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Active Power Filter LCL Filter Insertion Loss Calculation Analysis

G. Asmanis, O. Krievs, A. Asmanis
Faculty of Power and Electrical Engineering, Riga Technical University,
Kalku St. 1, Riga, Latvia
asmanisgundars@inbox.lv

***Abstract*—This paper introduces a new approach for active power filters LCL filter insertion loss calculation, treating it as two port T-network and describing it using scattering and impedance parameters. There is proposed usage of line impedance stabilization network in frequency range over 9*kHz* to enable insertion loss calculation neglecting mains impedance. In the study, importance of parallel elements of LCL filter components is analyzed.**

***Index Terms*—Active filters, power filters, load management, impedance.**

I. INTRODUCTION

Voltage source active power filters (APF) with, L type supply filters do not always sufficiently attenuate switching ripple currents, caused by the pulse width modulated (PWM) voltage. Therefore usage of third order LCL filter can lead to considerably lower current ripple, as shown in Fig. 1. In literature there are various sources that describe filter design, APF stability and filter resonance damping [1]–[4]. Various approaches are suggested to analyze LCL filters parameters such as inductance of both inductors and their ratio, tamping resistor in series with filter capacitor as stated in [5], [6]. However, there are lacks of publications related to LCL filter insertion loss (IL) estimation from electromagnetic compatibility (EMC) point of view. In [6] IL dependence are analyzed point of view of inductance slit ratio of LCL filter, but in IL calculation source impedance are ignored that significantly changes the IL calculation precision. Also LCL filter parasitics are ignored that has great impact on IL in high frequency region. These both factors are taken into account in current paper to examine simple LCL filter capability to satisfy EMC legislation.

In this paper, LCL filter is designed using guidelines given in [5], [6], for APF prototype and its insertion loss is calculated and analyzed taking into account filter component parasitic parameters.

II. FILTER INSERTION LOSS

Filters applied for EMI mitigation usually are characterized by insertion loss (IL). Conducted disturbances created by semiconductor switches are in frequency range up to few tens of *MHz* [7]. LCL low-pass filter are useful high frequency filter up to few hundreds of *kHz*. Filter limitations for the high frequency, usually are set by filter component self parasitic parameters, such as inductors equivalent parallel capacitance (EPC), equivalent series resistance (LESR) and capacitors equivalent series resistance (ESR) and inductance (ESL), moreover, component mutual couplings are of great importance in high frequency range [8]. LCL filter can benefit in achieving compliance with EMC regulations in conducted emissions (9*kHz*-30*MHz*).

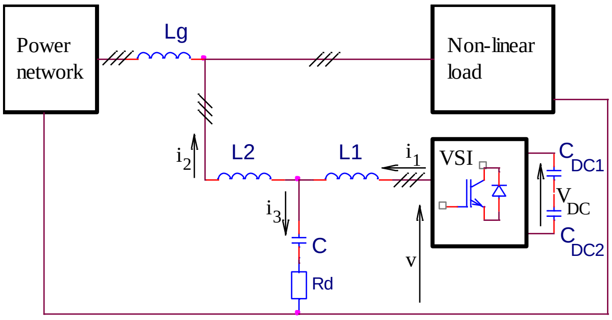

Fig. 1. Active power filter with LCL filter connected to power network.

IL of filter in EMC is defined as a voltage at load with inserted filter V_{Lw} versus voltage at load without filter V_{Lwo} [9]. Situation is described in Fig. 2. and mathematically expressed in (1)

$$IL_{dB} = 20 \log_{10} (\frac{V_{Lwo}}{V_{Lw}}). \tag{1}$$

IL depends not only on the filter parameters, but on source and load impedances Z_S and Z_L, thus these parameters should be taken into account in calculation. There has been proposed LCL low pass filter IL calculation in [6], but the source impedance is ignored, that can lead to inaccurate results. Proposed IL calculation is based on assumption that filter is two port T-network, taking into account Z_S and Z_L. There are proposed IL calculation based on filter S-parameters in [10]. S-parameters are characterizing filter in terms of waves independently from Z_S and Z_L, but in insertion loss calculation they appear in form of source and load reflection coefficients. IL in terms of S-parameters is defined as A_V in (2)

$$A_V = 20\ LOG_{10}\left(\frac{S_{21}(1-\Gamma_L\Gamma_S)}{(1-S_{11}\Gamma_S)(1-S_{22}\Gamma_L)-S_{21}\Gamma_L S_{12}\Gamma_S}\right), \tag{2}$$

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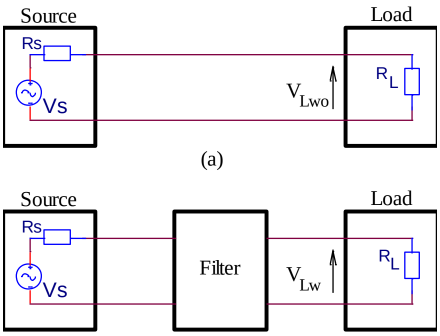
where load reflection coefficient is defined as in (3)

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}. \tag{3}$$

Source reflection coefficient is defined as in (4), where reference impedance Z_0=50 Ω

$$\Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0}. \tag{4}$$



(b)

Fig. 2. (a) Source directly connected to load, (b) Source connected to load through filter.

Two port T-network in Fig. 3 represented by LCL filter, also can be described using other network parameters, Z-parameters, respectively.

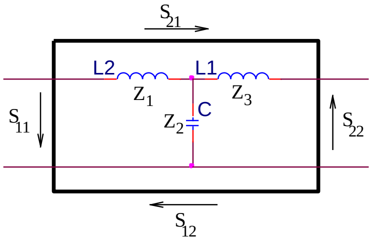


Fig. 3. LCL filter represented as two port T-network.

It is possible to write down the following equations for two pole network in Fig. 3:

$$Z_{11} = Z_1 + Z_2, \tag{5}$$

$$Z_{12} = Z_{21} = Z_2, \tag{6}$$

$$Z_{22} = Z_2 + Z_3. \tag{7}$$

S-parameters are connected with Z-parameters in the following manner [11]:

$$S_{11} = \frac{(Z_{11} - 1)(Z_{22} + 1) - Z_{12} Z_{21}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12} Z_{21}}, \tag{8}$$

$$S_{12} = \frac{2 Z_{12}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12} Z_{21}}, \tag{9}$$

$$S_{21} = \frac{2 Z_{21}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12} Z_{21}}, \tag{10}$$

$$S_{22} = \frac{(Z_{11} + 1)(Z_{22} - 1) - Z_{12} Z_{21}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12} Z_{21}}. \tag{11}$$

Inserting (3)–(11) into (2) IL can be rewritten as in (12)

$$IL = 20\,LOG_{10}\left(\frac{Z_2(Z_L + Z_S)}{Z_1 Z_2 + Z_1 Z_3 + Z_2 Z_3 + Z_L(Z_1 + Z_2) + Z_S(Z_2 + Z_3 + Z_L)}\right). \tag{12}$$

III. FILTER DESIGN

A simplified procedure to obtain LCL filter parameters is described in [5], [6]. The filter is designed for APF in Fig. 1 and parameters are stated in Table I. Filter IL for system can be calculated using (11). To calculate IL it is necessary to know the load and source impedances Z_L and Z_s. In real life, load impedance is defined by the mains network configuration and it varies from site to site. As compliance to EMC regulations are verified using line impedance stabilization network (LISN), it is reasonable to calculate IL using differential mode (DM) LISN impedance. Three phase DM model of LISN and filter is developed in [12], where LISN DM impedance, in three phase system, for one phase is assumed to be 50Ω. In lower frequency range 9*kHz*-150*kHz*, there are no EMC standard requirements for APF, such a requirements should satisfy only limited part of equipment- self ballasted lamps and induction cooking equipment. However, in future it is expected to have EMC standard requirements also for APF in range down to 9*kHz*. CISPR standards define LISN impedance in range 9*kHz*-30*MHz*, but in this case impedance cannot be approximated with a single value-50Ω, as in frequency range 150*kHz*-30*MHz*. It is possible to develop model of LISN in range of 9*kHz*-30*MHz* Fig. 4, that satisfies CISPR standard requirements [13], approximating LISN DM input impedance $Z_{DM\ LISN}$ with high precision (13), where R_{1LISN}=50 Ω, R_{2LISN}=5 Ω and L_{LISN}=50 uH

$$Z_{DM\ LISN} = \frac{R_{1LISN}\ (R_{2LISN} + sL_{LISN})}{R_{1LISN} + R_{2LISN} + sL_{LISN}}. \tag{13}$$

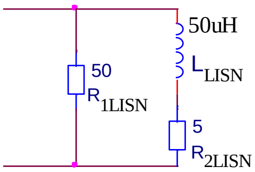


Fig. 4. LISN differential mode input impedance model for frequency range 9 *kHz*-30 *MHz*.

If APF filter is connected through LISN to mains network, inductance L_g is connected parallel to Z_{DM_LISN}, thus load impedance Z_L can be written as

$$Z_L = \frac{1}{\dfrac{1}{sL_g} + \dfrac{R_{1LISN} + R_{2LISN} + sL_{LISN}}{R_{1LISN} * (R_{2LISN} + sL_{LISN})}}. \tag{14}$$

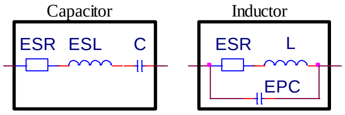
Z_s can be assumed to be impedance of the DC link capacitors taking into account similarities in developed models [12] and [14]. In this paper it is supposed that Z_S is represented by DC link capacitor impedance. In frequency range above 9*kHz* DC link capacitors do not act as pure capacitors, but as series connected capacitance C_{DC}, equivalent series inductance and equivalent series resistance as shown in Fig. 5, a. ESL and ESR values have a great impact on capacitor impedance Z_{CDC}. DC link capacitor impedance can be written as in (15). APF model for power flow analysis with LCL filter, where inductive and capacitive components are represented as ideal components is decent, yet for IL analysis in frequency range over 9*kHz* inductive and capacitive components should be characterized more precisely

$$Z_{CDC} = ESR + sESL + \frac{1}{sC_{DC}}. \qquad (15)$$

Filter capacitor can be described in the same manner as DC link capacitor in (15). Filter inductances L_1 and L_2 can be described with lumped element model shown in Fig. 5, b. Inductors impedance can be obtained using (16)

$$Z_{Inductor} = \frac{1}{sEPC} + \frac{1}{ESR_L + sL}. \qquad (16)$$

Core material used for inductors are iron powder, thus L_1 and L_2 are expected to be pure inductors up to 400*kHz*, thereafter core losses becomes dominant up to 10*MHz*, therefore core is no longer effective in frequency range over approximately 10*MHz*. In this paper calculation of IL are done neglecting core material losses and inductors nonlinearity, assuming that inductors are driven enough far from core saturation point.



(a) (b)

Fig. 5. (a) Capacitor lumped element model. (b) Inductor lumped element model.

Taking into account that Z_S and Z_L impedances and LCL filter component lumped element models, calculation can be done more precisely to predict LCL filter insertion loss in frequency range over 9*kHz* using (12). Impedances of filter components can be measured using precision impedance analyzer, however other methods exist where such expensive equipment is not needed [15], or they can be selected from component datasheet.

TABLE I. DESIGNED FILTER COMPONENT VALUES.

L1	0.9607mH
L2	0.25228mH
C	6uF
R_d	5Ω
L_g	0.2mH

Whole system model for LCL filter IL calculation is shown in Fig. 6, where all LCL filter component lumped models are presented, including APF simplified model, LISN model and network inductance L_g.

IV. ANALYSIS OF FILTERS COMPONENT PARASITIC PARAMETER IMPACT ON FILTERS INSERTION LOSS

Insertion loss changes are analyzed using model in Fig. 6 and IL is calculated using (12). In Fig. 7 there are shown IL dependence of filters load impedance Z_L, for two cases: Z_L are represented by LISN and inductance L_g and Z_L are represented only by LISN, thus neglecting L_g.

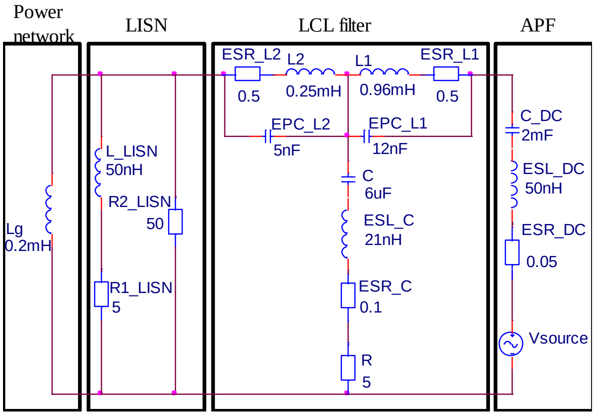


Fig. 6. Active power filter, LCL filter, mains network and LISN lumped element models.

As both IL are practically identical, it can be concluded, that usage of LISN in frequency range over 9*kHz* gives a chance to ignore inductance L_g. Site to site L_g variation impact on IL is analyzed in Fig. 8, where IL of LCL filter is calculated in case if LISN is not used and mains inductance L_g is changed.

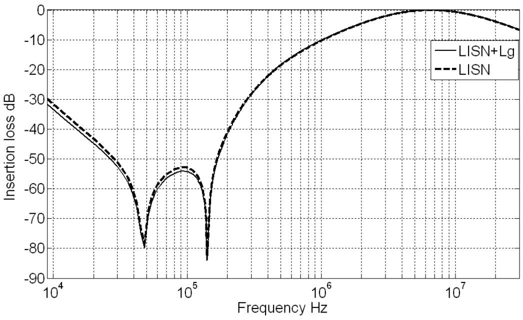


Fig. 7. Filter insertion loss dependence on LISN and line inductance L_g.

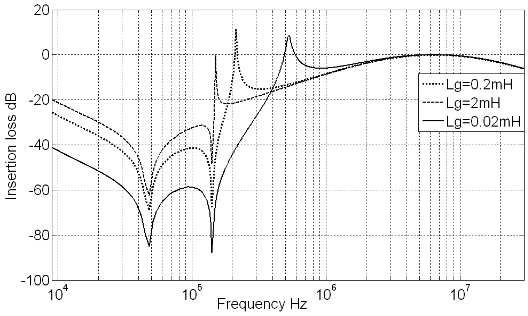


Fig. 8. LCL filter insertion loss calculation, if LISN is not used and L_g value is changed.

LISN model usage in LCL filter IL calculation is important, but it power flow model of APF inductance L_g still play important role, despite LISN usage. LCL filter IL in high frequency region is mainly affected by inductors EPC. The situation is shown in Fig. 9, where EPC values of inductors L_1 and L_2 are changed. The higher the parasitic capacitance, the more effective disturbances are conducted through the filter. Filter component lumped element models are of great importance in IL calculation, as shown in Fig. 10.

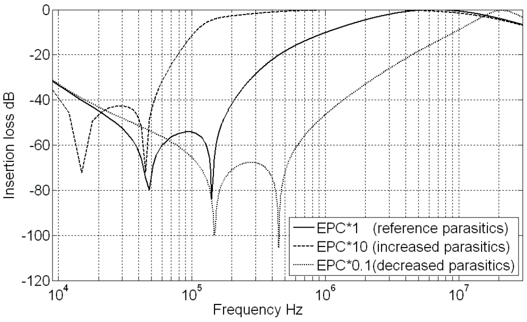


Fig. 9. LCL filter insertion loss calculation, if EPC is changed.

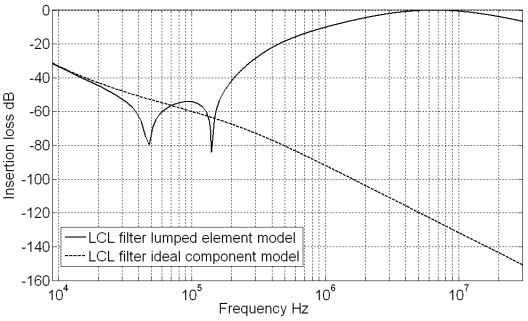


Fig. 10. LCL filter insertion loss calculation with ideal filter components and real filter components.

In Fig. 10 IL of LCL filter is plotted for two cases: filter components are ideal components and filter components are described as lumped element models as in Fig. 5.

V. CONCLUSIONS

LCL filters employed for active power filters are typically calculated to meet the EMC regulations for harmonic current emissions. Therefore, LCL filter can be described as two-port network using impedance parameters and S-parameters, which enables IL calculation to predict filter performance in high frequency range. This paper introduces the usage of LISN model in order to calculate IL in frequency range over 9*kHz*. LISN usage enables IL calculation for filter, neglecting mains inductance L_g. It is shown a simplified model of active power filter as a disturbance source that enables insertion loss calculation taking into account load impedance Z_L. LCL filter poor high frequency IL is mainly created by inductors equivalent parallel capacitance that creates short-cut for high frequency components. Also inductors core material limits the capability of LCL filter to considerably attenuate high frequency disturbances in frequency range over few hundreds of *kHz*.

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