A regulated line filter for low power applications

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This paper presents a practical design procedure of a regulated line filter (RLF) for low power applications. The proposed design offers both impedance compatibility at both sides of the filter and output voltage regulation. The proposed RLF uses input coil, output coil, and control coil, mounted on a standard three-limb core. A controlled external inductor is connected with the control coil to regulate the output voltage. A capacitor is connected across the output coil to meet the filter specifications. The validity of theoretical analysis and computed performance are corroborated by experimental results of a laboratory prototype. To show its effectiveness, the proposed filter is employed at the output of an Uninterruptible Power Supply (UPS), where good dynamic performance and voltage regulation are achieved.

للحصول على أداء جيّد لمغيرات القدرة يلزم استخدام مرشح قدرة لتقليل آثار التوافقيات الناتجة عن التغير النبضي لتيار المغير على كل من الحمل ومنبع التغذية. يقدم هذا البحث أسلوبًا مقترحا لتصميم مرشح يمكن ربطة مع مغير القدرة للحصول على موجة جهد جيبيه على الحمل متضمنا آلية لتنظيم مستوى جهد الخرج مع ضمان المحافظة على توافق معاوقة المرشح مع كل من مغير القدرة والحمل لتقليل الآثار السلبية عليهما. تم استنباط النموذج الرياضي للمرشح المقترح كما تم بناءه معمليا ودراسة خصائصه حيث وجد توافقا مرضيا بين النتائج المحسوبة والمقاسة. وقد استخدام المرشح لمرحلة خرج لعاكس مصدر قدرة لاانقطاعى حيث أظهرت النتائج تحسن خرج المصدر.

Keywords: Line filter, Voltage regulator, Power converter.

1. Introduction

Power electronic converters are extensively used in many applications. The major problem associated with those converters is the harmonic currents injected into the mains supply. The undesirable effects of harmonic distortion are well-known [1]. For most industrial applications, an intermediate line filter is usually employed to prevent the pulsating input current of the converter from being reflected to the load and the mains [2-7].

In this paper, a Regulated Line Filter (RLF) consisting of input coil, output coil and control coil is proposed. These coils are mounted on a standard three limb core arranged to give a reciprocated flux pass of the input to output flux linkage. This arrangement has been used in the linear mode as a voltage regulator [8-9] and in the saturated mode as a voltage stabilizer [9]. This paper uses the previous arrangement in the linear mode as a line filter as well as a voltage regulator.

A line filter could adversely interact with the converter and load, resulting in severe performance degradation [3,4]. Thus, an intermediate line filter should be designed in a way to avoid interaction not only with the load but also with the converter. Unlike the conventional design approaches [3-7], the proposed design procedure incorporates the input/ output impedance characteristics of the filter to avoid interactions at both sides, while satisfying an output voltage regulation.

The above filter requirements are included through an appropriate inductance in the control coil circuit to control the flux linkage from input coil to the output coil, and hence the output voltage. Also, a capacitor is connected across the output coil to increase the output voltage range and to meet the filter specifications. For this configuration, a sinusoidal output wave and voltage regulation can be achieved. Sensitivity of the RLF to the control inductor and the capacitor is investigated. The proposed filter is employed at the output of an Uninterruptible Power Supply (UPS), where good dynamic performance and voltage regulation are achieved.

2. Construction and operation

The RLF employs a standard three-limb core as shown in fig 1. The input coil is wound on one of the two outer limbs. The output coil is mounted on the second outer limb. While, the control coil is mounted on the center limb. The number of turns (N) of the three coils and their cross sectional areas are equal and depend on the desired rating.

2.1. Control coil

The flux of the input coil has two components, the first one through the output coil and the second one through the control coil. In linear mode of operation, i.e. in the linear region of the B-H characteristics, varying the impedance of the control coil can vary the flux of the output coil. Consequently, the output voltage level depends on both input voltage and control coil impedance. At no-load and no control coil current, the reluctance of flux path to output coil is higher than that to the control coil. So, the output voltage is much less than the input voltage. If an external resistance or inductance is connected with the control coil, the output voltage can be increased. Therefore, variable inductance is preferred to reduce the power loss and obtain a wide range of output voltage [7]. For the load conditions, the input current and consequently, the control coil current will be increased.

In principle, the RLF is similar to the high leakage transformer [10] as far as the construction is concerned. The basic construction of this arrangement is shown in fig 1, but with a control coil being added on the center limb. The equivalent circuit of the RLF can be constructed as shown in fig 2 depending on the same rules given in reference [11] to simulate such devices. The effect of inductance of the control coil with the external inductance can be represented in the equivalent circuit by a magnetizing inductance (ℓ_{m3}) in parallel with the control inductance (ℓ_s). All parameters of the equivalent circuit are referred to the primary side. These parameters are as explained in [11]. The measured parameters of the equivalent circuit are listed in the appendix.

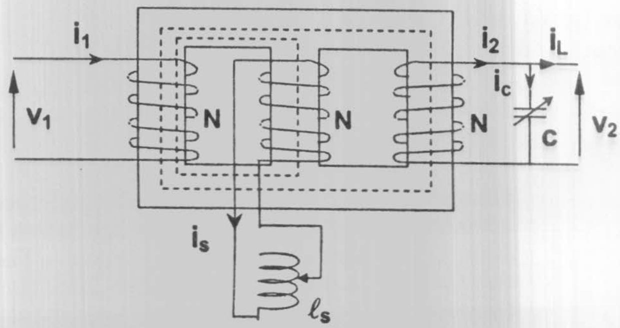

Fig. 1. Construction of the proposed RLF.

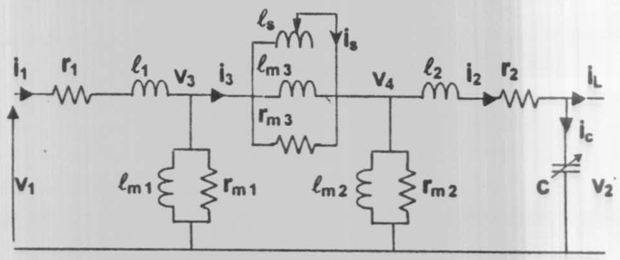

Fig. 2. Equivalent circuit of RLF.

2.2. Output capacitor

Using a suitable capacitor across the output terminals, as shown in fig. 2, two-resonance conditions are possible. The first may occur within the loop containing the capacitor with the sum of leakage inductance of input coil (ℓ_1), output coil (ℓ_2), and control inductance (ℓ_s). The second resonance may also occur within the loop containing leakage and magnetizing inductances of the output coil and the capacitor. Using the linear equivalent circuit, shown in fig 2, the theoretical analysis can be carried out to evaluate performance of the proposed line filter.

3. Mathematical model

In this analysis, core losses of the RLF are ignored. Due to the symmetry of input and output coils, winding resistances, leakage inductances, and magnetising inductances are equal i.e., $r_1 = r_2 = r$, $\ell_1 = \ell_2 = \ell_\ell$, and $\ell_{m1} = \ell_{m2} = \ell_m$, respectively. However, the magnetizing inductance of the control coil is different and much greater than the control inductance. Therefore, the effective equivalent inductance of the center limb can be taken as the control inductance. The behaviour of this filter is governed by node and loop equations, which are based on the equivalent circuit of fig 2. These equations are solved using Symbolic Matlab Software to obtain the transfer function between any of the circuit variables and the input as follows:

$$Z_{IF} = \frac{s[c\ell_m^2(\ell_s+2\ell_\ell)s^2 + 2\ell_m cr(\ell_s+2\ell_\ell+\ell_m)s + \ell_m(\ell_s+2\ell_\ell+\ell_m)]}{c\ell_m(\ell_s+2\ell_\ell+\ell_m)s^2 + cr(\ell_s+2\ell_m)s + (\ell_s+2\ell_m)}, \quad (1)$$

$$Z_{OF} = \frac{\ell_m(\ell_s+2\ell_\ell)s^2 + 2\ell_m r(\ell_s+2\ell_\ell+\ell_m)s + r^2(\ell_s+2\ell_m)}{s[c\ell_m^2(\ell_s+2\ell_\ell)s^2 + 2\ell_m cr(\ell_s+2\ell_\ell+\ell_m)s + \ell_m(\ell_s+2\ell_\ell+\ell_m)]}, \quad (2)$$

$$A_{VF} = \frac{V_2(s)}{V_1(s)} = \frac{\ell_m^2}{\left[\begin{array}{l} c\ell_m^2(\ell_s+2\ell_\ell)s^2 \\ +2\ell_m cr(\ell_s+2\ell_\ell+\ell_m)s + \ell_m(\ell_s+2\ell_\ell+\ell_m) \end{array}\right]}. \quad (3)$$

Where:

Z_{IF} input impedance of the RLF with the output port open,

Z_{OF} output impedance of the RLF with the input port shorted,

A_{VF} voltage gain of the RLF with the output port open.

The transfer functions given by eqs. (1 and 2) have the dimensions of impedance. All graphs of impedance transfer functions with these units are plotted as impedances with a log scale. A simple conversion between impedance and amplification is 1Ω=0dB, 10Ω=20dB. It is obvious from eqs. (1-3) that, the reactive components of the RLF significantly affect the filter specifications to give the impedance compatibility and voltage regulation. From these two points of view, in the following, the design of reactive components c and ℓ_s are considered.

4. Filter design

To simplify the RLF design, the terms $\ell_s\ell_\ell$, $\ell_s\ell_\ell\ell_m$, and $\ell_m\ell_\ell^2$ in the coefficients of all the transfer functions (eqs. (1-3)) are too small due to the low value of ℓ_ℓ (Appendix) and so, they can be neglected. Thus, Z_{IF}, Z_{OF}, and A_{VF} can be expressed as:

$$Z_{IF} \cong \frac{\ell_m}{2} \frac{s\left(\frac{s^2}{\omega_0^2} + \frac{2\xi s}{\omega_0} + 1\right)}{\frac{s^2}{\omega_1^2} + \frac{2\xi_1 s}{\omega_1} + 1}, \quad (4)$$

$$Z_{OF} \cong 2r \frac{\frac{\ell_s}{2}s + 1}{\frac{s^2}{\omega_0^2} + \frac{2\xi s}{\omega_0} + 1}, \quad (5)$$

$$A_{VF} \cong \frac{1}{\frac{s^2}{\omega_0^2} + \frac{2\xi s}{\omega_0} + 1}, \quad (6)$$

where $\omega_0 \cong \frac{1}{\sqrt{c\ell_s}}$, $\zeta \cong r\sqrt{\frac{c}{\ell_s}}$, $\omega_1 \cong \sqrt{\frac{2}{c\ell_m}}$, and

$\zeta_1 \cong r\sqrt{\frac{c}{2\ell_m}}$ are the RLF specifications.

As illustrated in fig. 3, the design requirements for avoiding interactions at both sides of the RLF while providing the desired voltage regulation can be itemized as follows:

1- Specified harmonic current attenuation, to smooth the pulsating input current of the converter.

2- The highest possible input impedance, Z_{IF}, to minimize interactions with the converter, i.e., $Z_{IF} >> Z_{OC}$.

3- The lowest possible output impedance, Z_{OF}, to minimize interactions with the load $Z_{OF} << Z_{IL}$.

4- Providing specified voltage regulation, $|A_{VF}|_{max}$.

5- Design the filter so that $|Z_{IF}|_{min} = |Z_{OF}|_{max}$ [2,12].

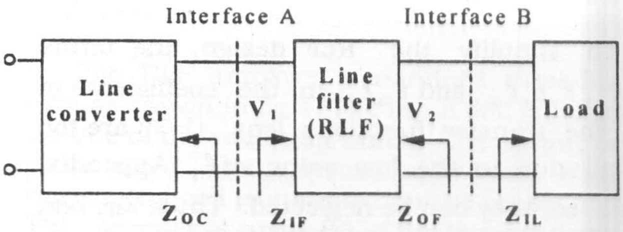

Fig. 3. Impedance compatibility requirements $Z_{IF} >> Z_{OC}$, and $Z_{OF} << Z_{IL}$.

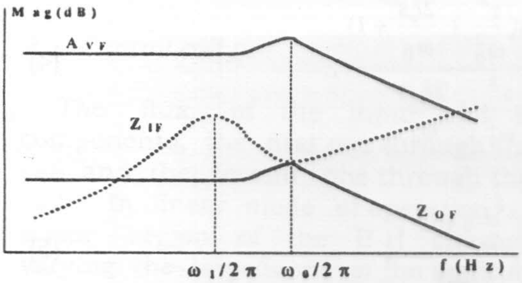

Fig. 4. Transfer functions of RLF.

Fig. 4, shows the asymptotic plots of the transfer functions given by eqs. (4- 6). The input impedance, eq. (4), has two resonance frequency as shown in fig 4, the first is ω_1 occurs within the loop containing c and ℓ_m. While the second is ω_0 occurs within the loop containing c and ℓ_s. The RLF will be designed depending on ω_0, whereas, the variations of c and ℓ_s can control the RLF specifications (ω_0 and ξ). Also, at ω_0, the power loss of the RLF is less than that at ω_1. Inspection of eq. (4) shows the input impedance to be inductive at low frequencies (less than ω_1), capacitive in a restricted middle range (from ω_1 to ω_0), and again inductive at frequencies greater than ω_0. At high frequencies, the input impedance has a 20dB/dec slope to ensure the harmonic current attenuation (item 1). The RLF must be designed to operate in the capacitive region and near ω_0 to ensure the output voltage regulation.

The input impedance is minimum at the resonance frequency ω_0 and can be approximated from eq. (4) as:

$$\left|Z_{IF}\right|_{min} = \left|Z_{IF}\right|_{s=j\omega_0} \cong 2r . \qquad (7)$$

While, the output impedance has a peak at the resonance frequency ω_0 and can be approximated from eq. (5) as:

$$\left|Z_{OF}\right|_{max} = \left|Z_{OF}\right|_{s=j\omega_0} \cong \frac{r}{\xi}\sqrt{1+1/4\xi^2} . \qquad (8)$$

To prevent any significant interactions with the converter and the load (items 2 and 3), the line filter offer at least a 15dB impedance gap at both interfaces A and B in fig 3, alternatively [2,12]:

$$\left|Z_{IF}\right|_{min} - \left|Z_{OC}\right|_{max} \geq 15\text{dB}, \quad \text{and}$$
$$\left|Z_{IL}\right|_{min} - \left|Z_{OF}\right|_{max} \geq 15\text{dB}. \qquad (9)$$

$\left|Z_{OC}\right|_{max}$ is measured using a small signal analysis and is found −10dB, while Z_{IL} should be chosen to be greater than Z_{OF} by at least 15dB.

To ensure the output voltage regulation (item 4), the voltage gain A_{VF} has one peak due to the parallel resonance between c and ℓ_c at ω_0 and a −40dB/dec slope at high frequencies. Tacking the derivative of eq. (4) and setting it equal to zero yielding that the frequency at the peak is $\omega_0\sqrt{1-2\xi^2}$ and the corresponding maximum gain is:

$$\left|A_{VF}\right|_{max} \cong \frac{1}{2\xi\sqrt{1-\xi^2}}, \qquad (10)$$

which is valid for $\xi \leq 0.7$, and consequently:

$$\xi = \left[0.5(1-\sqrt{1-1/\left|A_{VF}\right|^2_{max}})\right]^{0.5}. \qquad (11)$$

For $\xi > 0.7$, $\left|A_{VF}\right|_{max}$ becomes equal one.

To achieve the design goal of $\left|Z_{IF}\right|_{min} = \left|Z_{OF}\right|_{max}$, item 5, ξ can be determined using eqs. (7, 8) to verify the following condition:

$$K = \frac{\left|Z_{OF}\right|_{max}}{\left|Z_{IF}\right|_{min}} = \frac{1}{2\xi}\sqrt{1+1/4\xi^2} = 1 . \qquad (12)$$

Based on the preceding analysis, the proposed design procedure can be formulated to realize the RLF as follows:

1-calculate the $c\ell_s$ product from the RLF specifications depending on the fundamental frequency f_0 of the input waveform as $c\ell_s = \frac{1}{(2\pi f_0)^2}$,

2-determine ξ from eq. (11) depending on the desired $|A_{VF}|_{max}$,

3-check the impedance compatibility condition K using eq. (12),

4-calculate c and ℓ_s using the RLF specifications as:

$$\ell_s = \frac{r}{\xi(2\pi f_0)} \text{ and } c = \frac{1}{(2\pi f_0)^2 \ell_s}$$

The previous design requirements, eqs. (10, 12), of large $|A_{VF}|_{max}$ and small K are conflicting and are inversely proportional to ξ. These leads to, the RLF designed for a large $|A_{VF}|_{max}$ produced large K. Thus, careful design trade-off should be made to compromise these conflicting requirements for RLF. For example, for $|A_{VF}|_{max}$ =2, it is found that ξ is 0.257 and K is 4, yielding $|Z_{IF}|_{min} = 26\text{dB}$ and $|Z_{OF}|_{max} = 39\text{dB}$. While for $|A_{VF}|_{max}$ =1.2, yielding 0.65 and 1 for ξ and K, respectively. This results in $|Z_{IF}|_{min} = |Z_{OF}|_{max} = 26\text{dB}$. Fig. 5 and 6 show the bode diagrams for the exact transfer functions of eqs. (1- 3), of the resulting RLF for different values of c and ℓ_s. The RLF offers the desired $|A_{VF}|_{max}$ = 1.3 resulting in ξ=0.426, K of 1.8 and the design values of c and ℓ_s are 90μF and 0.07H, respectively.

5. Experimental results

The proposed RLF was fed from a 50V, 50Hz source via an ac thyristor controller. This will result in a harmonics source by delaying its firing angle α. The experimental prototype was designed to meet voltage amplification of 1.3 at power frequency of 50Hz, and to give ξ and K of 0.425 and 1.8, respectively. With these specifications and according to eq. (9), the load impedance must be greater than 150Ω. The experimental results were recorded using the data acquisition system, Lab-PC-1200 card and LabView Software.

Fig. 7 presents the input and output steady state voltages of the RLF and their harmonic spectrum. The output voltage v_2 is sinusoidal and its amplitude is approximately 1.3 of the input fundamental voltage, while the output harmonics are effectively eliminated. Figs. 8 to 10 show the RLF response at different values of both c and ℓ_s.

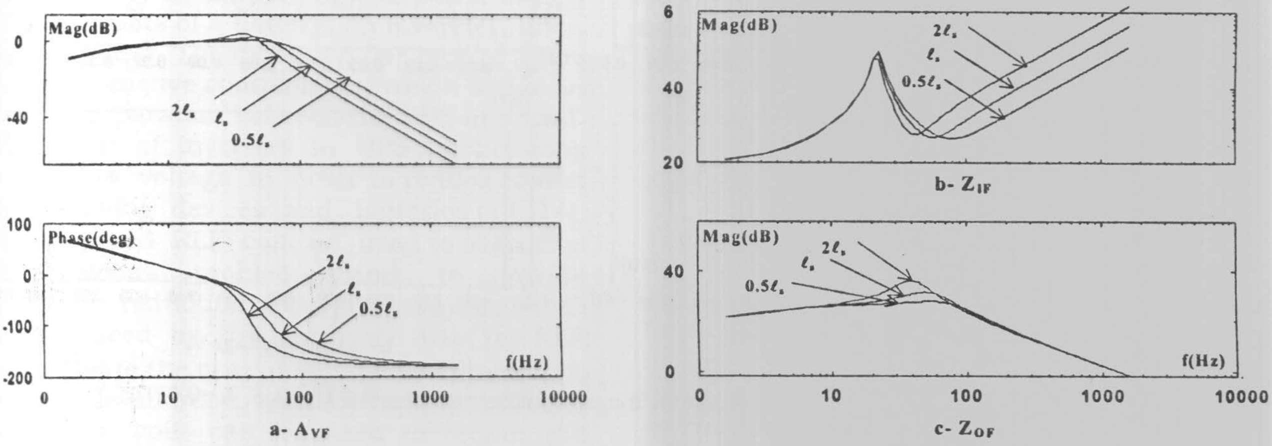

Fig. 5. Frequency response of RLF at different ℓ_s (c=90μF).

For the left hand side of fig. 8, ℓ_s and c are open, the three coils are weakly coupled, i.e the leakage flux is high and accordingly, the output voltage and current are very small. While, when ℓ_s is shorted, along the right hand side, the output voltage will be increased.

For fixed input frequency (50Hz) in fig. 5, increasing ℓ_s in the capacitive impedance region, yields a decrease in voltage gain, while increasing both input and output impedances. Hence, the output voltage (v_2), output current (i_L), and control current (i_s) will be decreased as shown in fig 9. Also, the input current (i_1) is nearly in phase with the input voltage as stated in eq. (7).

Referring to fig. 6, for fixed input frequency (50Hz), the voltage gain, the input and output impedances are decreased as c increased in the capacitive impedance region. Consequently, the output voltage will be decreased and both input and output currents increase as shown in fig. 10.

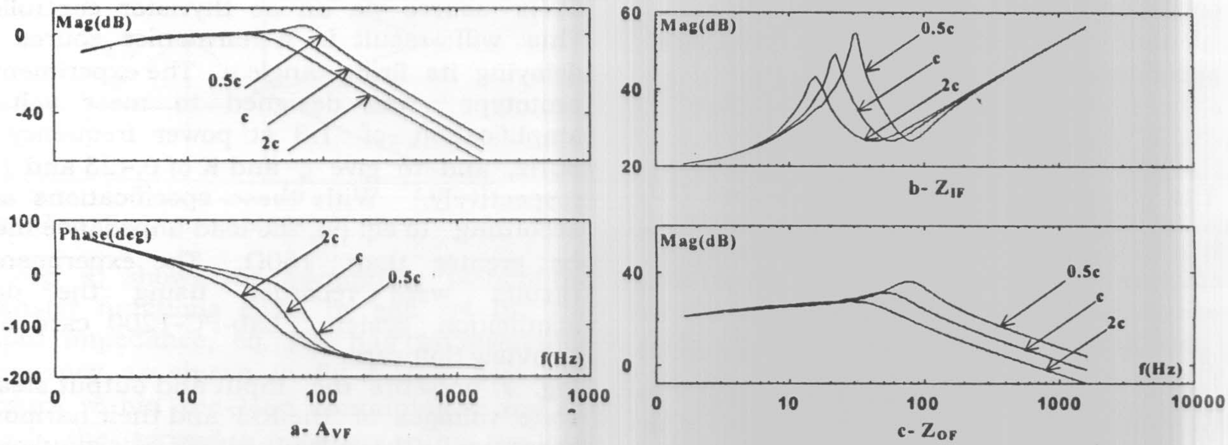

Fig. 6. Frequency response of RLF at different c (ℓ_s=0.07H).

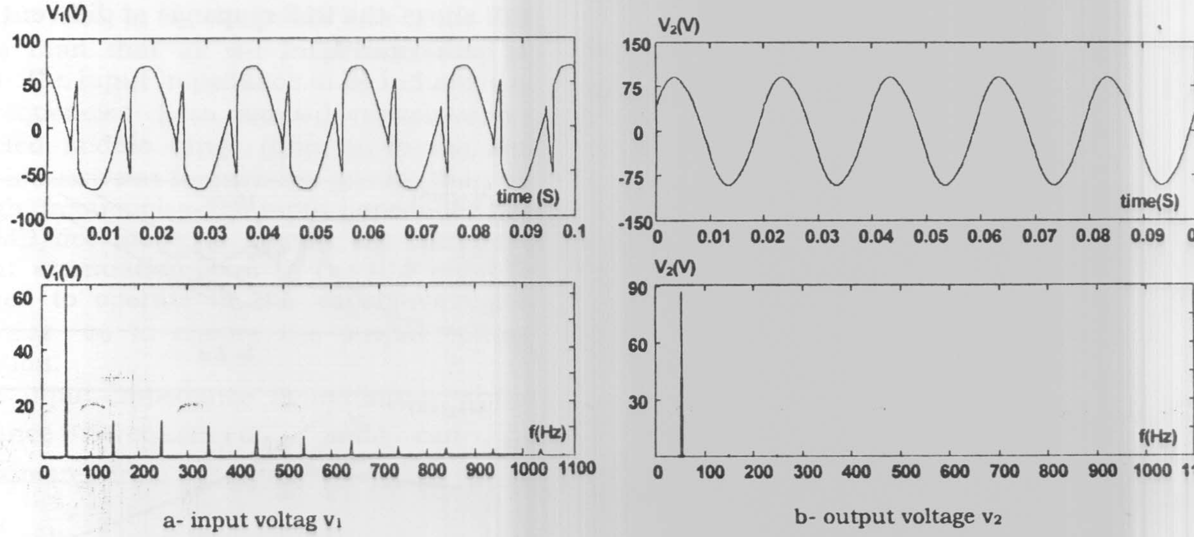

Fig. 7. Experimental waveforms and its frequency spectrum at $\alpha=45^{\circ}$ (c=90μF, ℓ_s =0.07H).

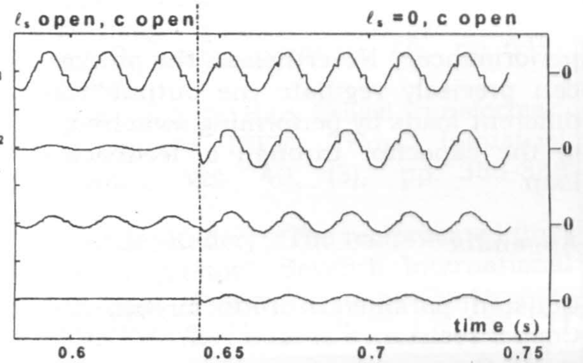

Fig. 8. Experimental RLF response for open c and α=45° at: open ℓ_s (left) and shorted ℓ_s (right) and v_1, v_2 (130V/div), i_L(0.4A/div), i_1, i_2(0.6A/div).

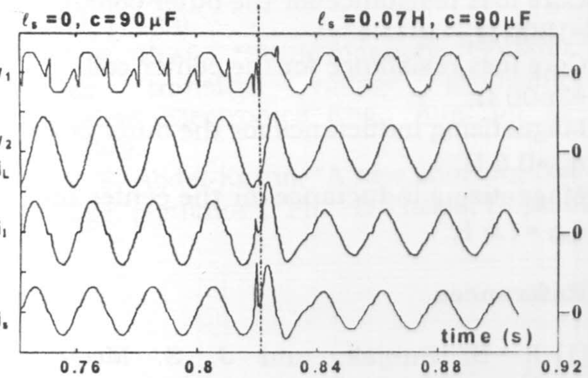

Fig. 9. Experimental RLF response for c =90μF and α=45° at: shorted ℓ_s (left) and ℓ_s =0.07H (right) v_1, v_2 (130V/div), i_L(0.4A/div), i_1, i_2(0.6A/div).

6. UPS application

Normally, an uninterruptible power supply (UPS) consists of a battery, an invereter, filter, and stabilizer. The most popular type of filters is of LC reactive components, which needs an electric separation between the UPS and load. Also, most of inverters in UPS applications run at low voltage in order to reduce cost of the switching devices and batteries [13, 14]. The proposed RLF can be used to overcome the previous problems and to provide acceptable reduction of output harmonics that are produced by the inverter. Also, the RLF can regulate the output voltage by adjusting ℓ_s and c. In addition, suitable number of turns of output coil can be used to obtain the required output voltage level.

The RLF was used as an output stage for a single-phase bridge invereter of type IGBT "25Q101" as shown in fig. 11. Fig. 12 shows the RLF response for varying the output of a square-wave voltage source invereter from 45 to 65V. While, fig. 13 shows the RLF response for a PWM voltage source inverter at switching frequency of 0.8KHz. The results show the capability of the RLF to yield sinusoidal output voltage with the required voltage amplification for different distorted input voltage waveforms.

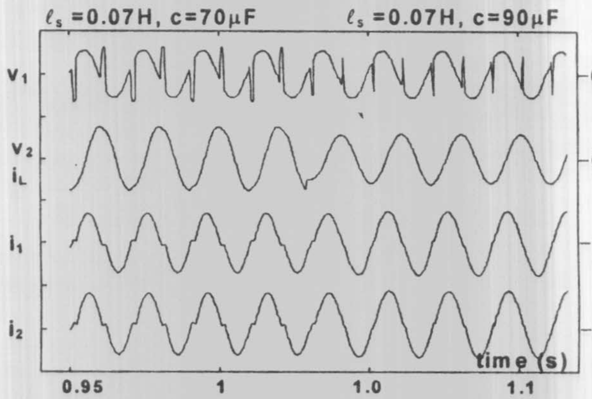

Fig. 10. Experimental RLF response for ℓ_s = 0.07H and α=50° at: c=70μF (left) and c =90μF (right) and v_1, v_2 (130V/div), i_L(.4A/div), i_1, i_2(.6A/div)

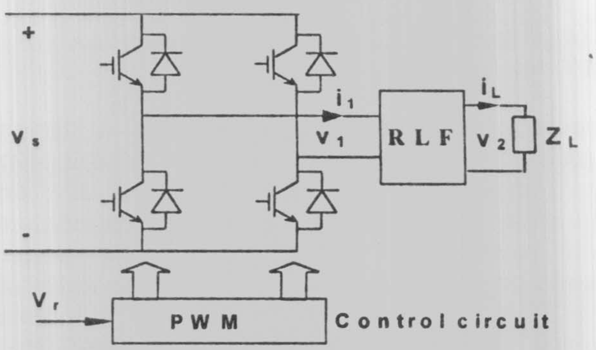

Fig. 11. RLF for power circuit of UPS.

7. Conclusions

A regulated line filter (RLF) located between line converter and load stage has been designed in a way to minimize interactions not only with the load but also with the line converter, while providing the desired voltage

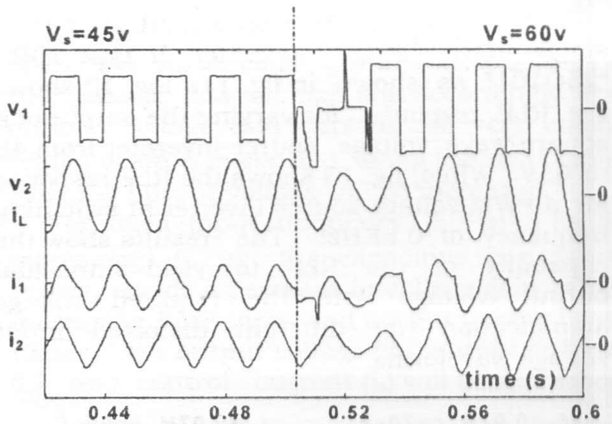

Fig. 12. Experimental UPS response for ℓ_s = 0.06H, c=95μFat: V_s=45V (left) to 65V (right) and v_1, v_2 (90V/div), i_L(0.5A/div), i_1, i_2(0.7A/div) •

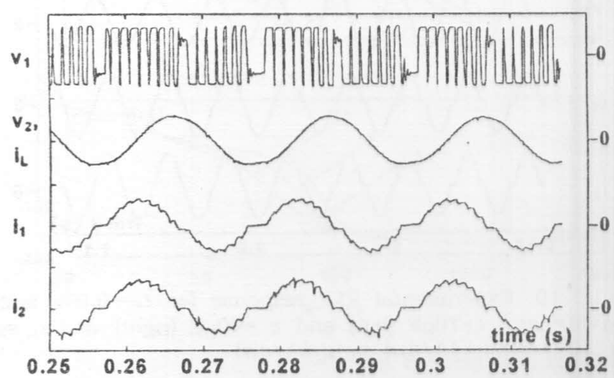

Fig. 13. Experimental UPS response for ℓ_s = 0.06H, c=95μF and switching frequency =0.8KHz and v_1, v_2 (90V/div), i_L(0.5A/div), i_1, i_2(0.7A/div) •

regulation. This paper presented a design procedure for the proposed RLF which offer the impedance compatibility RLF based on equating both its minimum input impedance and maximum output impedance under condition of impedance gap at both sides of the filter is greater than 15dB. It has been shown that the procedure offers a sufficient impedance gap at both interfaces to minimize the undesirable subsystem interactions, in order to avoid performance degradation. Also, it has been found that both the impedance compatibility and voltage regulation are conflicting. However, it has been shown that careful design can be made to compromise these conflicting requirements. The proposed design has been verified experimentally. Also, the RLF has been tested for control of UPS based on either single pulse or PWM voltage source invereter, yielding good dynamic performance. Nevertheless, the proposed RLF can precisely regulate the output voltage at different loads by performing switching control of the capacitor through a feedback voltage loop.

Appendix

Constant parameters of RLF circuit:
Copper resistance of each coil,
r =10 Ω,
Leakage inductance for each coil,
ℓ_ℓ =0.00005 H,
Core loss resistance for the outer coils, r_m =1800 Ω,
Core loss resistance for the center coil, r_{m3} =3600 Ω,
Magnetizing inductance for the outer coils,
ℓ_m =0.8 H,
Magnetizing inductance for the center coil,
ℓ_{m3} =1.6 H.

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