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 9kHz to enable insertion loss calculation neglecting mains impedance. In the study, importance of parasitic 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 (ESR) 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 (9kHz-30MHz).

In Fig. 1 the 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 \( V_{Lwo} \). Situation is described in Fig. 2. and mathematically expressed in (1)

\[
IL_{dB} = 20 \log_{10} \left( \frac{V_{Lwo}}{V_{Lw}} \right). \tag{1}
\]

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)

\[
A_V = 20 \log_{10} \left( \frac{S_{21} (1 - \Gamma_L \Gamma_S)}{(1 - S_{31} \Gamma_S) (1 - S_{22} \Gamma_L) - S_{21} S_{32} \Gamma_L \Gamma_S} \right). \tag{2}
\]
where load reflection coefficient is defined as in (3)

\[ \Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \]  

(3)

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

\[ \Gamma_S = \frac{Z_S - Z_0}{Z_S + Z_0} \]  

(4)

\[ Z_{11} = Z_1 + Z_2, \quad Z_{12} = Z_{21} = Z_2, \quad Z_{22} = Z_2 + Z_3. \]  

(5)

(6)

(7)

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

\[ S_{11} = \frac{(Z_{11} - 1)Z_{22} + 1}{Z_{11} + 1} \cdot \frac{Z_{12}Z_{21}}{Z_{22} + 1} - Z_{12}Z_{21}, \]  

(8)

\[ S_{12} = \frac{2Z_{12}}{(Z_{11} + 1)Z_{22} + 1} - Z_{12}Z_{21}, \]  

(9)

\[ S_{21} = \frac{2Z_{21}}{(Z_{11} + 1)Z_{22} + 1} - Z_{12}Z_{21}, \]  

(10)

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

(11)

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

\[ IL = 20 \, \log_{10} \left( \frac{Z_L(Z_L + Z_v)}{Z_L(Z_L + Z_v) + Z_s(Z_s + Z_v)} \right) \]  

(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 \( Z_v \). 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 9kHz-150kHz, 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 9kHz. CISPR standards define LISN impedance in range 9kHz-30MHz, but in this case impedance cannot be approximated with a single value-50Ω, as in frequency range 150kHz-30MHz. It is possible to develop model of LISN in range of 9kHz-30MHz. Fig. 4, that satisfies CISPR standard requirements [13], approximating LISN DM input impedance \( Z_{DM\_LISN} \) with high precision (13), where \( R_{L\_LISN}=50 \, \Omega, \, R_{C\_LISN}=5 \, \Omega \) and \( L_{L\_LISN}=50 \, \mu H \)

\[ Z_{DM\_LISN} = \frac{R_{L\_LISN} \left( R_{C\_LISN} + sL_{L\_LISN} \right)}{R_{L\_LISN} + R_{C\_LISN} + sL_{L\_LISN}} \]  

(13)

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

\[ Z_L = \frac{1}{\frac{1}{L_{L\_LISN}} + \frac{R_{L\_LISN}}{sL_{L\_LISN}}} \]  

(14)

\[ Z_L \] 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 \( Z_L \) is represented by DC link capacitor impedance. In frequency range above 9kHz 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 \( Z_{DC} \). 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 9kHz inductive and capacitive components should be characterized more precisely

\[
Z_{CDC} = ESR + sESL + \frac{1}{sC_{DC}}. \tag{15}
\]

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)

\[
Z_{Inductor} = \frac{1}{sEPC} + \frac{1}{sESR_L + sL}. \tag{16}
\]

Core material used for inductors are iron powder, thus \( L_1 \) and \( L_2 \) are expected to be pure inductors up to 400kHz, thereafter core losses becomes dominant up to 10MHz, therefore core is no longer effective in frequency range over approximately 10MHz. 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.

Taking into account that \( Z_g \) 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 9kHz 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.

\[
Z_{CDC} = ESR + sESL + \frac{1}{sC_{DC}}. \tag{15}
\]

As both IL are practically identical, it can be concluded, that usage of LISN in frequency range over 9kHz 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.

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 \( L_g \). In Fig. 8 IL of LCL filter is calculated in case if LISN is not used and \( L_g \) 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

| TABLE I. DESIGNED FILTER COMPONENT VALUES. |
|-----------------|-----------------|
| \( L_1 \)       | 0.9607mH         |
| \( L_2 \)       | 0.25228mH        |
| \( C \)         | 6uF             |
| \( R_0 \)       | 5Ω              |
| \( L_g \)       | 0.2mH           |

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

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

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.
are of great importance in IL calculation, as shown in Fig. 10.

![Fig. 9. LCL filter insertion loss calculation, if EPC is changed.](image)

![Fig. 10. LCL filter insertion loss calculation with ideal filter components and real filter components.](image)

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 9kHz. LISN usage enables IL calculation for filter, neglecting mains inductance Lg. It is shown a simplified model of active power filter as a disturbance source that enables insertion loss calculation taking into account load impedance ZL. 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.

REFERENCES


