Analysis of Passive Filters for High Power Three-level Rectifiers.

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Abstract- This paper studies passive filters for harmonic reduction in high power rectifiers. The paper presents some of the most important configurations of high power filter employed in medium voltage applications. The paper as well includes the ideal mathematic equations and models for those filters, and then compares the filter performances. In a very broad sense, the addition of some resonant harmonic traps to a conventional third order filter results in good filter adaptation to PWM strategies. The filter evaluation highlights this fact. Simulation of a high power three-level Neutral Point Clamped-NPC rectifier also confirms those ideas. Results comprise a high quality waveform under low switching frequency with reasonable converter operation performance. Experimental results for Selective Harmonic Elimination are included.

I. INTRODUCTION

PWM rectifier operation at ac mains generates undesired harmonic content. Some of the problems addressed to those PWM harmonics are voltage and current distortions, overheating of reactive elements (capacitances and inductances), global power factor deterioration and electromagnetic interference (EMI). For many years, passive filters have been employed for harmonic reduction at the input of different structures [1]-[3]. However, the filter requirements for high power converters are quite different from those of the low power rectifiers. This is mainly related to discrepancies in the semiconductor technologies of the power devices, which limit the maximum converter switching frequency. In the last case, the high frequency modulation sweeps the harmonic content to the high frequency regions where the passive filter exhibits superior frequency response and attenuation ratio. Oppositely high power rectifiers, whose switching frequencies are limited from about 500 to 1000 Hz, produce harmonics near to base (fundamental) frequency with practically all modulation strategies. Owing to a poor low frequency performance, (between the cut-off frequency and less than ten times its value) such low frequency harmonics are of difficult elimination. The filter must attenuate them properly in order to assure a good converter operation. Besides, the filter has to be able to deal with them to since they can also excite filter/system resonances.

The work analyzes some passive filters for high power rectifiers. For this purpose, paper brings six sections. The first section introduces the problem of employing passive filters in high power medium voltage applications. Section II presents some of the most important filter configuration in literature. Section III develops the filter mathematic models. Section IV compares the filter performances, and it reinforces the

analysis in previous section. Section V presents Selective Harmonic Elimination which is an important modulation technique considering the limited switching frequency in this work. It makes feasible the filter design due to its larger frequency range free of harmonics. Finally, simulations of a high power three-level NPC rectifier, in section VI, results in high quality waveforms, under low switching frequency, with reasonable converter operation performance. The paper also includes experimental results for the modulator and converter.

II. HIGH POWER FILTERS.

In general passive filters consist of reactive elements in either series or parallel branches according to a given filter configuration or profile (low-pass, high-pass, etc.). Fig. 1 brings some of the most important filter configurations for high power converters in the literature [1]-[4]. They are the first order L filter, the third order LCL filter, the tuned LCL/L filter and the LCL filter with harmonic traps.

III. MATHEMATIC EQUATIONS AND FILTER MODELS.

In order to simplify the analysis this section assumes:

- Ideal reactive elements, (no damping and losses).

Fig. 1. High power filter configurations a) L filter, b) Third order LCL filter, c) Tuned LCL/L filter and d) LCL filter with harmonic traps.

- The converter produces all system harmonic content, (the utility grid voltage is purely sinusoidal).
- All voltage distortions at utility grid results exclusively from harmonic currents through the series branch composed by transformer equivalent short-circuit impedance.

A. First order L filter.

Generically the first order L filter consists of a single inductance per phase with a low-pass profile. It is the most common filter configuration for PWM rectifiers. Fig. 2 presents the system equivalent circuit composed by the L filter, (represented by L_f and r_f , corresponding to filter reactive and resistive components), the input insulation transformer, (represented by a purely sinusoidal source v_g and the short-circuit impedance elements L_g and r_g), and the high power rectifier working as the unique harmonic source in the circuit, (represented by the pulse generator u).

The equivalent circuit permits to write the following expressions:

$$v_g = r_t i_g + L_t di_g/dt + u \quad (1)$$

$$v_g = r_g i_g + L_g di_g/dt + v \quad (2)$$

where $r_t = r_g + r_f$, $L_t = L_g + L_f$. i_g and v are respectively the utility grid current and voltage at the point of common coupling – PCC.

Taking the Laplace transforms of (1) and (2):

$$v_g(s) = (r_t + sL_t)i_g(s) + u(s) \Rightarrow \quad (3)$$

$$i_g(s) = (v_g(s) - u(s))/(r_t + sL_t)$$

$$v_g(s) = (r_g + sL_g)i_g(s) + v(s) \Rightarrow \quad (4)$$

$$v(s) = v_g(s) - (r_g + sL_g)i_g(s)$$

Defining the transfer functions $H_v(s) = i_g/v$ and $H_u(s) = i_g/u$:

$$i_g(s) = H_v(s)v_g(s) + H_u(s)u(s) \quad (5)$$

$$v(s) = [1 - (r_g + sL_g)H_v(s)]v_g(s) - (r_g + sL_g)H_u(s)u(s) \quad (6)$$

In this case, $H_v(s) = -H_u(s) = 1/(r_t + sL_t)$. Replacing the Laplace operator s with $j\omega_1$:

$$H_v(j\omega_1) = -H_u(j\omega_1) = 1/(r_t + j\omega_1 L_t) \quad (7)$$

$$v(j\omega_1) = [1 - (r_g + j\omega_1 L_g)H_v(j\omega_1)]v_g(j\omega_1) - (r_g + j\omega_1 L_g)H_u(j\omega_1)u(j\omega_1) \quad (8)$$

where ω_1 is the fundamental angular frequency of the source v_g and converter u voltages and n is the harmonic order.

Fig. 2. System model with L filter. a) Single phase equivalent circuit, b) equivalent circuit for the fundamental frequency, c) equivalent circuit for the harmonic frequencies.

Assuming that $\omega_1 L_x$ is in general greater than r_x $\{x = g, f \text{ or } t\}$, it is possible to neglect r_x since $n\omega_1 L_x \gg r_x$. Then:

$$H_v(j\omega_1) = -H_u(j\omega_1) = 1/j\omega_1 L_t \quad (9)$$

$$v(j\omega_1) = [1 - (j\omega_1 L_g)H_v(j\omega_1)]v_g(j\omega_1) - (j\omega_1 L_g)H_u(j\omega_1)u(j\omega_1) \quad (10)$$

The equivalent circuit of Fig. 2a can be split in two new circuits, one at fundamental frequency ω_1 and other at the frequency of n^{th} harmonic $n\omega_1$. Neglecting the transformer harmonic voltage v_g , $\{v_{gn} = 0, \forall n \in \mathbb{N}/n \neq 1\}$, $\mathbb{N}$ represents the mathematic set of natural numbers:

$$i_{g1} = (v_{g1} - u_1)/j\omega_1 L_t \quad (11)$$

$$i_{gn} = -u_n/j\omega_n L_t \quad (12)$$

$$v_1 = [1 - (L_g/L_t)]v_{g1} + (L_g/L_t)u_1 \quad (13)$$

$$v_n = (L_g/L_t)u_n \quad (14)$$

The rms value of grid current I_{dis} and voltage V_{dis} distortions defined in [5] are:

$$I_{dis} = \sqrt{\sum_{n=2}^{n_{max}} i_{gn}^2} = \left(\frac{1}{\omega_1 L_t}\right) \sqrt{\sum_{n=2}^{n_{max}} \left(\frac{U_n}{n}\right)^2} \quad (15)$$

$$V_{dis} = \sqrt{\sum_{n=2}^{n_{max}} v_n^2} = \left(\frac{L_g}{L_t}\right) \sqrt{\sum_{n=2}^{n_{max}} U_n^2} \quad (16)$$

Here n_{max} is the highest harmonic order selected to suit a given design specification and U_n is rms value of n^{th} converter harmonic voltage.

The expressions above show that the current harmonic attenuation increases with the harmonic order and the total inductance ($L_t = L_g + L_f$). Moreover, the voltage harmonic attenuation depends only on the inductance relation L_g/L_t , (typically, about from 1 to 20% since the transformer short-circuit inductance L_g is small). Therefore, further improvement in the voltage harmonic attenuation to suit some design specification requires some increment in L_f . This in general results in bulky and heavy filter elements.

B. Third order LCL filter.

The LCL filter is an alternative to the first order L filter. It consists of a third order low-pass configuration with reactive elements displaced in “T” as in Fig. 3. Recently, the LCL filter has been exhaustively investigated with PWM rectifiers, [4], [6], and others. From the system equivalent circuit:

$$v_g = r_t i_g + L_t di_g/dt + e \quad (17)$$

$$e = r_c i + L_c di/dt + u \quad (18)$$

$$v_g = r_g i_g + L_g di_g/dt + v \quad (19)$$

$$i_g = i_f + i \quad (20)$$

$$i_f = C_f de/dt \quad (21)$$

where L_c and r_c are respectively the converter side series branch inductance and resistance, i is current through this series branch, C_f is the parallel branch capacitor, and e is voltage across this branch. Then taking the Laplace transforms of (17)-(21) and assuming the expressions (5) and (6) valid for the LCL filter:

$$H_v(s) = (1 + s^2 L_c C_f) / s(L_t + L_c)(1 + s^2 L_{eq} C_f) \quad (22)$$

$$H_u(s) = -1 / s(L_t + L_c)(1 + s^2 L_{eq} C_f) \quad (23)$$

Fig. 3. System model with LCL filter. a) Single phase equivalent circuit, b) equivalent circuit for the fundamental frequency, c) equivalent circuit for the harmonic frequencies.

Here $L_{eq} = L_r L_c / (L_r + L_c)$. For simplification, all resistive and damping elements are neglected. Replacing the Laplace operator s with $j\omega_1$ and splitting the filter equivalent circuit in two new circuits, one at ω_1 and other at $n\omega_1$ and finally neglecting the transformer harmonic voltage v_{gn} :

$$i_{g1} = \frac{(1 - \omega_1^2 L_c C_f) v_{g1} - u_1}{j\omega_1 (L_t + L_c) (1 - \omega_1^2 L_{eq} C_f)} \quad (24)$$

$$i_{gn} = -u_n / jn\omega_1 (L_t + L_c) (1 - n^2 \omega_1^2 L_{eq} C_f) \quad (25)$$

$$v_1 = \left[1 - \frac{L_g}{(L_t + L_c)} \frac{(1 - \omega_1^2 L_c C_f)}{(1 - \omega_1^2 L_{eq} C_f)} \right] v_{g1} + \frac{L_g}{(L_t + L_c)} \frac{1}{(1 - \omega_1^2 L_{eq} C_f)} u_1 \quad (26)$$

$$v_n = \left[L_g / (L_t + L_c) \right] \cdot \left[u_n / (1 - n^2 \omega_1^2 L_{eq} C_f) \right] \quad (27)$$

The rms grid current I_{dis} and voltage V_{dis} distortions are:

$$I_{dis} = \left[\frac{1}{\omega_1 (L_t + L_c)} \right] \sqrt{\sum_{n=2}^{n_{max}} \left[\frac{U_n}{n(1 - n^2 \omega_1^2 L_{eq} C_f)} \right]^2} \quad (28)$$

$$V_{dis} = \left(\frac{L_g}{L_t + L_c} \right) \sqrt{\sum_{n=2}^{n_{max}} \left[\frac{U_n}{(1 - n^2 \omega_1^2 L_{eq} C_f)} \right]^2} \quad (29)$$

The above equations confirm that LCL improves the L filter performance. Here the product $\omega_1 L_{eq} C_f$, the sum of series branch inductances ($L_t + L_c = L_g + L_f + L_c$) and nearly the third power of n^{th} harmonic simultaneously affect the current harmonic attenuation. The voltage harmonic attenuation depends on the inductance relation $L_g / (L_t + L_c)$ and about the square of the product $\omega_1 L_{eq} C_f$, and of the n^{th} harmonic. The LCL filter introduces inductance L_c as a new design element for both current and voltage attenuations, which gives flexibility to the filter design and in general culminates in lighter filter elements, [6].

C. Tuned LCL/L filter.

The tuned LCL/L filter is another important filter configuration in literature. It is mainly employed in high power uncontrolled rectifiers and consists of reactive elements displaced in "T" but with a resonant parallel branch that can be tuned into a specific converter harmonic frequency as in Fig. 4. The only difference between this and the LCL filter is resonant parallel branch represented by:

$$e = L_r \frac{di_f}{dt} + r_d i_f + \frac{1}{C_f} \int i_f dt \quad (30)$$

In this case, the equations (17)-(20) of the LCL filter are still applicable. Taking the Laplace transforms of them and (30) with resistive elements neglected the transfer functions $H_v(s)$ and $H_u(s)$ are:

$$H_v(s) = \left[1 + s^2 (L_r + L_c) C_f \right] / s (L_t + L_c) \left[1 + s^2 (L_r + L_{eq}) C_f \right] \quad (31)$$

$$H_u(s) = -(1 + s^2 L_r C_f) / s (L_t + L_c) \left[1 + s^2 (L_r + L_{eq}) C_f \right] \quad (32)$$

Replacing the Laplace operator s with $jn\omega_1$ and splitting the filter equivalent circuit in two new circuits, one at ω_1 and other at $n\omega_1$ (with all harmonic voltage v_{gn} neglected):

$$i_{g1} = \frac{[1 - \omega_1^2 (L_r + L_c) C_f] v_{g1} - (1 - \omega_1^2 L_r C_f) u_1}{j\omega_1 (L_t + L_c) [1 - \omega_1^2 (L_r + L_{eq}) C_f]} \quad (33)$$

$$i_{gn} = - \frac{(1 - n^2 \omega_1^2 L_r C_f) u_n}{jn\omega_1 (L_t + L_c) [1 - n^2 \omega_1^2 (L_r + L_{eq}) C_f]} \quad (34)$$

$$v_1 = \left\{ 1 - \frac{L_g}{(L_t + L_c)} \frac{[1 - \omega_1^2 (L_r + L_c) C_f]}{[1 - \omega_1^2 (L_r + L_{eq}) C_f]} \right\} v_{g1} + \frac{L_g}{(L_t + L_c)} \frac{(1 - \omega_1^2 L_r C_f)}{[1 - \omega_1^2 (L_r + L_{eq}) C_f]} u_1 \quad (35)$$

$$v_n = \frac{L_g}{(L_t + L_c)} \frac{(1 - n^2 \omega_1^2 L_r C_f) u_n}{[1 - n^2 \omega_1^2 (L_r + L_{eq}) C_f]} \quad (36)$$

The rms grid current I_{dis} and voltage V_{dis} distortions are:

$$I_{dis} = \left[\frac{1}{\omega_1 (L_t + L_c)} \right] \sqrt{\sum_{n=2}^{n_{max}} \left\{ \frac{(1 - n^2 \omega_1^2 L_r C_f) U_n}{n [1 - n^2 \omega_1^2 (L_r + L_{eq}) C_f]} \right\}^2} \quad (37)$$

$$V_{dis} = \left(\frac{L_g}{L_t + L_c} \right) \sqrt{\sum_{n=2}^{n_{max}} \left\{ \frac{(1 - n^2 \omega_1^2 L_r C_f) U_n}{[1 - n^2 \omega_1^2 (L_r + L_{eq}) C_f]} \right\}^2} \quad (38)$$

The filter analysis shows that resonant branch has a strong influence on filter behavior. New terms in filter equations such as $\omega_1 (L_r + L_{eq}) C_f$, improve the filter current and voltage harmonic attenuations and also increase the flexibility of filter design. The product $n^2 \omega_1^2 L_r C_f$ as well enhances the harmonic attenuation in low frequency range. On the other hand, the

Fig. 4. System model with LCL/L filter. a) Single phase equivalent circuit b) equivalent circuit at the fundamental frequency, c) equivalent circuit at the harmonic frequencies.

great similarity of this configuration with the *LCL* filter leads to a dependence on the sum of inductances ($L_t + L_c$). In the case of voltage attenuation the inductance relation $L_g/(L_t + L_c)$ still affects the filter behavior. However, the filter performance deteriorates in the higher frequency range. The current and voltage attenuations respectively depends on the n^{th} harmonic and a constant value, ($[L_g/(L_t + L_c)][L_r/(L_r + L_{eq})]$ in this case). This resembles the first order *L* filter. It is a classical problem of this filter configuration though the filter performance is rather superior to that of the *L* filter.

D. Third order LCL with Harmonic Traps.

An alternative to the filters above consists of third order *LCL* configuration with some resonant traps tuned in specific converter harmonics and in parallel with the main filter parallel branch. The main filter has again the elements in “T” as Fig 5. The filter behavior is expressed by (17)-(20) and:

$$i_f = i_{f0} + i_{r1} + i_{r2} + \dots \quad (39)$$

$$i_{f0} = C_f de/dt \quad (40)$$

$$e = L_{r1} \frac{di_{r1}}{dt} + \frac{1}{C_{r1}} \int i_{r1} dt \quad (41)$$

$$e = L_{r2} \frac{di_{r2}}{dt} + \frac{1}{C_{r2}} \int i_{r2} dt \quad (42)$$

⋮

Taking the Laplace transforms of them with resistive elements neglected the transfer functions $H_v(s)$ and $H_u(s)$ are:

$$H_v(s) = \frac{\{1 + s^2 L_g [C_f + C_{r1}/(1 + s^2 L_{r1} C_{r1}) + C_{r2}/(1 + s^2 L_{r2} C_{r2}) + \dots]\}}{s(L_t + L_c) \{1 + s^2 L_{eq} [C_f + C_{r1}/(1 + s^2 L_{r1} C_{r1}) + C_{r2}/(1 + s^2 L_{r2} C_{r2}) + \dots]\}} \quad (43)$$

$$H_u(s) = \frac{1}{s(L_t + L_c) \{1 + s^2 L_{eq} [C_f + C_{r1}/(1 + s^2 L_{r1} C_{r1}) + C_{r2}/(1 + s^2 L_{r2} C_{r2}) + \dots]\}} \quad (44)$$

Replacing the Laplace operator s with $j\omega_1$ and splitting the filter equivalent circuit in two, at ω_1 and $n\omega_1$ (with all harmonic voltage v_{gn} neglected):

$$i_{g1} = \frac{\{1 - \omega_1^2 L_g [C_f + C_{r1}/(1 - \omega_1^2 L_{r1} C_{r1}) + C_{r2}/(1 - \omega_1^2 L_{r2} C_{r2}) + \dots]\} v_{g1} - u_1}{j\omega_1 (L_t + L_c) \{1 - \omega_1^2 L_{eq} [C_f + C_{r1}/(1 - \omega_1^2 L_{r1} C_{r1}) + C_{r2}/(1 - \omega_1^2 L_{r2} C_{r2}) + \dots]\}} \quad (45)$$

Fig. 5. System model with *LCL* with harmonic traps. a) Single phase equivalent circuit, b) equivalent circuit for the fundamental frequency, c) equivalent circuit for the harmonic frequencies.

$$i_{gn} = \frac{u_n}{j\omega_n (L_t + L_c) \left\{ 1 - n^2 \omega_n^2 L_{eq} \left[C_f + \frac{C_{r1}}{(1 - n^2 \omega_n^2 L_{r1} C_{r1})} + \frac{C_{r2}}{(1 - n^2 \omega_n^2 L_{r2} C_{r2})} + \dots \right] \right\}} \quad (46)$$

$$v_1 = v_{g1} \frac{L_g \{1 - \omega_1^2 L_g [C_f + C_{r1}/(1 - \omega_1^2 L_{r1} C_{r1}) + C_{r2}/(1 - \omega_1^2 L_{r2} C_{r2}) + \dots]\}}{(L_t + L_c) \{1 - \omega_1^2 L_{eq} [C_f + C_{r1}/(1 - \omega_1^2 L_{r1} C_{r1}) + C_{r2}/(1 - \omega_1^2 L_{r2} C_{r2}) + \dots]\}} v_{g1} - L_g u_1 \quad (47)$$

$$v_n = \frac{L_g}{(L_t + L_c)} \frac{u_n}{\left\{ 1 - n^2 \omega_n^2 L_{eq} \left[C_f + \frac{C_{r1}}{(1 - n^2 \omega_n^2 L_{r1} C_{r1})} + \frac{C_{r2}}{(1 - n^2 \omega_n^2 L_{r2} C_{r2})} + \dots \right] \right\}} \quad (48)$$

The rms grid current I_{dis} and voltage V_{dis} distortions are:

$$I_{dis} = \frac{1}{\omega_1 (L_t + L_c)} \sqrt{\sum_{n=2}^{\infty} \frac{U_n^2/n^2}{\left\{ 1 - n^2 \omega_n^2 L_{eq} \left[C_f + \frac{C_{r1}}{(1 - n^2 \omega_n^2 L_{r1} C_{r1})} + \frac{C_{r2}}{(1 - n^2 \omega_n^2 L_{r2} C_{r2})} + \dots \right] \right\}^2}} \quad (49)$$

$$V_{dis} = \frac{L_g}{L_t + L_c} \sqrt{\sum_{n=2}^{\infty} \frac{U_n^2}{\left\{ 1 - n^2 \omega_n^2 L_{eq} \left[C_f + \frac{C_{r1}}{(1 - n^2 \omega_n^2 L_{r1} C_{r1})} + \frac{C_{r2}}{(1 - n^2 \omega_n^2 L_{r2} C_{r2})} + \dots \right] \right\}^2}} \quad (50)$$

The analysis shows that the current and voltage harmonics depend among others on the product

$$n^2 \omega_1^2 L_{eq} [C_f + \sum_{k=1}^{nrr} C_{rk}/(1 - n^2 \omega_1^2 L_{rk} C_{rk})], \quad (nrr \text{ is the number of}$$

parallel resonant branches adopted in the filter design). The equations are undoubtedly more elaborated than that of *LCL* filter. This gives great flexibility to the filter design, [4]. The parallel branches add the capacitive terms $C_{rk}/(1 - n^2 \omega_1^2 L_{rk} C_{rk})$ $\{k = 1, 2, \dots, nrr\}$, to the main filter capacitor C_f in such a way that for the lower order harmonics $C_f + \sum C_{rk}/(1 - n^2 \omega_1^2 L_{rk} C_{rk})$ tends to $C_f + \sum C_{rk}$ and for higher frequency harmonics it tends to C_f . This implies that *LCL* filter with harmonic traps behaves like the third order *LCL* filter in high frequency region. On the other hand, it is possible to show that the filter works as *LCL* in low frequency range. This gives the filter high attenuation ratio and selectivity along with good high frequency response.

IV. FILTER EVALUATION.

Fig. 6 presents ideal (no damping and losses) filter frequency responses. Bearing in mind the current harmonic attenuation the *L* filter exhibits a typical first order frequency response, ($\approx -20\text{dB/dec.}$), but its voltage attenuation is poor, (constant in all frequency range). The third order *LCL* improves the filter performance but besides resonance, its attenuation in low frequency range is not so high. The *LCL* filter enhances this feature with a resonant branch, which can be tuned in a specific low frequency harmonic. A drawback in this case is the deterioration of its high frequency response to that of a first order filter, (-20dB/dec and constant for the current and voltage attenuations respectively). Instead, the Fig. 6 shows the following advantages of *LCL* filter with harmonic traps over the other filter configurations:

- Higher harmonic attenuation ratio due to harmonic traps;
- Attenuation of two or more low frequency harmonics according to the design specifications;
- No deterioration of its high frequency response due to the independent tuned branch;
- Good performance in both high and low frequency

regions. In the first case, it takes the advantage of *LCL* filter behavior. In the second case, it improves *LCL/L* attenuation capability in low frequency range;

- Better attenuation profile among all filter configuration, which results in a good adaptation to practically all modulation techniques, (with either well defined side-band harmonic components around multiples of switching frequency or specific non-eliminated harmonic resultant from pre-calculated pulse patterns).

Additionally, Table I compares the complexity of the filters in Fig. 6. According to [9] filter cost and size increases with its total reactive power and thus with individual values of reactive elements. Nonetheless, the improvement in filter performances justifies the increase in their complexities.

V. SELECTIVE HARMONIC ELIMINATION - SHEPWM.

The power circuits consist of a Neutral Point Clamped converter working as active rectifier and a passive sinusoidal input filter. References [7] and [8] discuss the generalized method of Selective Harmonic Elimination and state that an arbitrary number M of harmonic could be controlled and/or eliminated from a standard three level output voltage

Fig. 6. Frequency response of high power filter configurations.

TABLE I

RATINGS OF ELEMENTS FOR THE FILTER CONFIGURATIONS (PER UNIT).

Filter	L_c	L_f	C_f	L_{r1}	C_{r1}	L_{r2}	C_{r2}
<i>L</i>	0.180	-	-	-	-	-	-
<i>LCL</i>	0.100	0.081	0.100	-	-	-	-
<i>LCL/L</i>	0.100	0.081	0.100	0.027	-	-	-
<i>LCL+ht</i>	0.100	0.081	0.100	0.027	0.027	0.020	0.020

waveform if it is chopped M times per half fundamental period. Expanding the waveform into Fourier series and assuming odd quarter-wave symmetry, the cosine components vanish and (51) gives n^{th} harmonic coefficient of the sine components, ($n=1, 3, 5, \dots$).

$$a_n = (4E/\pi n) \sum_{k=1}^M (-1)^{k+1} \cdot \cos(n\alpha_k) \quad (51)$$

$$0 \leq \alpha_1 < \alpha_2 < \dots < \alpha_M < \pi/2$$

In order to control the fundamental component and eliminate $(M-1)$ harmonics it is essential to solve a nonlinear and transcendental system of equations. Based on the Newton's method in [7] it was developed an algorithm to solve those equations in order to control the converter fundamental component and eliminate 5th and 7th harmonics.

VI. RESULTS

Fig. 7 shows the results for a three-level NPC rectifier of 5MVA/4160V 60Hz, dc bus voltage $v_{dc} = 3236V$ simulated with MATLAB/SIMULINK. SHEPWM generates switching command at frequency $f_c = 180Hz$. The sinusoidal main filter elements are all about 0.15pu, (Table II). The system short-circuits inductance L_g is assumed equal to 0.025 pu. The rectifier is under control of voltage oriented synchronous reference frame current loop and the converter high power factor is achieved setting the reference current $i_q^* = -148A$ by the controller. In Fig. 7a, the grid line voltage V_{ab} is reasonably sinusoidal in contrast to U_{ab} , a typical 3-level line voltage. In this case, the former presents a $THD = 0.4\%$ with very low harmonic content in all frequency range, Fig. 8. The latter presents a $THD = 26.61\%$ and negligible low frequency harmonics below 660Hz. In Fig. 7b, V_a and i_a are basically in phase. The displacement power factor $DPF \approx 1$ and distortion factor given by $DF = (I_{s1}/I_s) = 1/[(THD)^2 + 1]^{1/2} \approx 1$. It results in system operation effectively with unity power factor ($PF = DPF \cdot DF$). Moreover i_a is highly sinusoidal with $THD = 1.37\%$ and all harmonic amplitudes below 0.8%, as in Fig. 8b.

TABLE II
RATINGS OF SINUSOIDAL FILTER ELEMENTS.

L_f	1.272mH	0.1385 pu
L_c	1.375mH	0.1498 pu
C_f	120μF	0.1566 pu

Fig. 7. a) Line grid V_{ab} and converter U_{ab} voltages b) grid currents i_a, i_b, i_c and phase voltage V_a (dashed) with sinusoidal filter.

Fig. 8. a) Line grid voltage b) current harmonic spectrum with filter.

Experimental results from a lab test bench for SHEPWM and a three-level NPC converter of 10kVA/460V 60Hz are in Fig. 9 and 10. Fig. 9 shows the converter pulse pattern of phase and line voltages. The line voltage spectrum in this case is in Fig. 10. The Table III shows the amplitude of the first 10 odd line voltage harmonics.

VII. CONCLUSIONS

This work investigated four important filter configurations for harmonic reduction in high power rectifiers. They are the first order L filter, the third order LCL filter, the tuned LCL filter and the LCL filter with harmonic traps. The paper presented and analyzed their idealized mathematic equations and models and compared their frequency responses. It is remarkable that the simpler filter configuration the worse its

Fig. 9. SHEPWM phase and line voltages, U_{ao} , U_{bo} and U_{ab}

Fig. 10. SHEPWM line voltage U_{ab} harmonic spectrum.

TABLE III
SHEPWM-LINE VOLTAGE HARMONICS.

n	Frequency f_n (Hz)	U_n (%)
1°	60	100.00000
3°	180	0.93443
5°	300	1.43095
7°	420	0.56376
9°	540	0.25467
11°	660	17.17404
13°	780	14.85169
15°	900	1.03137
17°	1020	0.63141
19°	1140	14.75186

performance is. This results in less flexibility of filter design and perhaps in heavier filter elements to suit some design specification. Oppositely, the LCL filter with harmonic traps is clearly more elaborated than the other filters and for this motive, it shows outstanding features and performance. Besides it presents superior attenuation profile among all filter configuration, which results in a good adaptation to practically all modulation techniques, (with either well defined sided-band harmonic components around multiples of switching frequency or specific non-eliminated harmonic resultant from pre-calculated pulse patterns). Along with it the work takes advantage of Selective Harmonic Elimination which is an important modulation technique considering the converter limited switching frequency and filter bandwidth. It makes feasible the filter design in low frequency conditions due to its larger frequency range free of harmonics. Simulation of a high power rectifier demonstrated that it is possible synthesize sinusoidal voltage and current with acceptable operation performance under low switching frequency, even with a reduced level structure such as the three-level NPC converter.

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