Comparison of the Effect of Output Filters on the Total Harmonic Distortion of Line Current in Voltage Source Line Converter – Simulation Study

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Abstract. Two different output filter topologies are considered, namely the LCL- and L+LC-filter. The space vector modulation (SVM) is used to control the power switches of the converter. Design methods for both filter types are proposed. The methods are used to dimension the filter components. The performances of the filters designed are verified by simulations to meet the given line current total harmonic distortion (THD) requirement. The study reveals that the LCL-filter is more effective a filter topology in attenuating line current harmonic components than the L+LC-filter.

Key words

LCL-filter, L+LC-filter, Voltage Source Converter, Pulse Width Modulation, Power Quality

1. Introduction

Renewable energy sources such as wind turbines and solar energy make significant and increasing contributions to electric utility networks. A grid-friendly interface between the energy source and the utility network is needed. A modern pulse width modulated (PWM) [2] converter provides nearly sinusoidal line current waveforms and therefore power quality is improved compared to the case where diode rectifiers are used. The importance of the power quality is crucial, because non-sinusoidal currents delivered to the grid can introduce an additional non-sinusoidal voltage drop across the line impedance and thereby increase the voltage distortion supplied to loads. With a PWM rectifier a low line current distortion could be obtained by filtering. A very typical PWM rectifier application's topology is illustrated in Fig.1. The power is produced to the dc-link from some renewable energy source and the output of the PWM rectifier is filtered to obtain a low line current distortion. Of all output filters used in the field of power electronic applications, the LCL-filter is currently probably the most frequently used topology [3-5]. The reason for the popularity of the LCL-filter is that good attenuation is achieved with a relatively small component values. That is, good power quality is achieved with a reasonable filter costs.

In this paper the performance of an LCL-filter is compared to the performance of an L+LC-filter. The stability of the system is often improved by introducing an extra damping resistor in the filter [3, 6]. In this paper

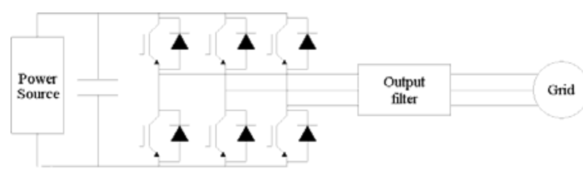


Fig. 1. A typical line converter system in renewable energy applications, where the power is produced by some source to the dc-link and is then rectified and filtered to the grid.

damping resistors are not used and the characteristics of filters are studied through the design process.

2. LCL-filter design

A topology of an LCL-filter used is seen in Fig.2a, where it is a part of the PWM rectifier system. A method proposed by Liserre [1] is based on defining the switching frequency line current amplitude. By following the procedure component values are obtained but the resonance frequency is not settled. To find the desired resonance frequency, the filter parameters must be iterated.

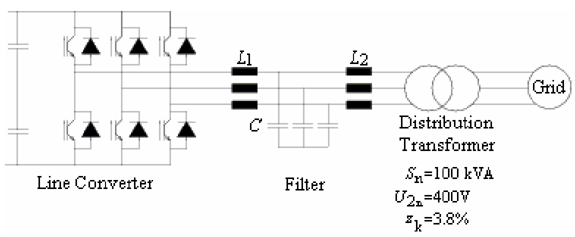
A. Method using resonance frequency as design parameter

By taking the resonance frequency f_{res} to be the primary design parameter, we are able to set the resonance frequency without having to iterate it. The requirement for the resonance frequency is that it should be included in the range $10f_{fund}<f_{res}<f_{sw}/2$ [3], where f_{fund} is the fundamental frequency of the utility network voltage.

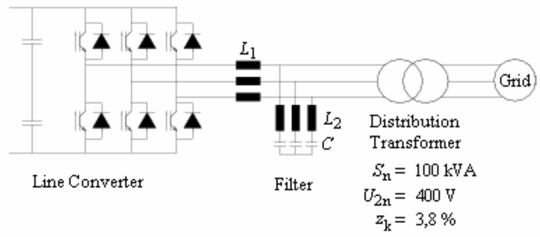
First, the converter side inductance L_1 is determined from the equation

$$\frac{i_1(n_{sw})}{u_1(n_{sw})} \approx \frac{1}{\omega_{sw} L_1} \qquad (1)$$

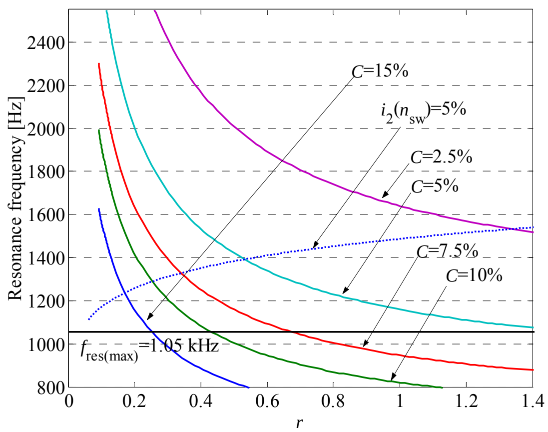
where ω_{sw} is the angular switching frequency, n_{sw} is the frequency multiple of the fundamental frequency at the switching frequency and u_1 and i_1 are the phase voltage and current on the converter side of the filter, respectively. The resonance frequency of the LCL-filter is defined as



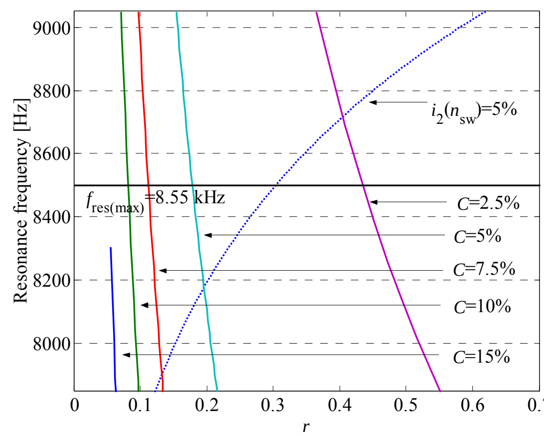
a) Line converter with an LCL-filter



(b) Line converter with an L+LC-filter



(c)



(d)

Fig.2. Filters resonance frequency as a function if inductor ratio r. In (c) f_{sw} = 2.1 kHz and the highest permitted resonance frequency f_{res} = 1.05 kHz and the frequencies in (d) for f_{sw} = 17.1 kHz and f_{res} = 8.55 kHz.

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} = \frac{1}{2\pi}\sqrt{\frac{1+r}{rL_1 C}} \qquad (2)$$

Then by selecting the desired capacitor values, curves of f_{res} as a function of the inductor ratio $r = L_2/L_1$ can be drawn. Curves are illustrated in Figs.2c and 2d, where switching frequencies 2.1 kHz and 17.1 kHz are chosen at the ends of the area that includes nearly every switching frequency used in converter applications. The amplitude of the switching frequency voltage in Figs.2c and 2d is chosen to $u_1(n_{sw})$ = 0.3 p.u.

In Fig.2c f_{sw} = 2.1 kHz and the allowed $i_1(n_{sw})$ = 0.1 p.u. It can be noticed that no matter how small filter parameters that fulfill the requirement of f_{res} are chosen, the amplitude of the line current at the switching frequency $i_2(n_{sw})$ is always smaller than 0.05 p.u. Furthermore, when the low switching frequency f_{sw} is used, the resonance frequency f_{res} must be chosen very low (in order to avoid low frequency voltage components). Then bigger filter component values must be used not to attenuate the switching frequency current amplitude $i_1(n_{sw})$ but to fulfill the resonance frequency f_{res} requirement.

In Fig.2d curves are shown in the case where f_{sw}=17.1 kHz and the allowed $i_1(n_{sw})$=0.2p.u. The switching frequency that high, is only a theoretical and is represented only to point out the behavior between the current amplitude at the switching frequency, the filter resonance frequency and filter component values. Now, from the Fig.2d it is deduced, that when the switching frequency f_{sw} is increased the resonance frequency f_{res} is no more the property that limits the filter component values. Fig.2d also shows that $i_2(n_{sw})$ becomes dominant at least when bigger capacitor values are deployed. Finally, when comparing Fig.2c and Fig.2d it is noticed that when the switching frequency f_{sw} is increased, higher capacitor values no longer produce applicable solutions which fulfill both requirements.

B. *Modified design method for LCL-filter*

The key idea in the modified design method is that any point where the resonance frequency f_{res} and the amplitude of the line current at the switching frequency $i_2(n_{sw})$ have a common solution could be determined. In other words, the solution may be found where f_{res} and $i_2(n_{sw})$ requirements are fulfilled.

The attenuation of the line current amplitude at the switching frequency is defined as

$$\frac{i_2(n_{sw})}{i_1(n_{sw})} = \frac{1}{|1 + r(1 - \omega_{sw}^2 L_1 C)|} = \frac{1}{|1 + r - k_{LCL}^2 \omega_{res}^2 L_2 C|} \qquad (3)$$

where $k_{LCL}=\omega_{sw}/\omega_{res}$. The resonance frequency in Eq.(2) can be presented as $\omega_{res}^2 L_2 C = 1 + r$, and then Eq.(3) is

$$d = \frac{1}{|1 - k_{LCL}^2|(1 + r)} \qquad (4)$$

where $d = i_2(n_{sw})/i_1(n_{sw})$ is the attenuation of the switching frequency line current amplitude across the filter. Finally, r is obtained and it is

$$r = \frac{1}{d\,|1 - k_{LCL}^2|} - 1 \qquad (5)$$

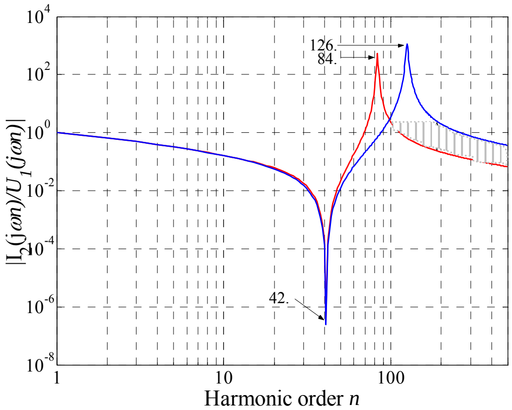


Fig. 3. Frequency response of an L+LC-filter, when f_{sw} = 2.1 kHz (n = 42) is used as the switching frequency.

In order to achieve the capacitor value C, Eq.(3) is reformulated. The equation for the capacitor C is

$$C = \frac{1}{\omega_{\text{res}}^2 L_1 (1 - d\,|1 - k_{\text{LCL}}^2|)} \tag{6}$$

When filter is designed using Eqs.(1), (5) and (6), the switching frequency f_{sw}, filter resonance frequency f_{res}, converter side current amplitude at the switching frequency $i_1(n_{sw})$ and the attenuation d across the filter can be specified.

3. L+LC-filter design

The L+LC-filter topology could be arranged in two ways. The difference between filter topologies is the placing of the LC part of the filter. The function is similar in both topologies but the way filters are dimensioned differs from each other. The topology used here is shown in Fig.2b.

The difference between the LCL-filter and the L+LC-filter is that the L+LC-filter has two resonance frequencies while the LCL-filter has only one. Actually, the LCL-filter has three resonance frequencies, but the one defined by Eq.(2) is the essential from the practical viewpoint. The two resonance frequencies of the L+LC-filter are called the antiresonance frequency and the resonance frequency due to the nature of resonances. At the antiresonance frequency the frequency components of the line current are attenuated whereas at the resonance frequency they are amplified.

The design method proposed is based on placing the resonance frequencies so that the component values are minimized. Obviously, the antiresonance frequency is placed on the switching frequency. When placing the resonance frequency of the L+LC-filter, a couple of things should be considered. First, when a so called fixed switching frequency modulation method is used, frequencies of the switching frequency harmonics are known [2]. Thus, the frequencies that should be avoided are known. Second, a considerable loss of attenuation occurs when the ratio between the antiresonance f_{ares} and the resonance frequency f_{res} ($k_{L+LC}=\omega_{ares}/\omega_{res}$) is diminished. In other words, the higher the resonance frequency is compared to the antiresonance frequency, the lower is the attenuation on the higher frequencies. The difference in attenuation is illustrated in Fig.3.

A. *Design method applying [1]*

When only the L+LC-filter is considered, the resonance frequencies could be characterized as the serial and the parallel resonance of the filter. That is, the antiresonance frequency could be calculated as

$$f_{\text{ares}} = \frac{1}{2\pi}\frac{1}{\sqrt{(L_1 + L_2)C}} \tag{7}$$

and the resonance frequency as

$$f_{\text{res}} = \frac{1}{2\pi}\frac{1}{\sqrt{L_2 C}} \tag{8}$$

But when the line impedance is taken into a consideration the resonance frequency differs from that of Eq.(8). Now, the resonance frequency of the L+LC-filter is expressed as

$$f_{\text{res}} = \frac{1}{2\pi}\frac{1}{\sqrt{L_1 \,||\, L_s + L_2 C}} \tag{9}$$

On the other hand, the line impedance has only a negligible effect on the antiresonance frequency.

In the design method presented in [1], the converter side inductance L_1 value is determined by using Eq.(1). In order to solve the design problem with Eqs.(7) and (9), one of the remaining variables' must be specified. If the capacitor value is fixed and the antiresonance frequency is known, then the inductance L_2 can be calculated as

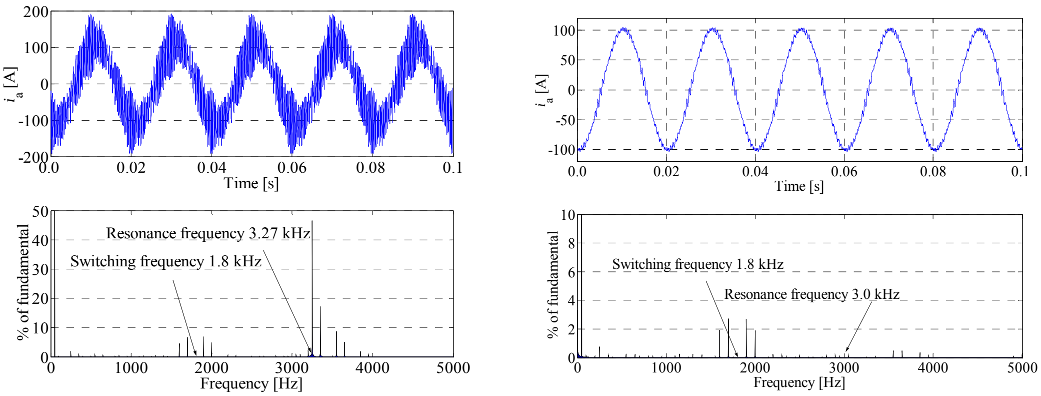
$$L_2 = \frac{1}{\omega_{\text{ares}}^2 C} - L_1 \tag{10}$$

If the value of the inductor L_2 is chosen instead, then the value of the capacitor could be calculated using Eq.(10), first, by solving C.

B. *The novel design method for the L+LC-filter*

The first step, again, is to choose the value for the capacitance. Then by assuming the parallel connected inductance $L_1||L_s$ to be equal to inductance L_s, the inductance L_2 can be solved from Eq.(9). When L_2 is solved and substituted in Eq.(10), the value for inductance L_1 is obtained . When all parameters are solved, the resonance frequencies could still be inappropriate. To get the frequencies match with the frequencies specified, some iteration has to be done. The step-by-step procedure for solving the parameter values goes as follows:

1) The value for parallel connected network inductance L_s and inductance L_1 is to be calculated.
2) The new value for inductance L_2 is calculated by substituting $L_1||L_s$ to Eq.(9).
3) The inductance value L_2 is substituted to Eq.(10) and the new value for inductance L_1 is obtained.
4) The antiresonance frequency and the resonance frequency are confirmed with Eqs.(7) and (9). If the resonance frequency value has not settled to the desired value, next iteration round should be



(a) (b)

Fig. 4. Phase currents and their frequency spectrums, when S_n = 50 kVA, cosϕ=1 and f_{sw} = 1.8 kHz. In (a) it can be seen that when the resonance frequency f_{res} is not carefully selected the line current is very distorted. In (b) both resonance frequencies are carefully placed and the current waveform is much better.

performed using the component values obtained from the previous round.

After the iteration of the filter component values, the resonance frequencies are settled to the desired frequencies. It is assumed that by placing carefully the resonance frequencies the filter effectiveness on the ripple attenuation can be utilized better.

4. Numerical examples and simulations

The purpose of this section is to demonstrate by numerical examples how the design methods are used. Furthermore, by specifying THD limit for the line current, the differences between two filter types are brought up. In other words, designing the filters so that they fulfill the line current distortion requirement the performance differences between the filter types are seen in sizes of the filter parameters. A 5 percent THD limit for the line current is specified, that is a typical rule-of-thumb value for acceptable current waveform.

The parameter values are given in per unit (p.u.). The per unit system is based on the nominal apparent power S_n of the converter and line-to-line voltage U_n. The filter is designed for S_n=50 kVA and U_n=400 V converter. The switching frequency of the converter is 1.8 kHz. The base values are determined as

$$Z_b = \frac{U_n^2}{S_n} \tag{11}$$

The value for the base impedance equals Z_b = 3.2 Ω. Base values for the inductance is expressed as

$$L_b = \frac{Z_b}{\omega_b} \tag{12}$$

and for the capacitance as

$$C_b = \frac{1}{\omega_b Z_b} \tag{13}$$

The base values for the inductance equals 10.2 mH and for the capacitance 995 μF, when the base angular frequency is ω_b=2πf_s= 314 rad/s (f_s = 50 Hz).

A. LCL-filter

The allowed switching frequency current amplitude at the converter side inductor L_1 is $i_1(n_{sw})$ = 0.1 p.u. and $i_2(n_{sw})$ = 0.05 p.u. at the grid side inductor L_2. The resonance frequency is selected as 0.5f_{sw}. The amplitude of the voltage components at the switching frequency are assumed to be as $u_1(n_{sw})$ = 0.2 p.u. Then 0.056 p.u. is obtained for the inductor L_1. While d = 0.5 and k_{LCL}= 2, the ratio between the filter inductors r = -1/3. The reason for the negative result is that the resonance frequency and the switching frequency current amplitude have not got a common solution. The problem is solved by either increasing the attenuation d or decreasing f_{sw}. Decreasing the switching frequency f_{sw} is not reasonable and the attenuation is increased. That is, d is decreased to 0.3 resulting now r = 0.11. Now, L_2 = 0.006 p.u. and C = 0.56 p.u. are obtained with inductor ratio r and from Eq.(6), respectively. The reason for the high value of the capacitor is that when using a low switching frequency the resonance frequency requirement is fulfilled by choosing a large capacitor. To obtain smaller capacitance values a smaller $i_1(n_{sw})$ is to be allowed, which causes L_1 to increase. Values $i_1(n_{sw})$ = 0.067 p.u. and d = 0.23 are used. Achieved filter component values are given in Table I.

B. L+LC-filter

For L+LC-filter, the key idea was in placing the resonance frequencies. With f_{sw} = 1.8 kHz the placement of f_{ares} is also selected. Next, the resonance frequency f_{res} should be placed so that its frequency equals to the triplen harmonic of the fundamental frequency. In a three-phase three-wire network the triplen harmonics sum up to zero. Furthermore, because SVM is used as a modulation method, the resonance frequency should be placed between the first and the second carrier groups. By placing the resonance frequency between the carrier groups, a good attenuation is achieved.

The resonance frequency is selected as 3 kHz (k_{L+LC} = 0.6) and 0.01 p.u. capacitance C is chosen. Now the parallel connected inductance $L_1||L_s$ is assumed to equal the line inductance L_s = 0.02 p.u. Then the inductance L_2 = 0.008 p.u. is obtained from Eq.(9). Using Eq.(10), the value for L_1 = 0.07 p.u. is obtained. With these filter parameter values, a very poor THD = 51 % for the line current is achieved. This can be observed from Fig.4a where the line current waveform and the frequency spectrum are illustrated. With the parameters presented the resonance frequency f_{res} equals 3.27 kHz and thereby the lower sideband frequencies of the second carrier group are amplified, causing the line current distortion merely alone. By choosing the capacitance C to equal 0.003 p.u., new values for other filter components calculated according to the method are L_1 = 0.2 p.u. and L_2 = 0.08 p.u. Now, THD ≈ 5 % is achieved for the line current and the resonance frequency equals to 3.0 kHz. Component values for the L+LC-filter that fulfill the THD requirement for the line current are presented in Table I.

5. Conclusions

Filter design methods presented, revealed some important issues that should be noticed while designing a filter for a PWM voltage source converter. When using a modulation method that applies fixed switching frequency, the resonance frequency of the filter has to be placed carefully. In particular, it was shown that when an L+LC-filter is used the placement of the resonance frequencies has a major impact on the performance of the filter.

The performance comparison between LCL- and L+LC filters in terms of the component sizes showed very clearly the superior performance of the LCL-filter over the L+LC-filter.

TABLE I.
FILTER PARAMETERS OF LCL- AND L+LC-FILTERS WHEN S_N = 50 KVA AND U_N = 400 V. FILTERS USING THE COMPONENT VALUES FULFILL THE REQUIREMENT FOR THE LINE CURRENT DISTORTION (THD < 5 %)

f_{sw} [kHz]	L_1 [p.u.]	L_2 [p.u.]	C [p.u.]	THD [%]	Filter Type
1.8	0.08	0.02	0.12	4.9	LCL
1.8	0.19	0.08	0.003	4.8	L+LC
3.6	0.04	0.01	0.046	4.9	LCL
3.6	0.09	0.03	0.0016	4.9	L+LC

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