Bulletin of the *Transilvania* University of Braşov
CIBv 2015 • Vol. 8 (57) Special Issue No. 1 - 2015

EMI FILTERING OF AIR HANDLING UNITS

M. BUZDUGAN[1] H. BĂLAN[2]

Abstract: *The paper deals with electromagnetic conducted emissions due to brushless direct current motors (BLDC) used in driving air handling units. According to the standards, these emissions have to be cancelled and the most straightforward method is to use passive EMI filters. In the main section the nonideal behavior of passive components use in EMI filters is presented along with their "hidden schematics" in the frequency range of interest.*

Key words: *air handling units (AHU), brushless DC motors (BLDC), electromagnetic interference, EMI filters, spectrum analyzer, line impedance stabilization network (LISN).*

1. Introduction

The energy efficiency of HVAC systems is considered as a vehicle for accomplishing energy savings. Many research efforts related to the modeling and optimization of HVAC systems are reported in the literature.

A typical simple air handling unit (AHU) is illustrated in a simplified schematic diagram (Fig. 1), depicting the two centrifugal fans, the heat exchanger, the heating (+) and the cooling (-) coils and the air flow directions. The supply air is at a specific temperature and flows at a specific rate in order to meet the heating or cooling load and ensure thermal comfort. Outdoor air mixes with the return air, and the mixed air passes through cooling coils, heating coils, and the supply fan. Chilled water in the cooling coils cools the mixed air and hot water or steam in the heating coils heats the mixed air to maintain the desired temperature of the supply [1].

Besides, air handling units are provided with temperature sensors for the return and outside air, dampers for fresh and exhaust air, making sure that there will be airflow only if the fans are running, pressure difference switches that monitor the airflow in the ducts and generates an alarm in case there is a conflict between the fan run status and airflow status. At the same time, air handling units are usually provided with CO_2 and humidity sensors.

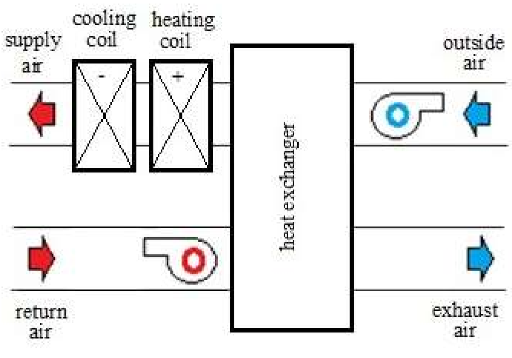

Fig. 1. *Schematic diagram of an air handling unit*

The two centrifugal fans are provided with external rotor brushless DC motor

[1]Faculty of Building Engineering, Technical University of Cluj-Napoca.
[2]Faculty of Electrical Engineering, Technical University of Cluj-Napoca.

(BLDC), an inside-out motor (i.e. the rotor appears outside of the stator).

Let us remind that one of the main advantages of brushless configuration in which the rotor (field) is inside the stator (armature) is simplicity of exiting phase windings and the absence of brushes which reduce motor length. At the same time BLDC motor drives are high efficiency, low maintenance and long life, low noise, control simplicity, low weight, and compact construction.

On the other hand, the main disadvantages of the BLDC motor drives are: high cost of permanent magnet materials, the demagnetization problem, limited extended speed and constant power range (compared to a switched reluctance machine).

Another drawback of the brushless configuration relative to the commutator motor is the increased complexity of the electronic controller and need for shaft position sensing.

A BLDC motor drive is also responsible for generating an additional source of ripple torque, known as commutation torque, taking the form of torque spikes or dips, generated at each discrete time instant when any of the square-wave current excitation waveforms change levels [2-5].

Several companies have developed new series of compact, high-functionality, and highly efficient power semiconductor devices called Smart Power Modules (SPMs). SPM based inverters are nowadays considered an attractive alternative to conventional discrete-based inverters for low power motor drives, specifically for appliances such as air-conditioners, water pumps, compressors, etc.

Power electronics and the lately developed power semiconductor devices offer a plenty of advantages in efficiency and controllability. However, they draw nonsinusoidal currents from AC power systems; these currents react with system impedances creating voltage harmonics and, in some cases, resonances in distribution feeders as power electronic loads continue to proliferate.

Harmonics and resonances create in their turn conducted electromagnetic interference in the radio frequency range, namely from 150 kHz to 30 MHz.

In order to perform the conducted interference tests, a HM 6050-2 LISN and a HM 5014 spectrum analyzer (both manufactured by HAMEG Instruments) have been used. The schematic setup is presented in Fig. 2.

The line impedance simulation network (LISN) is often used as the source impedance for these tests and is closer to the real-world requirements. Basically a LISN is nothing else but a low pass filter, having the ability to block higher frequencies, beyond the mains low voltage. The real intent of the filter is to attenuate conducted emissions of differential and common mode origins from both the device and the line. The two objectives of the LISN are: to present constant impedance (50Ω) between the phase conductor and the neutral conductor, and to prevent external conducted noise on the power system net from contaminating the measurement.

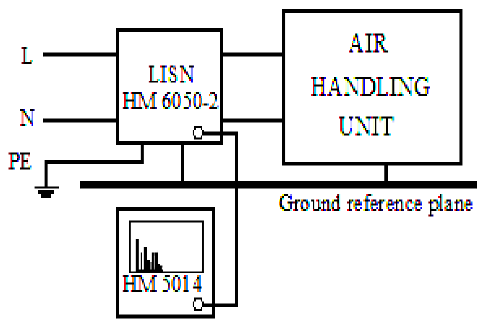

Fig. 2. *The schematic test setup for conducted interference*

Basically spectrum analyzers are not an alternative to a measuring electromagnetic compatibility receiver in a full compliance set-up because of their limited sensitivity and dynamic range, and susceptibility to overload. However, the spectrum display is extremely valuable for confirming the frequencies and nature of offending emissions, as is the ability to narrow-in on a small part of the spectrum. Generally, this includes the amplitude indication in Quasi Peak and Average modes. For the precise evaluation of the signals a marker is provided that will give the readout for amplitude and frequency on-screen.

One can easily observe that both the average and quasi-peak values of electromagnetic interference exceed the limits imposed by the standard EN 55014-1:2006 (+A1+A2) in the range from 150 kHz up to 18.46 MHz (a high quasi-peak value of almost 20.0 dBμV is noticeable around this frequency value), while the average value has more or less the same shape as for a single BLDC drive (see Figs. 3 and 4).

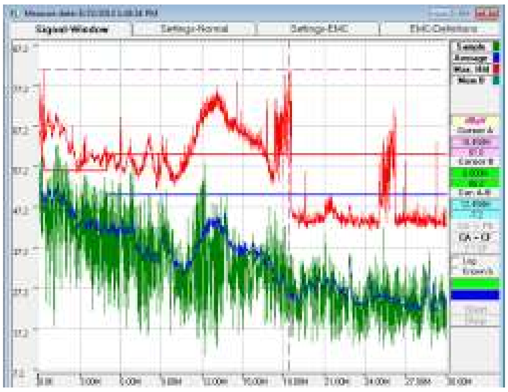

Fig. 3. *Conducted interferences of the AHU in linear scale*

The most frequent method of mitigating these emissions is the EMI (electromagnetic interference) passive filtering.

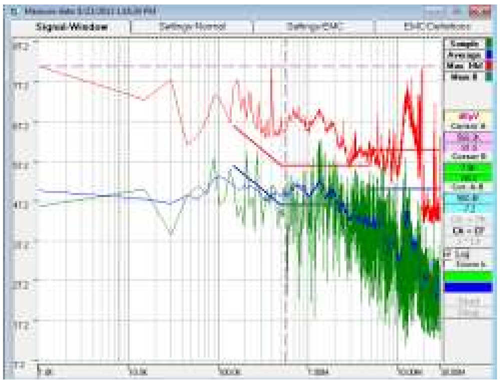

Fig. 4. *Conducted interferences of the AHU in logarithmic scale*

2. EMI Filtering

Standard filters differ greatly from EMI filters. Most EMI filter manufacturers design need only the low-pass filters (all pole networks) for the required EMI attenuation. They rarely build band pass or other conventional filters. The technology used in standard filters is truly different from that used in EMI filters.

The EMI filter design is very loose compared with that used by the standard filter manufacturer. The EMI filter component values are very flexible, so the engineer can use standard values. These filters are adjusted only to meet the required insertion loss specification assuming the rest of the specification is met.

Generally, mains EMI filters carry potentially high currents at dangerously high voltages, so care is essential in their choice. The operating voltage and current ratings of components can be decided once the specification is known. The basic specification should also include mechanical details such as the enclosure size, and the limit of weight. The electrical specification should include the voltage and current rating. In addition the EMC performance and the allowable leakage current should be specified. The electrical specification must also comply with national safety standards.

Filters work on the principal of providing a large discontinuity in the characteristic impedance seen by an unwanted signal. The intention is to reflect most of this unwanted energy back to its source. The remaining energy is expended into the inductors through the resistance of the coil, the core losses (eddy currents and hysteresis) and the equivalent series resistance of the capacitors.

If a filter contains lossy elements, such as a resistor or ferrite component, then the noise energy may be absorbed and dissipated within the filter. If it does not – i.e. if the elements are purely reactive – then the energy is reflected back to its source and must be dissipated elsewhere in the system. This is one of the most important features which distinguish EMI filter design from conventional signal filter design.

Mains filters are tested with a 50Ω source and load impedance because most RF (radio frequency) test equipment have a characteristic impedance of 50Ω.

This allows consistent test results and allows direct comparison between one design and another.

However, because the source and load impedance in practical situations are not generally 50Ω, the attenuation predicted for a design based on this specification is generally optimistic compared with the performance in working equipment.

Currently there are two modes of interfering signals. Common-mode signals which means a current that travels along both mains wires in the same direction and returns through earth or ground. Differential signals have a current that travels along one mains wire and returns along the other; thus the sum of the current carried by the two wires is zero, as is the earth current.

The mains power supply is a differential signal with a low frequency. Since the differential mains supply signal carries high current, the filter inductors must be designed so they do not saturate their magnetic cores.

Most mains filters use common-mode chokes that are wound so that no magnetic flux is produced in the core by a purely differential signal. This is achieved by using an inductor with two windings and arranging for the go and return current to flow through them in opposing directions. Since no magnetic flux is produced, there is no inductive reactance. A common-mode current that flows in the same direction through both supply wires will generate a magnetic flux in the core and will thus have an inductive reactance. The common-mode choke thus appears as having a high series impedance to common-mode signals, but low series impedance to differential signals.

Differential-mode signals are presented with low impedance between the go and return wires by so-called "X capacitors." These X capacitors provide some degree of attenuation to the unwanted signals, but if high levels of attenuation are required, differential-mode chokes may have to be used.

Because they must handle mains current these inductors tend to have low values of differential inductance and are physically quite large.

Most mains filters use so-called “Y capacitors” connected between earth and the go and return wires. These Y capacitors typically have values of around a few nanofarads (larger values would exceed earth leakage limits imposed by the relevant safety authorities).

Typical commercial EMI filters (type Π) are balanced. Although they seem mainly common mode in appearance, they include components to block both common mode and differential mode components. The basic topology of an EMI filter is presented in Fig. 5.

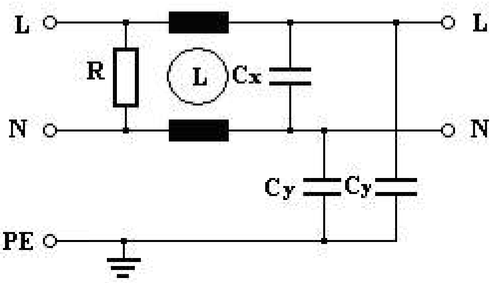

Fig. 5. *Typical topology of mains filter*

The EMI choke is the main part of an EMI filter. Generally they are manufactured using ferrites, low-density ceramic materials with composition Fe_2O_3XO, where X is a different metal (cobalt, nickel, zinc, manganese, etc.), which has reduced electrical conductivity and therefore very low eddy currents.

There are several types of ferrite devices: toroid, chokes, single or multi-hole beads, tubular or split, spherical, etc. They can be slipped over wires and cables (generally split), or wires and component leads can be passed through the beads.

The concept of complex magnetic permeability permits the formal separation of the cores into two components: $\underline{\mu} = \mu' - j \cdot \mu''$. Its real part, denoted by μ', is related to the ability of the material to concentrate magnetic flux, an ideal inductive component (without losses) $X = \omega \cdot L_0 \cdot \mu'$, where L_0 represents the air coil inductance (without magnetic core).

The imaginary part, μ'', is related to the dissipation of magnetic energy, as it flows through the material, a resistive component, frequency dependent, which quantifies the losses in the material of the magnetic core $R = \omega \cdot L_0 \cdot \mu''$. The impedance $|\underline{Z}| = \sqrt{R^2 + X^2}$ and the loss tangent angle $(\tan\delta = \mu''/\mu')$ are both function of frequency.

This formal approach may represent a basic characteristic that allows discriminating efficiently between inductors and ferrites [6].

Combining a tracking generator and a spectrum analyzer is useful setup for checking the HF response of circuit networks, including the characteristics of EMI filters.

3. The Nonideal Behavior of Lumped Components

It is important to keep in mind that if a postulated model fails to predict experimentally observed phenomena, it is useless [7]; that is why the focus of this section will be on the nonideal behavior of passive components involved in EMI filters which implies a “hidden schematics”.

- **The Resistor**

Fig. 6 presents the model suitable in a large range of frequency of a resistor having the resistance R=1 MΩ, which has the parasitic values of C_p=1,2pF and L_t=10nH.

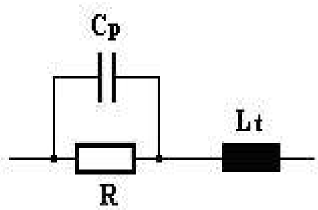

Fig. 6. *Equivalent schematics of a high frequency resistor*

The frequency characteristics of the behavior of the lumped resistor (Fig. 6) are simulated using MATLAB, both in amplitude and phase (Fig. 7).

One can observe that with the increase of the frequency, the influence of the parasitic elements become dominant.

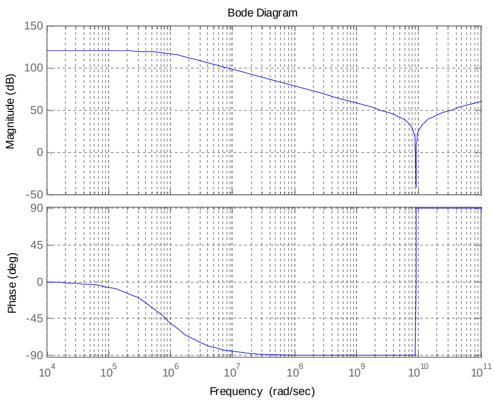

Fig. 7. *Bode diagram of the behavior of a high frequency resistor*

• The Capacitor

The parasitic components associated with the capacitor produce important changes in its performances. The equivalent circuit of a capacitor valuable in a large range of frequency consists in a combination of its intrinsic capacity, of its terminal inductances and of its resistors due to the dielectric losses and the armature resistances.

Fig. 8 depicts the model suitable in a large frequency range of a ceramic capacitor of C=100 nF, L_t=350 μH and R=0,085 Ω, along with its frequency characteristics (Fig. 9).

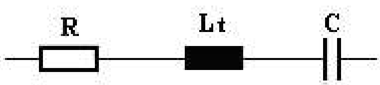

Fig. 8. *Equivalent schematics of a high frequency capacitor*

One can observe that the value of the impedance of the capacitor is decreasing inversely proportional with the frequency till the proper frequency of resonance

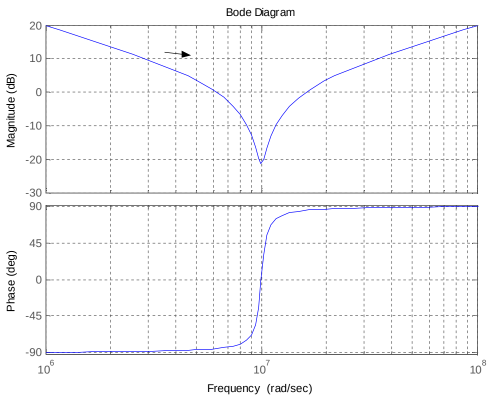

Fig. 9. *Bode diagram of the behavior of a high frequency capacitor*

$$f_0 = \frac{1}{2 \cdot \pi \sqrt{L_t \cdot C}} . \qquad (1)$$

Its value is variable depending on the constructive type of the capacitor (from a few kHz for electrolytic capacitors to several MHz for surface mounted capacitors).

• The Inductor

The equivalent circuit of an inductance, depicted in Fig. 10, consists besides the intrinsic inductance *L*, in a parasitic capacitance C_p and in the series and parallel resistors which are modeling the magnetic core. The values of the inductance are Lt=50 μH, Rs=1 Ω, Rp=2 kΩ şi Cp=1.5 pF. Fig. 11 depicts the frequency characteristics of the inductor.

• The Common Mode Choke

In circuits' theory, the electromagnetic interference issues were always a real concern. In most systems the common mode perturbations represent the principal actors in generating interference; that is why a distinction between the differential and the common mode perturbations has to be made.

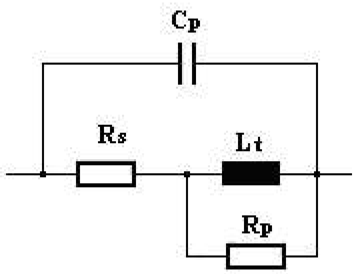

Fig. 10. *Equivalent schematics of a high frequency inductor*

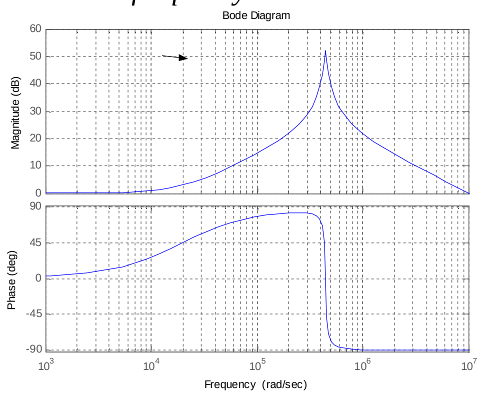

Fig. 11. *Bode diagram of the behavior of a high frequency inductor*

Fig. 12 presents an equipment supplied by a low voltage grid, the last one being under the influence of a radiofrequency field.

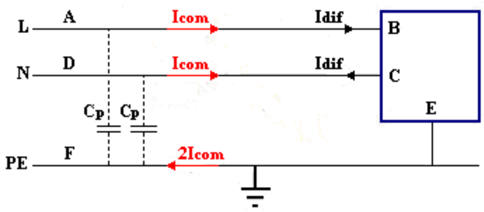

Fig. 12. *Equipment affected by emissions on the low voltage grid*

One can easily see that three current loops may be defined.

Loop 1: ABCDA formed by the supply wire *L*, the neutral wire *N* and the equipment through which a differential current I_{dif} is circulating.

Loop 2: ABEFA formed by the supply wire *L*, the protective earth *PE* and the equipment through which a common mode I_{com} current is circulating.

Loop 3: DCEFD formed by the neutral wire *N*, the protective earth *PE* and the equipment through which a common mode I_{com} current is circulating.

As Fig. 12 suggests, the common mode currents are always trying to close through parasitic capacities, common mode perturbations having always greater values and more insidious effects than the differential ones, due to the fact that the common mode loops are always larger than the differential mode ones. Common mode loops appear due to the asymmetries and non-uniformities of the circuits.

Loop 1 (ABCDA) shows that the differential mode perturbations produce a voltage at the input of the circuit, which in the most situations is benign whether it does not overcome certain standard limits.

Examination of loops 2 (ABEFA) and 3 (DCEFD) shows that common mode perturbations are seeking for a closing path to the ground. Whenever a local closing path of low impedance through the ground is not available, common mode currents will circulate through the parasitic distributed capacities.

The common mode choke presents a high value of the impedance for common mode signals and a low value of the impedance for the differential mode signals. It is built similarly to an inductor, but due to its special winding it is a so called a "two-wire product".

Fig. 13 depicts the equivalent circuit of a common mode choke suitable in the frequency range of interest for electromagnetic compatibility, where L_s is the stray inductivity of the choke, C_{ii} the inter-winding capacity and C_{is} the inter-wire, R_i the winding resistance and R_{cm} the magnetic core losses, depending on the magnetic material, frequency and the input/output voltage.

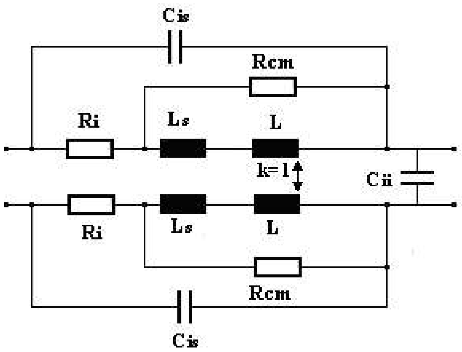

Fig. 13. *Common mode choke*

Due to the stray inductances, modeled as longitudinal inductances, the common mode chokes, basically intended to cancel common mode perturbations, succeed to cancel also the differential mode ones.

According to the model of the components suitable in a large frequency range, the EMI filter presented in Fig. 5 can be rewrote in Fig. 14.

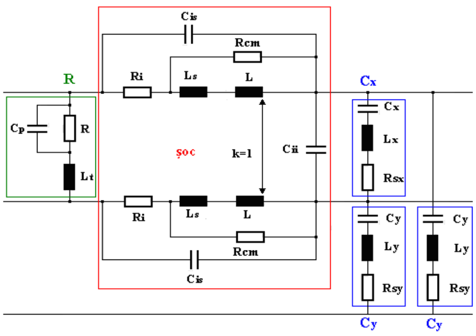

Fig. 14. *Equivalent schematics of an EMI filtering cell*

4. Conclusions and Further Work

The paper deals with the electromagnetic conducted emissions and their mitigation using input EMI filters.

The design philosophy of EMI filters must take into account of the "hidden schematics" of the components all over the frequency spectrum of conducted emissions, i.e. from 150 kHz to 30 MHz.

Furthermore the point is to set a design and a test methodology for EMI filters using the well-known equipment, namely a tracking generator and a spectrum analyzer.

References

1. Buzdugan, M. I., Bălan, H. *Testing EMC performances of Adjustable Speed Drives*. In Proceedings of ICREPQ'15, La Coruña (Spain), 25th to 27th March, 2015.
2. Kim, I., Nakazawa, N., Kim, S., Park, C., Yu, C. "*Compensation of torque ripple in high performance BLDC motor drives*", Control Engineering Practice, 18, Pages 1166-1172, 2010.
3. Sathyan, A., Krishnamurthy, M., Milivojevic, N., Emadi, A. "*A low- cost digital control scheme for Brushless DC motor drives in domestic applications*", IEMDC'09, Pages 76-82, 3-6 May 2009.
4. Baszynski, M.; Pirog, S. "*A Novel Speed Measurement Method for a High-Speed BLDC Motor Based on the Signals From the Rotor Position Sensor*", Industrial Informatics, IEEE Transactions on, Pages: 84 - 91 Volume: 10, Issue: 1, Feb. 2014.
5. Ransara, H.K.S., Madawala, U.K. „*A low cost brushless DC motor drive*", Industrial Electronics and Applications (ICIEA), 2011 6th IEEE Conference, 21-23 June 2011, Pages: 2723 – 2728
6. Gerfer, A, Ralf B, Zenker, H, (2002). *Trilogy of Inductors*, Swiridoff Verlag.
7. Clayton, R. *Introduction to electromagnetic compatibility*, John Wiley & Sons, 2006, ISBN-13: 978-0-471-75500-5.