Optimal Design for LCL-SRC Type

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Abstract

The LCL Series Resonant Converter (LCL-SRC) type offer nearly load- independent output voltage under some operating conditions . By this way the output voltage can be regulated against a wide load and line variations with a small variation of switching frequency.

In this paper a simple method for optimization of LCL-SRC is presented. This method takes the stored energy as a theoretical index to obtain the minimal size of the converter inductors L_1 and L_2 which contribute significantly to the converter size and weight.

The R_{ac}-method for the analysis of resonant converter is discussed. This method was found fairly accurate for operation above resonant frequency.

التصميم الأمثل لمغير توالي نوع (LCL)

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الخلاصة

مغيرات(LCL-SRC) تعطي تقريبا عدم أعتما دية فولتية الإخراج للحمل تحت بعض شروط العمل،بهذه الطريقة يمكن لفولتية الخرج ان تنضم بمدى واسع في الحمل وتغييرات الخط بتغيير قليل في تردد الغلق-فتح. في هذا البحث، تم مناقشة طريقة مبسطة لإيجاد مغير أمثل من نوع LCL-SRC ، حيث تأخذ هذه الطريقة الطاقة المخزونة كملحق نظري للحصول على أقل حجم لمحاثات المغير والتي تسهم بصورة كبيرة في تقليل حجم المغير و وزنه . وتجدر الاشارةالى أن طريقة المقاومة المتناوبة R_{ac} قد أستخدمت لتحليل المغير الرنيني،حيث وجد أن هذه الطريقة دقيقة للتحليل عند العمل بتردد أعلى من تردد الرنين.

1.Introduction

At the present time ,the series and parallel resonant converters are very popular converter circuits used for high frequency applications. They offer many potential advantages over the conventional pulse width modulation (PWM) power converters , such as reduced component stresses , less electromagnetic interference (EMI) problem , smaller size and lighter weight [1]. Because of their high efficiencies and power density ,series resonant converter (SRC) are widely used throughout the aerospace industry. But this topology does not have load independent output voltage under some operating conditions . This paper proposed a novel type of LCL series resonant converter (LCL-SRC) with an approximately load independent output voltage under some operating conditions. Therefore, the output voltage can be regulated against wide load range and line variation of switching frequency. Furthermore ,the load-independent operation occurs in the lagging input-current mode, which is the most preferred mode of operation of a resonant converter. The price for these advantages is the form of the shunt inductor L_2 ,that adds some size and weight to the converter.

Figure(1) shows a half-bridge LCL-SRC. In the design of the converter, a suitable choice of switching frequency (and therefore , the resonant frequency on which the resonant components depend),full quality factor $Q=w_oL_1/R_L$;where w_o is the resonant frequency and R_L is the load resistance, and the ratio of shunt –to-series inductance ($K=L_2/L_1$) are required. These three quantities indicate the performance of the converter.

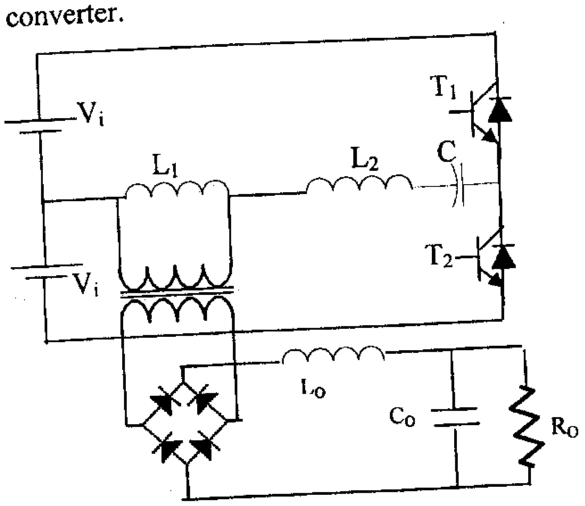

Fig.1. Half bridge LCL-SRC Type

Conventionally, the procedure for the design of the converter will be simplified if a mathematical relation for optimal condition expresses them. In this paper a simple method for optimization of the LCL-SRC is proposed.

2.LCL-SRC Resonant Converter Analysis

The classical ac-analysis techniques will be used to derive the characteristics of LCL-SRC type the resonant component has the effect of filtering the higher harmonic voltages so that , essentially ,a sine wave of current appears at the input of the resonant circuit[2] and by this method we can replace the transformer, rectifier and filter by equivalent ac-resistance. From Fig.2, the LCL-SRC uses a capacitive output filter and therefore drives the rectifier with a current source. In this case the a.c. source current and the output currents are,

$$I_{ac}(rms) = \frac{\pi}{2\sqrt{2}} I_p \qquad (1)$$

$$I_o = \frac{2}{\pi} I_p = \frac{2\sqrt{2}}{\pi} I_{ac}(rms) \qquad (2)$$

where Ip is the peak value of the input current and I_o is the output current. A square wave voltage appears at the input to the rectifier with

$$E_{ac}(rms) = \frac{\pi}{2\sqrt{2}} E_o \qquad (3)$$

where E_o is the output voltage

For this case the equivalent ac-resistance is given by

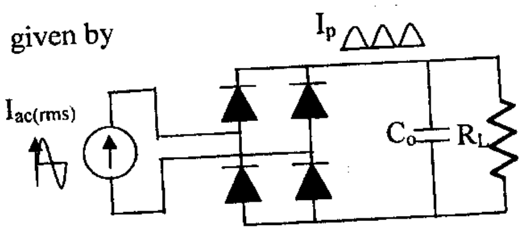

Fig.2. Drive Rac model

$$R_{ac} = \frac{8}{\pi^2} R_L \qquad (4)$$

The DC-gain of the converter is derived from Fig.3 as:

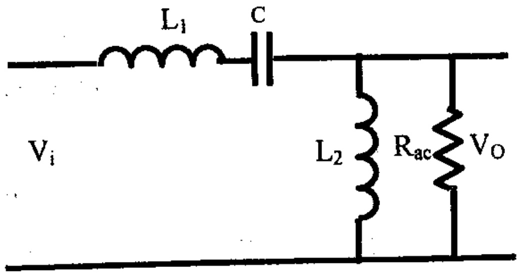

Fig.(3) Ac equivalent circuit for LLC-SRC

$$Z_{in} = SL_1 + \frac{1}{SC} + \frac{SL_2 R_{ac}}{SL_2 + R_{ac}} \qquad (5)$$

$$M = \frac{V_o}{V_i} = \frac{Z_o}{Z_{in}}$$

$$= \frac{S^2 L_2 R_{ac} C}{S^3 L_1 L_2 C + S^2 (L_1 C R_{ac} + L_2 C R_{ac}) + SL_2 + R_{ac}} \qquad (6)$$

$$\text{where } Z_o' = \frac{SL_2 R_{ac}}{SL_2 + R_{ac}} \qquad (7)$$

$$\left.\begin{aligned} &\text{define } K = \frac{L_2}{L_1} \\ &Q = \frac{w_o L_1}{R_L} \\ &w_o = \frac{1}{\sqrt{L_1 C}} = 2\pi f_o \\ &Z_o = \sqrt{\frac{L_1}{C}} \end{aligned}\right\} \qquad (8)$$

Where Z_0 is the characteristic impedance
Equation (6) can be rewritten as

$$M = \frac{K\left(\frac{S}{w_o}\right)^2}{\left(\frac{\pi^2}{8}\right)QK\left(\frac{S}{w_o}\right)^3 + (1+K)\left(\frac{S}{w_o}\right)^2 + \left(\frac{\pi^2}{8}\right)\left(\frac{S}{w_o}\right)KQ + 1} \qquad (9)$$

Equation (9) can be plotted for a certain inductor ratio and for different quality factor. Figure(4) shows the DC gain plotted against F (F normalized switching frequency= $\frac{f_s}{f_o}$) for K=2 and for two different quality factor Q=0.05 and Q=0.5. From this figure, it can be noted that the converter operates over nearly load independent DC gain for switching frequencies near the series resonant frequency.

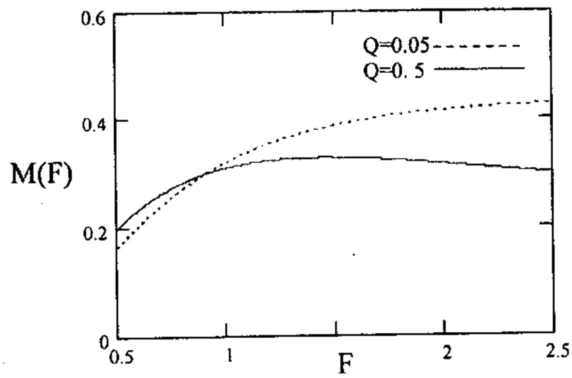

Fig.4 DC-Gain in LCL-SRC for K=2

Figure(5) shows the DC gain plotted for K=5 for two different quality factor Q=0.05 and Q=0.5.

For higher quality factor the load independent vanishes. Therefore, the normal choice of operating frequency is equal to frequency $(w_o = \frac{1}{\sqrt{L_1 C}} = 2\pi f_o)$, the resonant frequency for the specified operating condition.

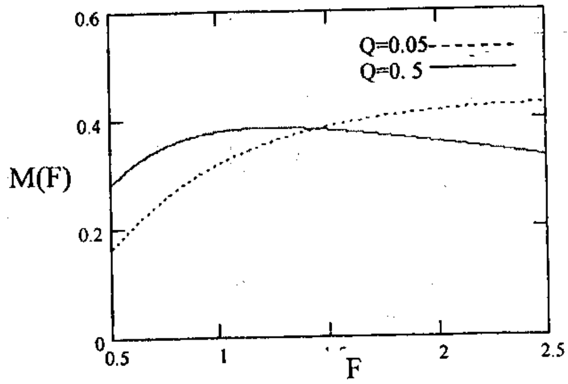

Fig.5 DC-Gain in LCL-SRC for K=5

Figure(6) shows DC gain variation in SRC ,from this figure we can note that there is a very poor regulation in this type of converter and for any disturbance in the switching frequency the output voltage changes also in a high range. This problem is disappeared in LCL-SRC.

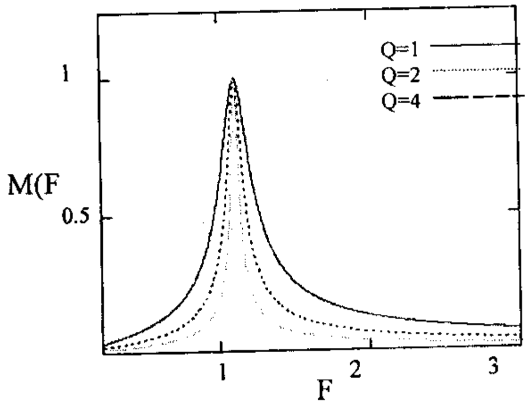

Fig.6 DC-Gain for SRC

3.Current taken from the source as a function of quality factor

The current taken from the source can be taken as a factor of efficiency estimation for the converter . Figure (7) shows this relation as a function of quality factor for the SRC When compared this figure with Fig.8,which shows the current taken from the source as a function of quality factor for the LCL-SRC it can see that the current decreases as the quality factor increases. therefore the efficiency in LCL-SRC type becomes higher for lower values of quality factor this is because the losses will increase as the source current increases ,the main part of losses are the heat and conduction losses [4] and these types of losses are associated with the source current.

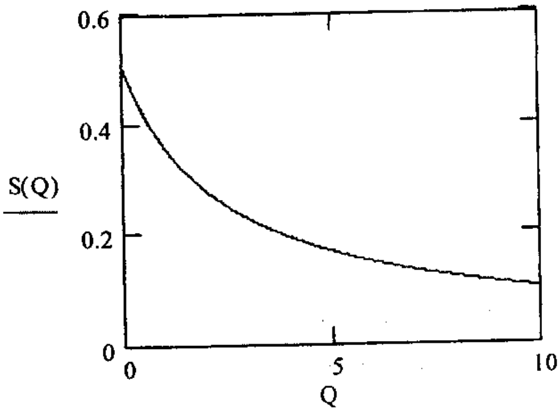

Fig.7 Current taken from the source as a function of quality factor in SRC

4.Optimization of the two inductors

The physical size of an inductor is indicated by the area product quantity associated with the energy of the inductor E. The current density and peak flux density govern the area product. For a specified operating condition these factors are fixed, thus one can use the energy as a theoretical index of the physical size of an inductor.

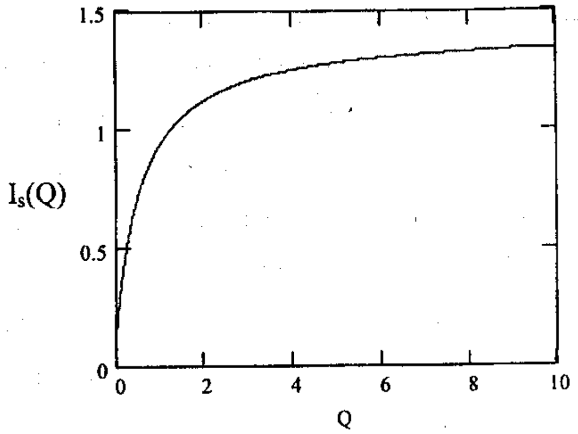

Fig.8 Current taken from the source for LCL-SRC as a function of quality factor

In this section a simple method for optimization of the LCL-SRC is proposed to obtain the value of quality factor Q for a given K at $w=w_o$,so that the sizes of inductors $L_1$and L_2 are minimum.

The total energy stored in inductors L_1 and L_2 is

$$\varepsilon=\frac{1}{2}I^2{}_{L1}L_1+\frac{1}{2}I^2{}_{L2}L_2 \tag{10}$$

Where I_{L1} and I_{L2} are the inductors currents. So to find the currents in the first and second inductors we can use circuit analysis to find the normalized current in the first inductor as[5]

$$I_{L1n}=\frac{2\sqrt{2}}{\pi}\frac{KQ\left(\frac{\pi^2}{8}\right)\left(\frac{S}{w_o}\right)^2+\left(\frac{S}{w_o}\right)}{\left(\frac{\pi^2}{8}\right)QK\left(\frac{S}{w_o}\right)^3+(1+K)\left(\frac{S}{w_o}\right)^2+\left(\frac{\pi^2}{8}\right)\left(\frac{S}{w_o}\right)QK+1} \tag{11}$$

replacing each S by jw_o ,the normalized current in the first inductor is

$$|I_{L1n}|=\frac{2\sqrt{2}}{\pi}\frac{\sqrt{1+\left(\left(\frac{\pi^2}{8}\right)KQ\right)^2}}{K} \tag{12}$$

and the normalized current in the second inductor

$$I_{L2n}=\frac{2\sqrt{2}}{\pi}\frac{\left(\frac{S}{w_o}\right)}{\left(\frac{\pi^2}{8}\right)QK\left(\frac{S}{w_o}\right)^3+(1+K)\left(\frac{S}{w_o}\right)^2+\left(\frac{\pi^2}{8}\right)\left(\frac{S}{w_o}\right)QK+1} \tag{13}$$

Putting each $S=jw_o$

$$|I_{L2n}|=\frac{2\sqrt{2}}{\pi}\frac{1}{K} \tag{14}$$

Substituting eq.(12) and eq.(14) in eq.(10) yields

$$\varepsilon=\frac{1+K+\left(\left(\frac{\pi^2}{8}\right)QK\right)^2}{K^2Q}\frac{2}{\pi^2}\frac{V_i}{w_oR_L} \tag{15}$$

where V_i is the input voltage. Defining base energy as

$$\varepsilon_b=\frac{2}{\pi^2}\frac{V_i}{w_oR_L} \tag{16}$$

the normalized energy is given by

$$\varepsilon=\frac{1+K+\left(\left(\frac{\pi^2}{8}\right)QK\right)^2}{K^2Q} \tag{17}$$

Figure(9) shows the variation of the stored energy in the two inductors as a function of quality factor.

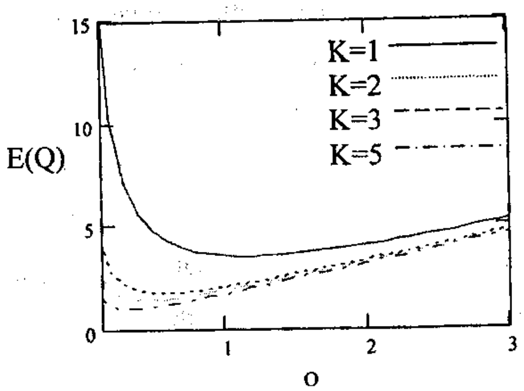

Fig.9 Stored energy in the two inductors as a function of quality factor

It can be conclude that for a given inductor ratio and a certain value of quality factor the stored energy will be minimum and this value of quality factor can be compared from eq.(18) as

$$Q_{opti} = \frac{8}{\pi^2}\frac{\sqrt{1+K}}{K} \qquad (18)$$

For lower values of K the curve has smooth curvature and conversely for higher values of quality factor there is a sharp curvature in the curve at the optimum value of quality factor[5].

5 . Choice of the inductor ratio

The formula of Eq.(18) give the optimum value of Q, which is a function of K. therefore, to complete design of LCL-SRC, the proper choice of K is a must. There is no clear out demarcation between a good and bad choice. It governed by the requirements and specifications of a circuit. If K is high the circuit tends to become as convention SRC . By this way , we get better part-load efficiency, but the regulation requires wide range of frequency variation. On contrary the lower value of inductor ratio will force the system to loss the part –load efficiency , but the required frequency variation is significantly lower.

From eq.(18) which give the optimal value of quality factor in eq.(12)and eq.(14) yields

$$|I_{L1n}| = \frac{2\sqrt{2}}{\pi}\frac{\sqrt{2+K}}{K} \qquad (19)$$

$$|I_{Rac}| = \frac{2\sqrt{2}}{\pi}\frac{\sqrt{1+K}}{K} \qquad (20)$$

Dividing eq.(19) by eq.(20) yields

$$\left|\frac{I_{L1n}}{I_{Rac}}\right| = \sqrt{\frac{2+K}{1+k}} \qquad (21)$$

At no load condition and from eq.(14)

$$|I_{L2n}| = \frac{2\sqrt{2}}{\pi}\frac{1}{K} \qquad (22)$$

Therefore , the per unit-reduction in the inverter output current from full load to no load is given by

$$R(K) = 1 - \frac{1}{\sqrt{2+K}} \qquad (23)$$

The efficiency of the converter is indicated from the inverter current at full load , $Q=Q_{opti}$. Equation(23) can be plot to depicate the load efficiency of the converter as shown in Fig.10. From this figure it can be noted that inductor ratio increases, the inverter output current decreases and the per-unit reduction in the current increases. By acknowledgment of such information a better full load and part-load efficiency for higher values of K can be realized. However the required frequency variation for the regulation of output voltage against line and load variation also decides the value of K. In practice , the converter load can vary from no-load to full load ,and the input-line voltage can vary within the range usually specified.

6.Design of the proposed LCL-SRC

The design of the proposed converter is performed with the following requirements:

V	200
I_{max} I_{min}	5 Amp (input) 0.5 Amp (output)
P	100 Watt

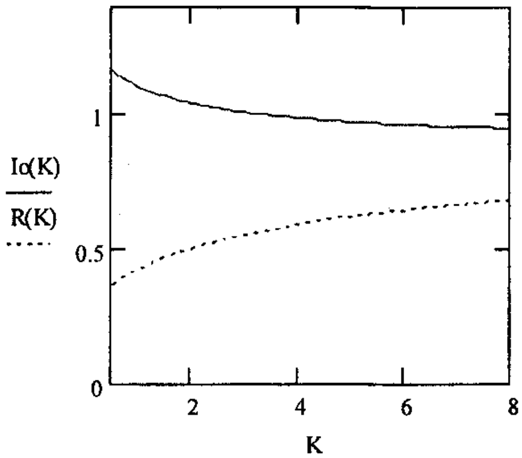

Fig.(10) Normalized inverter output current and the per unit-reduction from full -load to no load as a function of K

Half bridge configuration is chosen for low output power . K=5 is chosen for higher part –load efficiency and to limit the frequency variation for regulation. For K=5 the proposed ,method gives Q_{opti}=0.4. at the specified minimum the load value of Q is 0.004 the DC-gain can be plotted for these specification. When the quality factor equal to 0.4 and 0.004 .Also in this figure there are two levels of DC-gain ,M_{max} and M_{min} corresponding to the maximum line voltage and minimum line voltage. The nominal DC gain is M_{min} =0.56 . It can be seen that for the specified line and load variation ,the switching frequency needs to be varied by 0.7 from w_o .

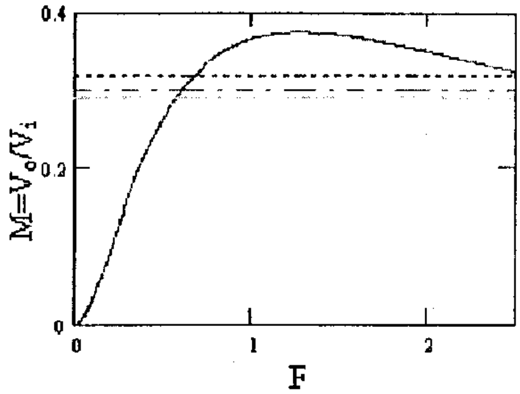

Fig.(11) Normalized output voltage for the proposed converter

The natural frequency may be selected to be 90 kHz and the circuit element can be summarized as in Table(1)

Table (1)

Parameter	*Proposed Value*
Natural frequency	90KHz
C	0.1μF
L_1	31.27μH
L_2	0.156μH
N_1:N_2	1:10
Switching Frequency Variation	$0.7w_o$
Total Energy(mJ)	0.3

7.Conculution

The method of designing LCL-SRC with optimal sizes for inductors is presented. Simple and fast method concerned to take the energy stored in the two inductors as a theoretical index to obtain their optimal sizes.

A comparison between conventional SRC and the proposed converters is presented , this comparison shows that the proposed converter has many advantages as compared with the conventional one as in that it has smaller size, light weight and solves the inherent disadvantages of the conventional type.

Design examples is given to show the performance of this converter, with a specified optimal design condition as given in table.1

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