converter ability to follow the current reference. The second task is devoted to assess the converter capability to supply constant current under different loading conditions.

5.1. Simulation results using PI control

The dynamic performance of the converter for a step change in the current reference is presented in figs. 6 and 7. Fig. 6 presents a step-up change in the reference from 0.09 A to 0.13 A and fig. 7 presents a step-down change from 0.13 A to 0.09 A. The RMS values of output current and voltage are shown in parts (a) and (b) respectively while part (c) shows the error signal. It is observed that the output current follows up the current reference with good transient characteristics. Figs. 8 and 9 show the same waveforms under load step changes. The load resistance is changed from 11.1 to 23 Ω in fig. 8 and from 23 to 11.1 Ω in fig. 9. These results reveal that the proposed converter has a fast response and accurate performance in supplying constant current under different loading conditions. In addition, the output waveforms of current and voltage are sinusoidal.

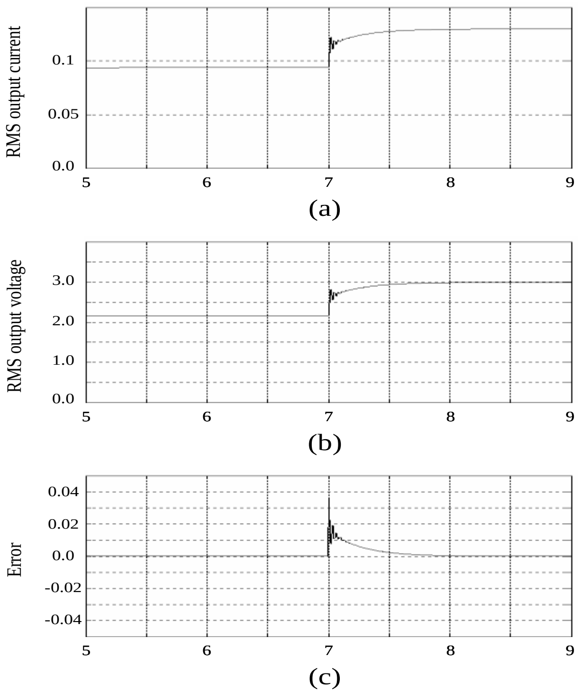


Fig. 6. Simulation results for a step-up change in the current reference from 0.09 A to 0.13 A using PI control (a) RMS output current (b) RMS output voltage (c) error signal.

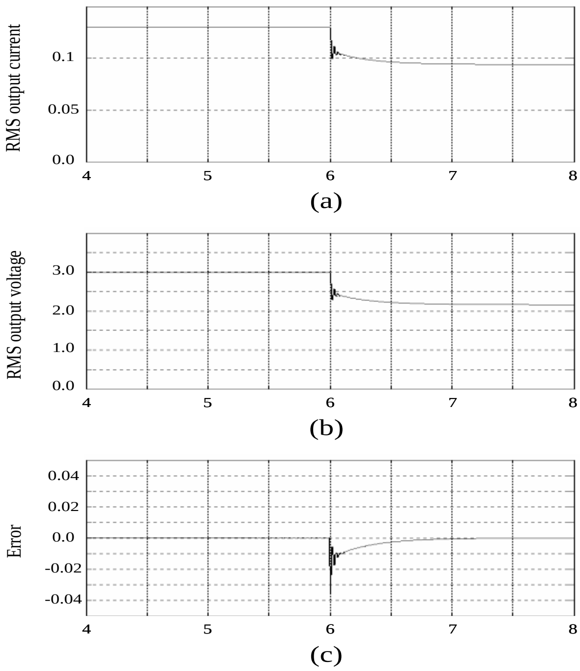


Fig. 7. Simulation results for a step-down change in the current reference from 0.13 A to 0.09 A using PI control (a) RMS output current (b) RMS output voltage (c) error signal

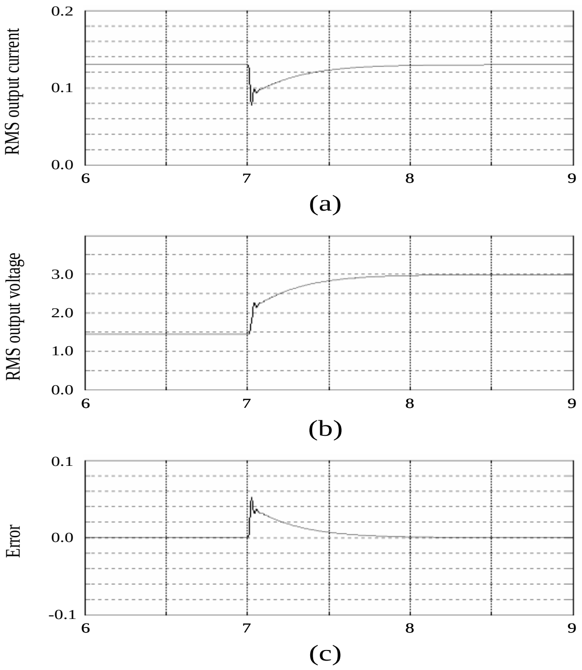


Fig. 8. Simulation results for a step-up change in the load resistance from 11.1 Ω to 23 Ω using PI control (a) RMS output current (b) RMS output voltage (c) error signal.

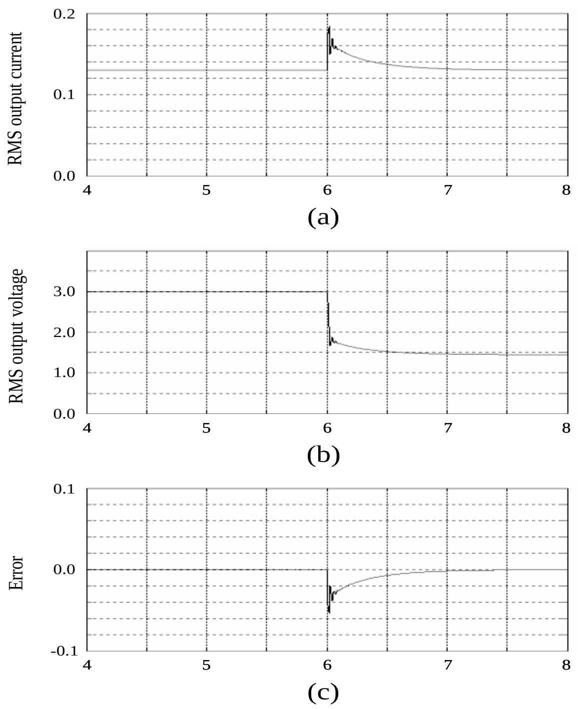


Fig. 9. Simulation results for a step-down change in the load resistance from 23 Ω to 11.1 Ω using PI control (a) RMS output current (b) RMS output voltage (c) error signal.

5.2. Simulation results using FLC

This section studies the converter performance using fuzzy logic based control. The output waveforms and error signals of the transient response for a step change in load and reference respectively are depicted in figs 10 and 11. The values of load resistance and current reference in different cases are the same values as that used with PI control. It is clear that the transient stage in different cases is less than that obtained using PI control.

6. Reliability of the proposed converter

This section encompasses the reliability of the proposed converter against common Power Quality (PQ) problems. The term power quality refers to a wide variety of electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system [10].

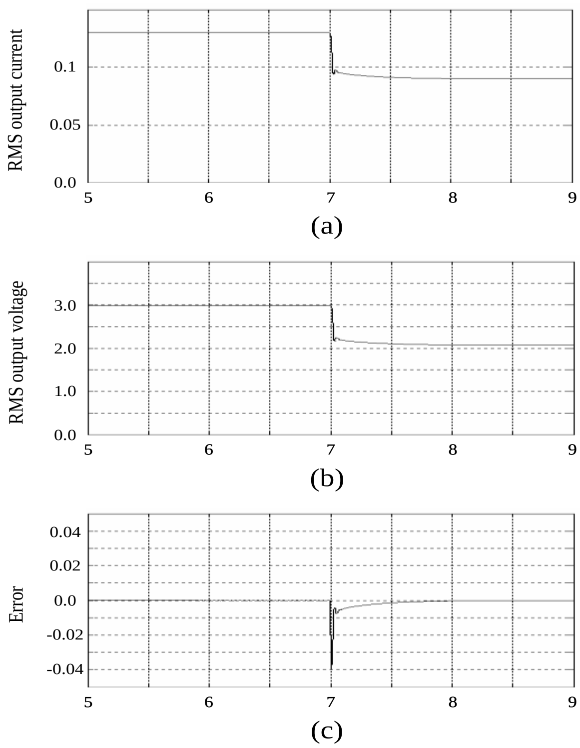


Fig. 10. Simulation results for a step change in the current reference from 0.13 A to 0.09 A using FL control (a) RMS output current (b) RMS output voltage (c) error signal.

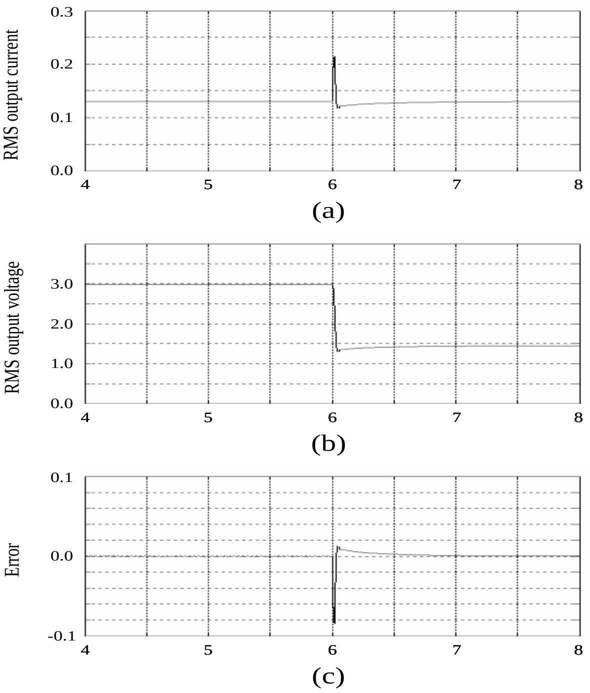


Fig. 11. Simulation results for a step change in the load resistance from 23 Ω to 11.1 Ω using FL control (a) RMS output current (b) RMS output voltage (c) error signal.

The growing number of power electronics based equipments has produced an important impact on the quality of electrical power supply. These equipments produce distorted current and voltage waveforms in the network. At the same time, most of the equipments are quite sensitive to deviations from the ideal sinusoidal line voltage. Therefore, power quality problems may originate in the system or may be caused by the consumer itself. The result is harmonic pollution that degrades the power quality causing different problems such as transformer overheating and rotary machine vibration. Therefore, safe operation necessitates that the system must be protected against power quality problems.

The most widespread power quality problems in power system are voltage sags, voltage swells, short interruption, and harmonics. In this study, all of these problems are simulated in the input voltage and are tested. MATLAB/SIMULINK software tools are again used for these simulation studies.

Voltage sag is defined as a short-duration reduction, up to a few seconds, in voltage magnitude. The principal cause of all voltage sags is a short-duration increase in current. The main contributions are motor starting, transformer energizing, and faults. Despite their short duration, such events can cause serious problems for a wide range of equipment.

Voltage swell is an increase in RMS voltage at the power frequency for durations from 0.5 cycles to 1 min. As with sags, swells are usually associated with system fault conditions but they are much less common than voltage sags.

The detailed test results under voltage sag condition are shown in fig. 12. Fig. 12-a clearly shows the waveform of input voltage after sag initiation. Fig. 12-b, c show the output current and error signal respectively. It is observed that the control action actively compensate the drop in output current due to voltage sag. Likewise, fig. 13 shows the same waveforms and signals but for a voltage swell problem. It is clear that the control circuit behaves in an inverse manner to that with voltage sag in order to handle the sudden increase in output current.

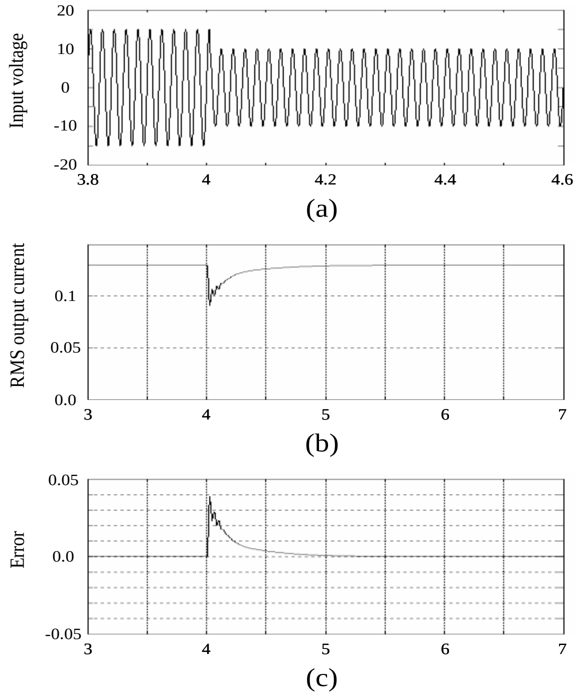


Fig. 12. Simulation results for a 33% voltage sag problem in the supply voltage (a) input voltage (b) RMS output current (d) error signal.

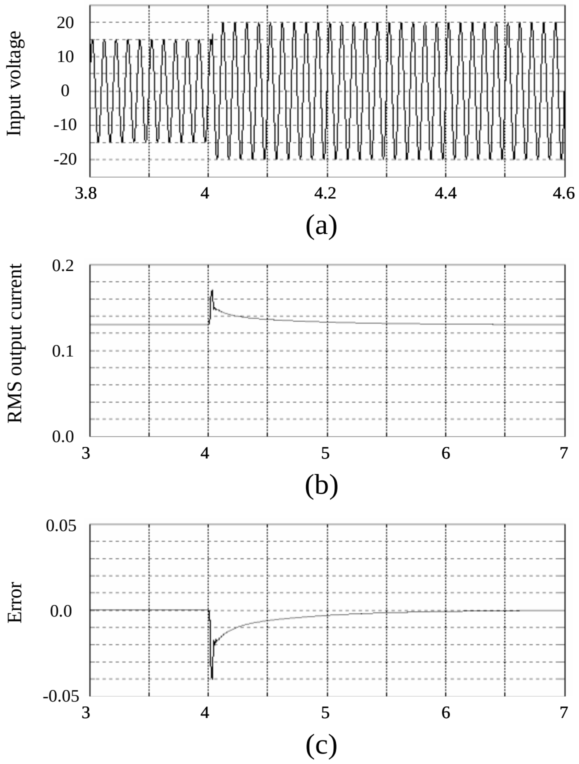


Fig. 13. Simulation results for a 33% voltage swell problem in the supply voltage (a) input voltage (b) RMS output current (d) error signal.

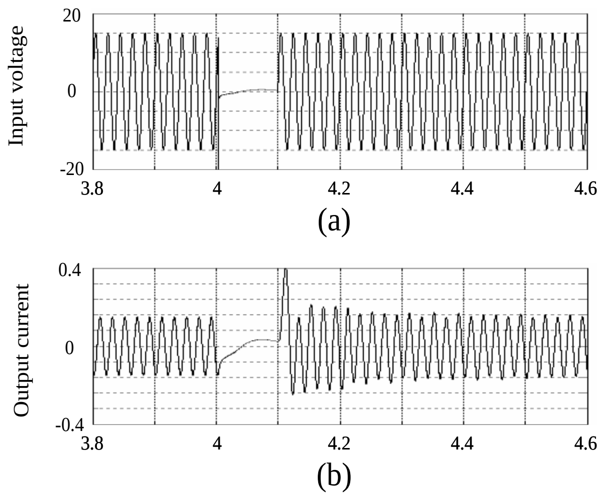


Fig. 14. Simulation results for a short interruption case in the supply voltage (a) input voltage (b) output current

The transient performance of the proposed converter in case of short interruption is depicted in fig. 14. These results reveal that the proposed converter has a fast response in returning to the initial state after the interruption vanishes.

For studying the waveform distortion case, an input signal comprising 1 pu of the fundamental component, 1/3 pu of the third harmonic and 0.2 pu of the fifth harmonic is considered for the simulation as shown in fig. 15-a. The output voltage of the proposed converter is presented in fig. 15-b. Fig. 15-a, b also reports the spectral component of the input and output voltages respectively. It is evident that the output voltage is sinusoidal with drastically reduced harmonics in spite of the highly polluted input signal (THD = 39%).

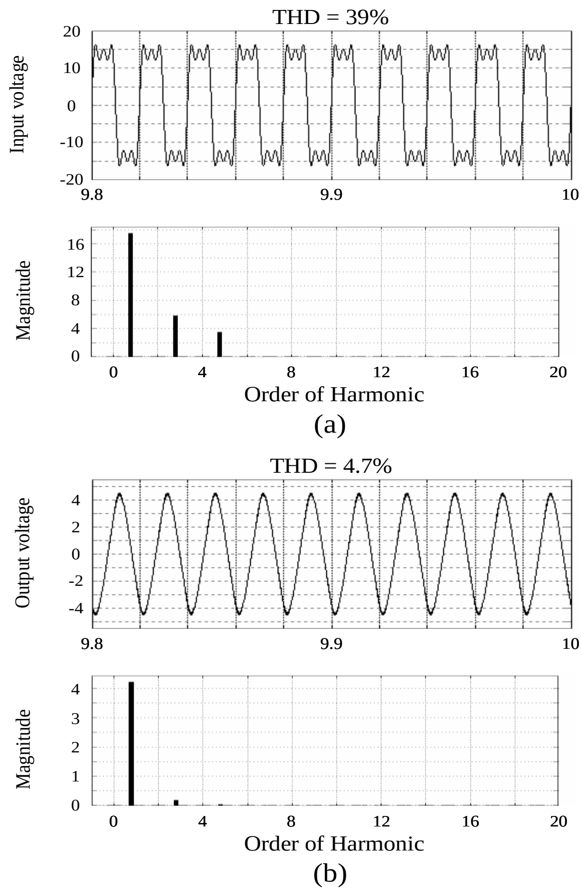


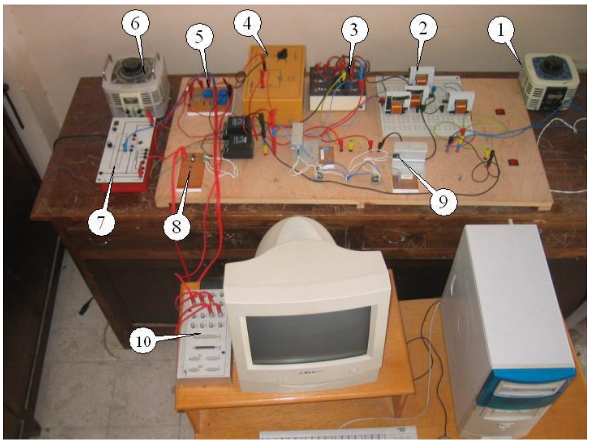
Fig. 15. Simulation results of the proposed converter in case of harmonic distortion (a) input voltage (b) output voltage.

7. Experimental results

In order to validate the effectiveness of the proposed converter configuration and to check out the simulation results, a laboratory prototype based on DSP has been designed and constructed, as represented in fig. 16. The experimental results are carried out for the single phase arrangement only due to existent laboratory restraints. It has to be pointed out that a relatively small input voltage is used to ensure an unsaturated operation of the intermediate inductors, L_1, L_2 and L_3. This can be modified to a large scale if large inductors are available. The values of inductors L_1, L_2 and L_3 are 75 mH, 30 mH and 30 mH respectively, and their wiring resistance measures 1 Ω. The fixed capacitor on the output terminals is set to 95 µF while the switched capacitor is 247 µF. A variable resistive load is used to examine the converter performance with load change. In the proposed converter, the digital signal processor type used is TMS320C31. First, the controller and the PWM blocks are designed in MATLAB/SIMULINK. Afterwards, the interface between MATLAB/ SIMULINK and digital signal processor allows the control algorithm to be run on the hardware. One analog-to-digital converter is used for the sensed load current. An optoisolated interface board is also designed for isolation between the entire DSP and the power circuit. The gating signal is then applied to the power switches. The application of DSP-based control offers many features that are not found in analog control such as programmability, flexibility, and insensitivity to aging and environmental variations.

Fig. 17 and 18 show transient response waveforms of the converter to step changes in the current reference and load resistance respectively. Figs. a, b show the output current and its RMS value while fig. c shows the RMS output voltage. In fig d the error signal between the reference and RMS output current is displayed.

These results reveal that the output current not only follows the reference but also remains constant under load impacts.



Input inductor.	Output inductor.
Intermediate inductors.	±15 V DC source.
Output capacitors.	Optoisolated board.
Variable resistive load.	MOSFET switch.
Current transducers.	I/O interface.

Fig. 16. Experimental setup of the proposed converter.

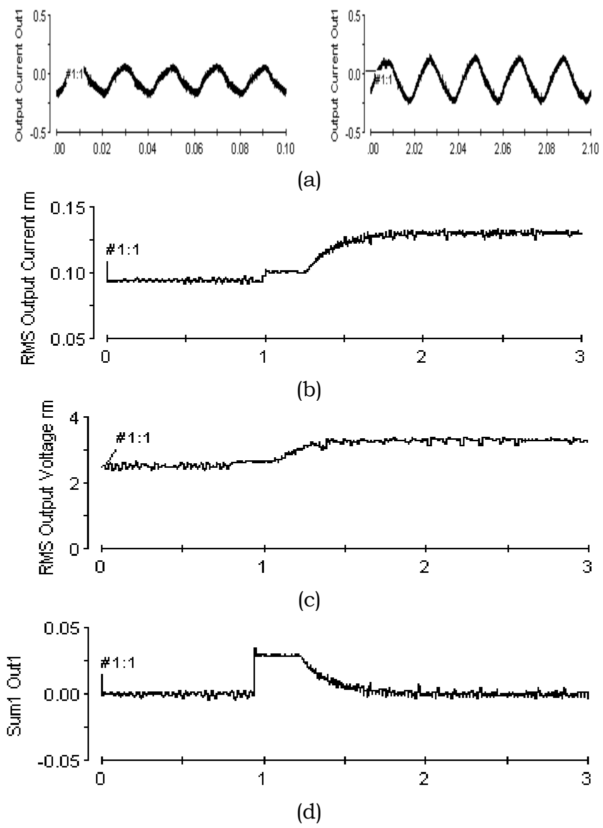


Fig. 17. Experimental results for a step-up change in the current reference from 0.09 A to 0.13 A (a) output current. (b) RMS output current (c) RMS output voltage (d) error signal.

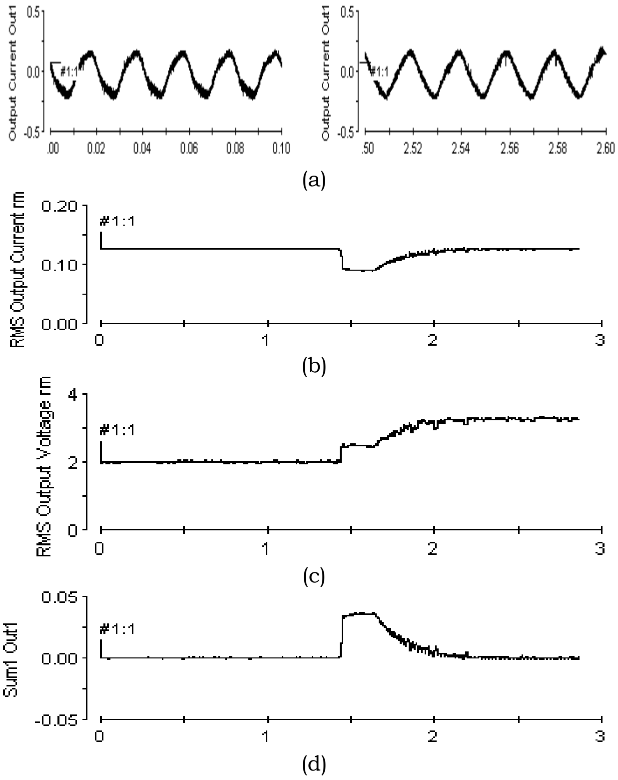


Fig. 18. Experimental results for a step-up change in the load resistance from 11.1 Ω to 23 Ω (a) output current (b) RMS output current (c) RMS output voltage (d) error signal.

The sensitivity of the proposed converter to different power quality problems is also studied on the basis of experimental work. Fig. 19 shows transient response waveforms of the current compensation capability of the converter under voltage sag condition. The inverse case is depicted in fig. 20, where a voltage swell is imposed on the input voltage. It is interesting to note that the transient stage does not exceed three seconds in the first case and one second in the other case.

The other two tests that should be made for the proposed converter is transient response to a short interruption in the mains and harmonic suppression performance. Experimental results probing these features are shown in figs. 21 and 22. From these figures, it can be proved that the proposed converter has a fast transient response and a good harmonic suppression capability.

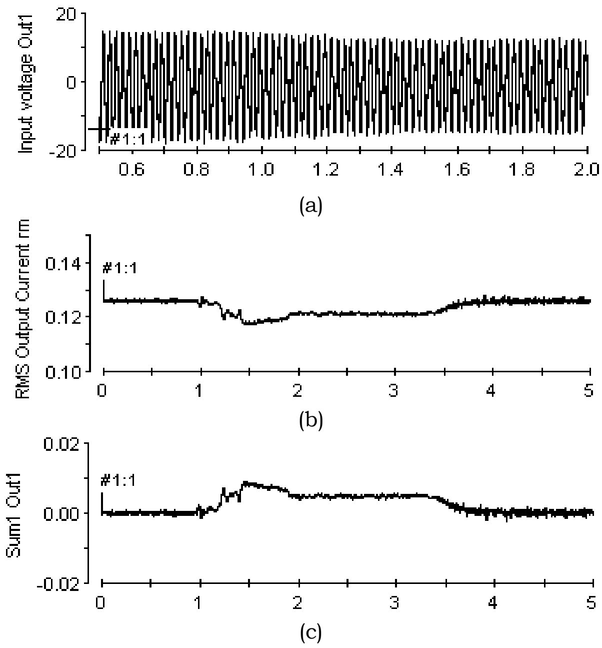


Fig. 19. Experimental results for a 30% voltage sag problem in the supply voltage (a) input voltage (b) RMS output current (c) error signal.

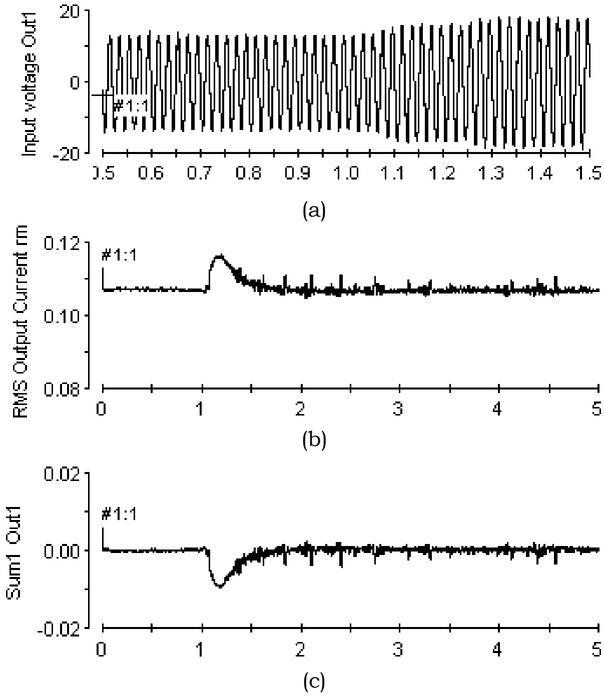


Fig. 20. Experimental results for a 35% voltage swell problem in the supply voltage (a) input voltage (b) RMS output current (c) error signal.

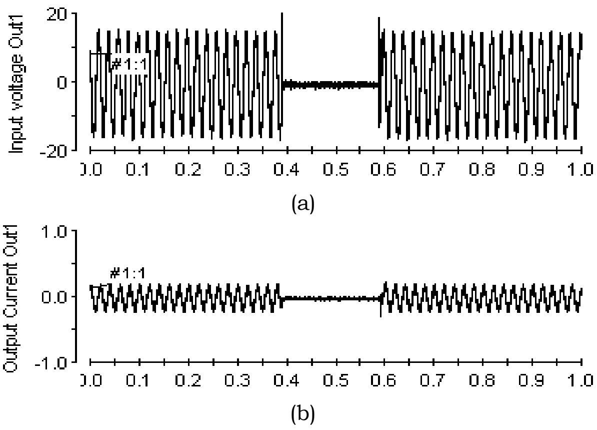


Fig. 21. Experimental results for A 0.2 S Short Interruption in The supply voltage (a) Input voltage (b) output current.

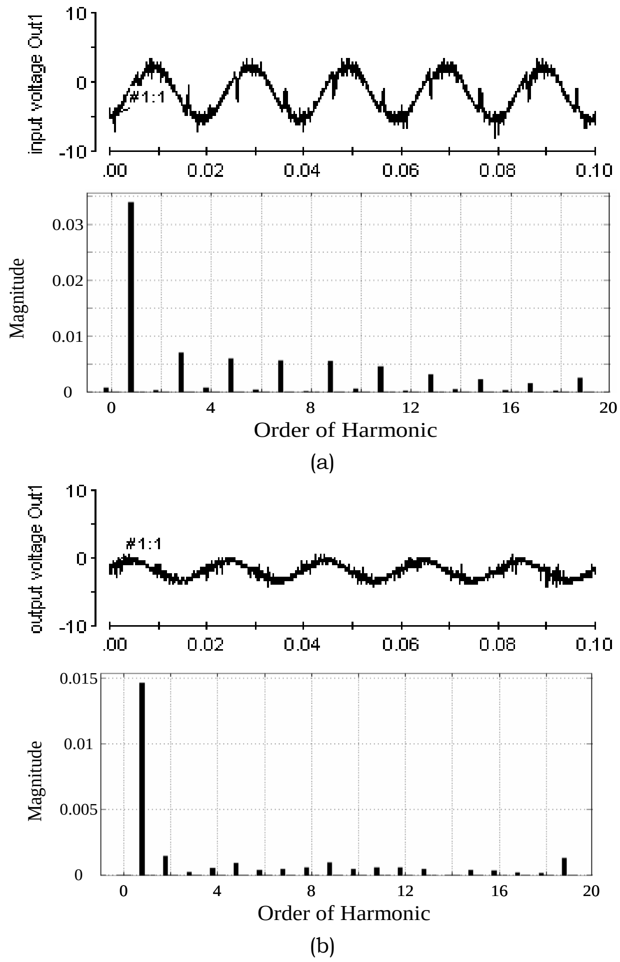


Fig. 22. Experimental results for a distorted supply voltage (a) input voltage (b) output voltage.

8. Conclusions

A novel current source converter was proposed in this paper. The power circuit topology and control scheme of the proposed converter were discussed. The design of the proposed converter exhibited the advantage of using less number of semiconductor devices and consequently, reducing switching losses. The analysis of the proposed converter showed that the output current is in direct proportion with the output capacitance. Thus, this current can be kept constant by the appropriate control of the capacitance value. The proposed converter was simulated using MATLAB/ SIMULINK software and the simulation results showed that the proposed converter had succeeded in supplying constant output current with high accuracy under different loading conditions. The simulation results also showed that the proposed converter has good transient characteristics in tracking the current reference.

A comparison between using PI control and fuzzy logic based control was made and the results showed that the transient response is faster in case of fuzzy logic based control. Experimental work was conducted using digital signal processor and the results validated the converter effectiveness in keeping the output current constant with load change as well as following the current reference. The experimental results showed a good agreement with simulation results. Simulation and experimental results showed that the proposed converter is capable of dealing with the change in output current due to voltage sags or swells. The results also showed that the proposed converter has excellent performance in suppressing harmonics.

References

[1] J.R. Espinoza and Others, "Selective Harmonic Elimination and Current/Voltage Control in Current/Voltage-Source Topologies: A Unified Approach", IEEE Transactions on Industrial Electronics, Vol. 48 (1), pp. 71-81 (2001).

[2] Y. Neba, "A Simple Method for Suppression of Resonance Oscillation in

PWM Current Source Converter", IEEE Transactions on Power Electronics, Vol. 20 (1), pp.132-139 (2005).
[3] J.S. Lai and F.Z. Peng, "Multilevel Converters-A New Breed of Power Converters", IEEE Transactions on Industry Applications, Vol. 32 (3), pp. 509-517 (1996).
[4] L.M. Tolbert, F.Z. Peng and T.G. Habetler, "Multilevel Converters for Large Electric Drives", IEEE Transaction on Industry Applications, Vol. 35 (1), pp. 36-44 (1999).
[5] S. Fukuda, Y. Kubo and M. Kitano, "Introduction of a Hybrid Multi-Converter System and Its Control Strategy", Proceedings of the Power Conversion Conference, PCC 2002, Osaka, Japan, pp. 372-377 (1999).
[6] D.G. Holmes and T.A. Lipo, "Implementation of a Controlled Rectifier Using AC-AC Matrix Converter Theory", IEEE Transactions on Power Electronics, Vol. 7 (1), pp. 240-250 (1992).
[7] P. Nielsen, F. Blaabjerg and J.K. Pedersen, "New Protection Issues of a Matrix Converter: Design Considerations for Adjustable-Speed Drives", IEEE Transactions on Industry Applications, Vol. 35 (5), pp.1150-1161 (1999).
[8] M.E. Abdel-Karim, "A Regulated Line Filter for Low Power Applications", Alexandria Engineering Journal, Vol. 40 (6), pp.835-843 (2001).
[9] R.L. Boylestad, "Introductory Circuit Analysis", Seventh Edition, ISBN 0023131616 Macmillan Publishing Company, New York (1994).
[10] IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE Std. 1159 (1995).

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