Electrical Power Quality and Utilisation, Journal Vol. XIV, No. 2, 2008

Wiener Filtering Applied to Conducted EMI Estimation in Soft Switching Inverter

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Summary: **This paper presents an estimation method of the conducted electromagnetic interference EMI emissions in soft switching inverters. Estimation process is carried out by a number of Wiener filters, which represent different operation conditions as reflected through subsequent power converter states determined by initial commutation event conditions and propagation paths layout. Filters are fed by a semiconductor power switch voltage or current waveforms regarded as sources of perturbation. The EMI emissions are measured on the line impedance stabilization network LISN terminals. Optimal filter adaptation is effected in the frequency domain by measuring input and cross power signal spectra. Analysis of parallel quasi resonant dc link voltage inverter PQRDCLI is outlined to distinguish filters assigned for inverter operation and those for an external DC/DC converter interaction. Experimental results are given to illustrate the Wiener filtering estimation quality. Possibility of detailed decomposition of the LISN-EMI waveforms is depicted in both time and frequency domain. Comparative analysis of frequency responses for PQRDCLI link voltage changes is given.**

Key words:
Wiener filtering, estimation, electromagnetic interference, resonant power conversion

1. INTRODUCTION

Nowadays, there is a trend for increasing switching frequencies of power semiconductor devices in order to reduce geometrical dimension and weight of power converters. This is unfortunately relied with increasing electromagnetic interference (EMI) of conducted and radiated emissions. Many official regulations have been issued for limiting the EMI [15, 16]. Therefore, for optimization of power electronic converters, better understanding and awareness of EMI generation phenomena is needed. Reliable emission estimation at the early stage of converter development, possibly before experimental prototype validation, could drastically reduce production time and improve final design. State of the art evaluation of EMI in power electronics can be effected by:

— Expert knowledge and systems [1–2],
— Simplified modeling in time and frequency [7, 14]
— Accurate computer simulation [3, 8, 10]
— Signal processing and estimation [11]

In this paper, digital signal processing approach exploiting the Wiener filtering has been considered. While in previous papers it has been proved this theory relevance to conducted EMI estimation applied for a *dc/dc* boost converter [12] and for conventional hard-switched voltage source inverter [13]. The paper objective is to focus on the EMI estimation in soft switching inverter, identifying perturbation voltage waveforms across the Line Impedance Stabilization Network (LISN) terminals, sources of perturbation and its propagation paths. The Wiener filtering is applied to estimation by a number of filters corresponding exactly to converter states at different initial conditions (Fig. 1). The definition and detection of subsequent states and commutation between them is crucial for optimal filtering using available for measurement transient voltage- or current-waveforms.

2. WIENER FILTERING

Theory of optimum linear filters for the general case of minimum mean square error criterion was developed by Wiener for continuous time and independently by Kolmogorov for discrete time systems [5, 6]. In this approach, the Wiener filters used for the EMI estimation are fed by power switch voltage or current transients, as represented by the source of disturbances *v* in Figure 2. Corresponding conducted network emissions *p,* that can be isolated in the LISN terminals, consist of reconstructed disturbances p_v – available to be estimated with the aid of filtering source *v* and inevitably present additive noise term p_o.

As the assumptions of Wiener filter theory claim:

— Filter system *H* is linear and time-invariant,
— Noise p_o coming form other sources is additive and not correlated with the source of disturbances *v*

one can express *v* and p_v by the Fourier transforms:

$$P_v(j\omega) = H(j\omega)\ V(j\omega) \tag{1}$$

where *H(jω)* is the filter frequency response.

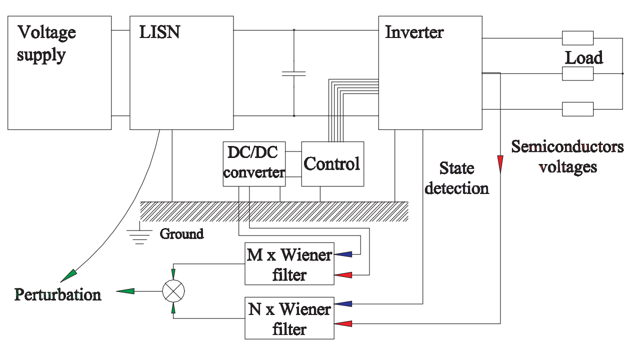

Fig. 1. Wiener filters applied to EMI estimation in the voltage inverter

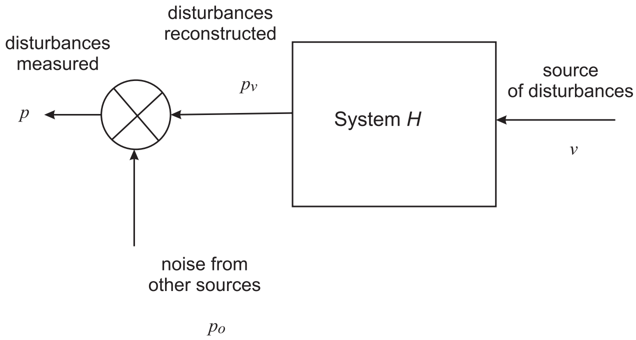

Fig. 2. Wiener filtering in estimation of EMI

The estimation error $E_r(j\omega)$ is defined as the difference between the measured and reconstructed disturbances:

$$E_r(j\omega) = P(j\omega) - H(j\omega)V(j\omega) \tag{2}$$

Then mean square estimation error is given as follows:

$$E\left\{\left|E_r(j\omega)\right|^2\right\} = E\left\{E_r(j\omega)^* E_r(j\omega)\right\} \tag{3}$$

where $E\{.\}$ denotes mean value operator. Using the mean square error criterion, the derivative of (3) with respect to $H(j\omega)$ is calculated from:

$$\frac{\partial}{\partial H(j\omega)} E\left\{\left|E_r(j\omega)\right|^2\right\} = 0 \tag{4}$$

Hence, the optimal value of $H(j\omega)$ is the frequency response of the optimal Wiener filter:

$$H(j\omega) = \frac{S_{vp}(j\omega)}{S_{vv}(j\omega)} \tag{5}$$

where $S_{vv}(j\omega)=E\{[V(j\omega)]^2\}$ is the power spectrum of v, and $S_{vp}(j\omega)=E\{[P(j\omega)V^*(j\omega)]\}$ is the cross power spectrum between v and p. In order to obtain $H(j\omega)$, one must first measure data of input v and output p signals. Once the filter has been determined, it can be used to any form of source disturbance v. To optimally estimate EMI transients p_v, equation (1) should be accompanied with inverse Fourier transform of resulting $P_v(j\omega)$.

3. SOFT SWITCHING INVERTER

The soft switching inverters have less influence on the EMI generation because of lower *dv/dt* and *di/dt*, moreover allow decreasing voltage stress across the power semiconductor switches without deterioration of overall efficiency of converter [9]. In this section is described the parallel quasi resonant dc link voltage inverter (PQRDCLI) [17], as is depicted in Figure 3 and in detailed analysis with gating control procedure described in [4]. This circuit allows zero voltage switching (ZVS) for inverter transistors

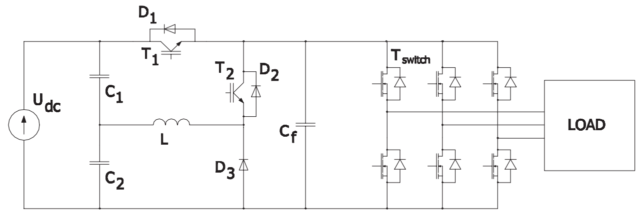

Fig. 3. PQRDCLI circuit topology

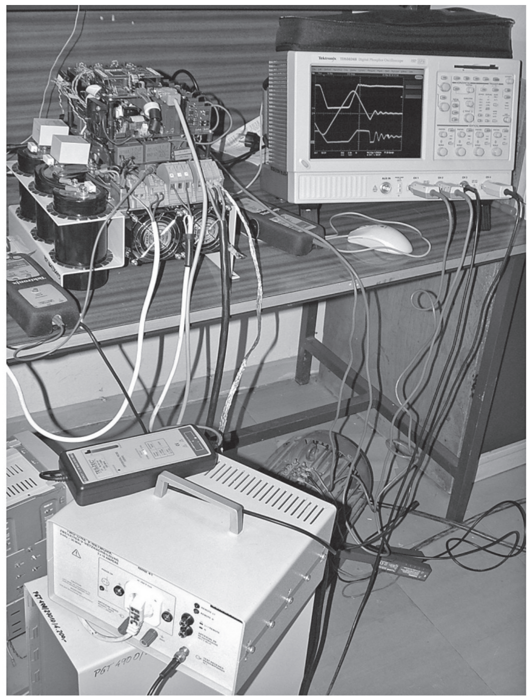

Fig. 4. Laboratory test bench

and also gives ZVS or zero current switching (ZCS) for auxiliary circuit transistors T_1 and T_2. The parallel quasi resonant circuit is located in the dc link of indirect frequency converter. It consists of two input electrolytic capacitors C_1, C_2 connected in series. The inverter is separated from dc voltage source by the bilateral switch based on transistor T_1 with diode D_1.

The capacitors midpoint is connected to the inductor L, to form quasi resonant circuit with the capacitor C_f through auxiliary switching devices: transistor T_2 with diode D_2 or diode D_3.

The every commutation in the inverter is preceded by reloading resonant circuit in order to discharge of the input capacitor C_f. The main source of EMI of the PQRDCLI is changing of the DC link voltage across input inverter capacitor C_f. However, the rise and fall time of this voltage is much lower than in hard switching inverter. Based on the circuit topology, perturbation propagation paths do not change significantly for various inverter conduction states as has been recognized in the case of hard switched inverter.

This phenomenon can be explained by common zero voltage initial conditions (turn-on state) of all inverter switches when the commutation occurs. Therefore, taking into account major differences in propagation paths when voltage across C_f rises up or falls down, two states (N = 2) for the PQRDCLI operation and two states (M = 2) for DC/DC external converter have been distinguished.

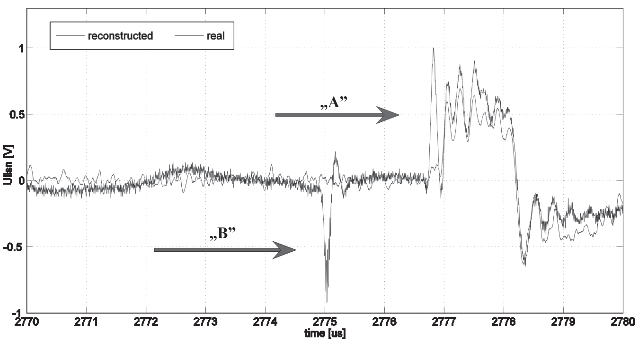

Fig. 5. Comparison of real and estimated LISN-EMI transients („A” — T2 ZCS commutation, „B” — DC/DC converter)

4. EXPERIMENTAL RESULTS

Experimental unit presented in Figure 4 contained the PQRDCLI fed from dc power supply through the LISN (Schaffner NNB41). The prototype inverter was built with Insulated Gate Bipolar Transistors (IGBT). Transistor drivers were supplied from the separate DC/DC converter constituting additional EMI source. Voltage waveforms and perturbations have been registered for different operation conditions using the oscilloscope TDS5034B of Tektronix with voltage differential probes. The sampling frequency was 100 MHz. The symmetrical inverter load was the induction machine (SZJe34a 220/380V 3 kW).

The Wiener filtering method, as described in section II, has been used with data obtained from measurement. In Figure 5 influence of the external DC/DC converter and transistor T2 commutation on total perturbation waveform is shown. These two signals are not correlated with the assigned to the filter dc link voltage disturbance signal; hence the impact of them in reconstructed signal is not observable.

Therefore, adding appropriate number of filters one can separate EMI noise influence from the external DC/DC converter. In Figure 6 with the aid of filter assignments, total LISN perturbations are decomposed among separate sources. The respective signal spectra are depicted in the following Figure 7.

The changing dc link voltage across Cf is the main source of perturbations. Comparing filter frequency response H(jω) for the case, when voltage across C_f rises up or falls down in Figure 8 one can proof differences in propagation paths in the frequency range above 10 MHz. It results from the differences of circuit components states and parameters (e.g. semiconductor capacitances) for these two inverter states. Indeed, the falling time of voltage across the input capacitor is shorter than the rising time. It reflects influence on the perturbation currents distribution, changing of a currents density in the conductors, of electric and magnetic couplings. The perturbation spectra generated by inverter, as in Figure 7b can be equally decomposed into two separate frequency transmittances for each inverter state.

5. CONCLUSIONS

Wiener filtering applied to estimation of the conducted EMI emissions in soft switching inverters confirms to be

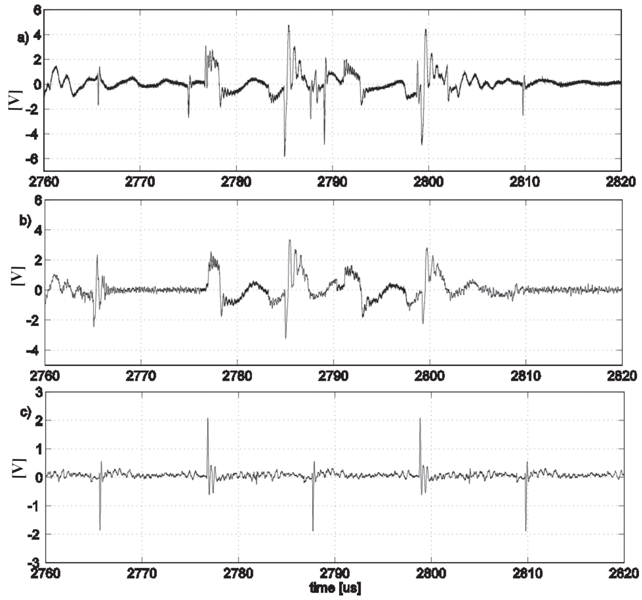

Fig. 6. Estimation and separation of experimental EMI waveforms; a) total LISN-EMI, b) PQRDCL inverter, c) DC/DC external converter estimated contribution

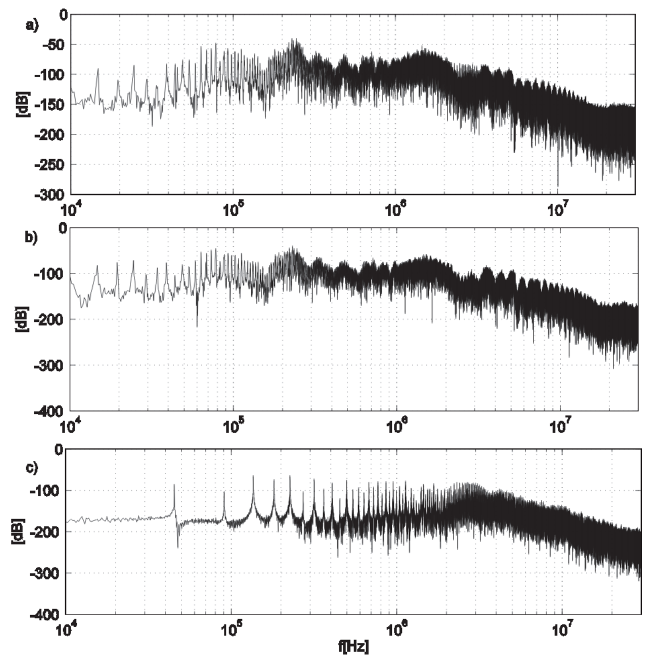

Fig. 7. Estimation and separation of experimental EMI spectra; a) total LISN-EMI spectrum, b) PQRDCL inverter part; c) DC/DC external converter estimated contribution

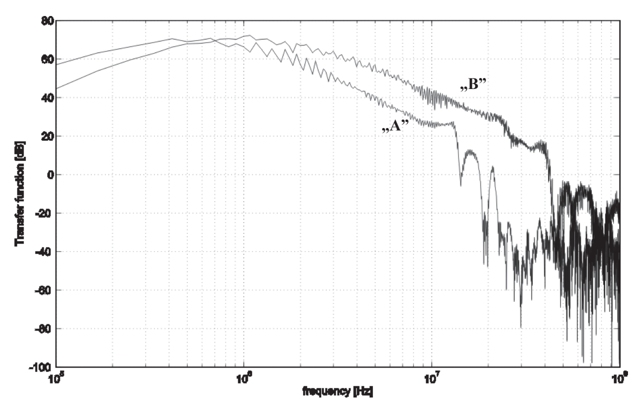

Fig. 8. Comparison of Wiener filters frequency response for rising (marked „A”) and falling (marked „B”) input inverter voltage.

an efficient identification technique as has been previously tested for the case of hard switching inverter and DC/DC boost converter.

The proper selection of different EMI propagation conditions defining minimal number of converter states with its propagation path layout reflects a necessary number of the Wiener filters. Such an estimation structure gives a powerful insight into EMI distribution. Moreover, it enables to decompose the EMI transients indicating its origin sources contribution and evaluating its propagation transfer function.

In the particularly examined method application to the PQRDCLI: two filters for DC link voltage changes and two filters for DC/DC converter operation have proved the efficient EMI estimation.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of J.-L. Schanen and P. Granjon from the Grenoble Institut of Technology for their helpful discussion and initialization of the paper research objectives.

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This work was supported in part by the Polish Committee for Scientific Research under Grant 3 T10A 038 28