EMI Filter Design and Stability Assessment of DC Voltage Distribution based on Switching Converters.

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Abstract

The design of DC power distribution for LHC front-end electronics imposes new challenges. Some CMS sub-detectors have proposed to use a DC-power distribution based on DC-DC power switching converters located near to the front-end electronics.

DC-DC converters operate as a constant power load. They exhibit at the input terminals dynamic negative impedance at low frequencies that can generate interactions between switching regulators and other parts of the input system resulting in instabilities. In addition, switching converters generate interference at both input and output terminals that can compromise the operation of the front-end electronics and neighbour systems. Appropriated level of filtering is necessary to reduce this interference.

This paper addresses the instability problem and presents methods of modelling and simulation to assess the system stability and performance. The paper, also, addresses the design of input and output filters to reduce the interference and achieve the performance required.

I. INTRODUCTION

DC power distribution has been used by aerospace and telecommunication industries [1][2]. This topology distributes a high voltage (HV) and converts it to low voltage (LV) either locally or near the electronics equipment. In high-energy physics (HEP), some CMS and Atlas sub-detectors [3][4] have proposed similar topologies to power-up the front-end electronics. In such proposals, the AC mains is rectified in the control room and DC high voltage (200-300V) is distributed a distance about 120-150 mts. to the periphery of the detector. At that location, DC-DC converters transform with high efficiency the HV into the LV required by the front-end (FE) electronics. Those converters are located about 10-20 mts. from the front-end electronics due to the intense magnetic field that exists inside the detector.

For LHC experiments, converters have to operate reliably under high-energy neutron radiation and fringe magnetic field. Converters have to present high efficiency, galvanic isolation between input and output, and couple low amount of noise to the surrounding electronic equipment. Intrinsically switching power converters generate a noise level that, in general, is not compatible with the sensitive electronics used in HEP experiments. Input and output filters are necessary to attenuate the level of noise coupled by conduction and radiation through the cables. Also, interactions among converters with input filters and distribution lines can deteriorate the performance or induce instabilities in the system because the converter operate as a constant power load.

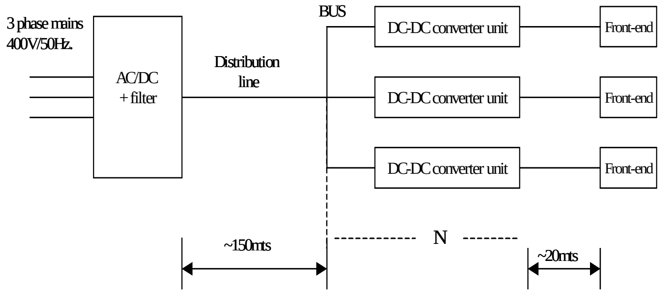


Figure 1: DC distribution system

In this paper, analysis and design approaches for the system are presented. Section II presents an overall view of the problem, section III resumes the standards related with conducted interference emissions, section IV describes the design of the system considering stability issues, while section V addresses the design of the input filter to reduce conductive interference.

II. PRESENTATION OF THE PROBLEM.

All switching converters generate and emit high frequency noise. The emission can be coupled to the sensitive FE electronics and neighbour subsystem electronics by conduction and/or radiation. This noise can interfere with the sensitive FE electronics and cause malfunction. The frequency range of the electromagnetic interference (EMI) spectrum generated by power electronics equipment can extend up to 1GHz.

For conducted EMI there are two principal modes of propagation, *differential* (DM) and *common mode* (CM). The propagation of the differential mode EMI takes place between conductor pairs, which form a conventional return circuit (e.g. negative/positive conductors, line phase/neutral conductors). The DM EMI is the direct result of the fundamental operation of the switching converter. The propagation of the common mode EMI takes place between a group of conductors and either ground or another group of conductors. The path for the CM EMI often includes parasitic capacitive or inductive coupling. The origin of the CM EMI is either magnetic or electric. CM EMI is electrically generated when a circuit with large *dv/dt* has a significant parasitic capacitance to ground. Magnetically generated CM EMI appears when a circuit loop with large *di/dt* in it has significant mutual coupling to a group of nearby conductors. Also, it is important to mention there is an important energy exchange between modes. This effect is known differential-common mode conversion.

In switching power converters, the same fundamental mechanisms that are responsible for conducted EMI can also generate radiated EMI. Metal cases around the converter tend to attenuate the internal high frequency electromagnetic fields. Input and output cables or improperly grounded apparatus can still lead to substantial radiation.

Additional filtering is necessary at the input and output of converters to reduce the conducted noise. Filters have to provide attenuation in a wide range of frequencies between the switching frequency and up to 30-50 MHz. To fulfil these requirements, cascade of low-pass filters attenuating both low and high frequency ranges are used. Figure 2 depicts the DC-DC converter unit composed by two commercial VICOR converters [5]. Low-pass filters attenuating the high frequency (HF) range are included at the output of each converter to reduce both differential and common mode noise conducted to the distribution cable located inside the detector. A HF low-pass filter, common to both VICOR converters, is present at the input. This filter is in cascade with the internal input filter of the converters and the set has to be designed to provide noise attenuation in a wide range of frequencies. The HF filter is designed to attenuate both DM and CM in high frequency while the internal filter is tuned to reduce DM low frequency components. These filters can interact adversely with the converter at low frequency, resulting in severe performance degradation or even instability.

Power converters, operating with tight close-loop regulation of the output voltage, present negative input impedance in a range of frequencies where the feedback is effective. This negative impedance interacts with the input filter, input distribution cables, and other converters connected to the same distribution line, giving place to instabilities or deterioration of the dynamic performance. Input EMI filters have to be properly designed to avoid this problem and also to provide the adequate attenuation in a wide frequency range.

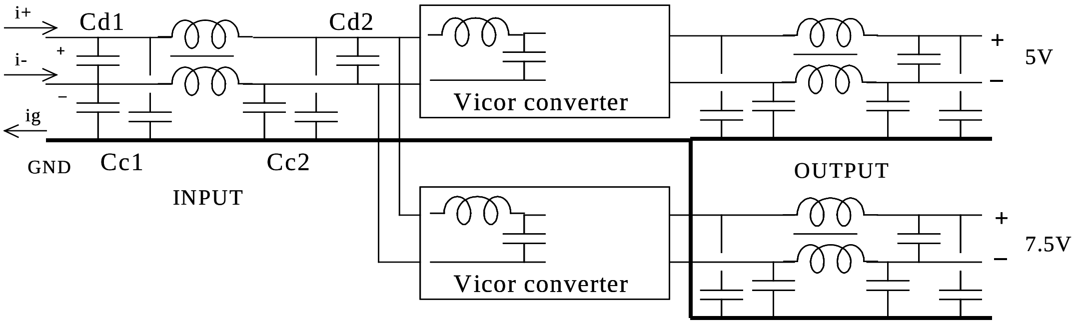


Figure 2: Scheme of the DC-DC converter unit

III. EMI REGULATIONS AND STANDARDS.

Regulation about EMIs began in early days of electronics. Today exists a vast collection of standards covering equipment in industry, military, commerce and residence. In Europe, limits for high frequency interference are specified either by generic standards (EN50081-1 for residential, commercial, and light industry, EN50081-2 for industrial environment) or by standards for specific product families (EN55014 for household appliances, EN55022 for information technology equipment, or EN55011 for radio-frequency equipment) for industrial, medical and scientific applications. In USA, the Federal Communication Commission (FCC) issues electromagnetic compatibility (EMC) standards, with different limits for class A and class B devices. Both FCC standards are defined for digital equipment marketed for use in commerce, industry or business environment (class A) and a residential environment (class B). Typically, European standards for conducted high frequency emissions are specified in the frequency range from 150KHz to 30MHz, and in the United States form 450KHz to 30MHz. The allowed conduction emission levels are between 46 dBuV and 79 dBuV. These limits are imposed to the input cord of the equipment under test and the compliance is verified inserting a line impedance stabilization network (LISN) in series with the unit's AC power cord. The measured values correspond to the voltage level registered across any input wire when it is terminated at the source by 50 ohms impedance to ground (LISN termination). The standards do not distinguish between CM and DM coupling mechanism. Military standards for conducted emissions (MIL-STD-461 CE-03) differ from the other standards. It does not use the LISN, it directly measures the emission current using a current probe. Also it specifies that conducted emissions have to be measured on other cables in addition to the power cord. The range of frequencies covered is between 14 KHz and 50 MHz and the emission level are between 86dBuA and 20dBuA [6]. To compare these standards we should normalize the measurement to dBuA or dBuV assuming a normalized impedance of 50 ohms. Figure 2 compares three standards normalized in dBuV.

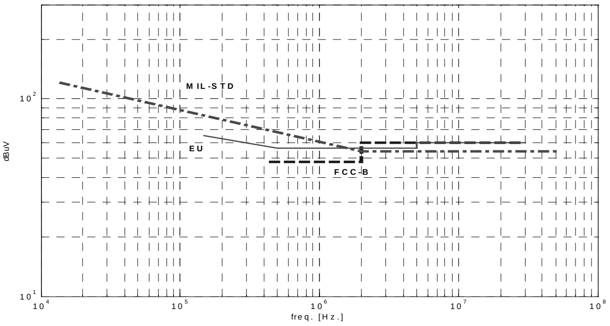


Figure 3: Conductive EMI standards [Normalized to 50 ohms]

In HEP community there has not been a systematic approach to define both emission and susceptibility policies of EMI signals [7]. Some experiments have written policies considering issues about grounding and shielding. Also, they have included as a rule to purchase equipment that complain with either European or American standards, but there is no quantitative limit in the emission level of power distribution and signal cables routed inside the detectors. CMS is trying to define limits for both emission and susceptibility of the electronic equipment to be installed in the experiment. They will be based on measurements of prototypes and analysis of the cross effect among radiator-receiver electronics. The future standards applied to power supply distributions will be based on direct measurement of the noise current level as required by the military standard and the level imposed will be close to that required by commercial standards. Also it will address some limitations on the common mode current levels to avoid cross-talk among equipments due to ground currents.

IV. NEGATIVE INPUT IMPEDANCE OF DC-DC CONVERTERS

DC-DC switching converters with tight output voltage regulation operate as constant power loads. The instantaneous value of the input impedance is positive but the incremental or dynamic impedance is negative. Due to this negative input impedance characteristic interaction among switching converters and another part of the system connected to the same distribution bus may result in system instability.

To analyse the behaviour of the converter and the interaction with the rest of the system a reduced model of the system is necessary. The reduced model has to represent the behaviour of the system at low frequency in the range between DC and frequencies near the bandwidth of the power converter. In this frequency range, the power converter behaves at the input as a constant power load in cascade with the input filter. The rest of the system can be modelled as follows: the distribution line can be approximated by a lumped inductance in series with a resistor and the HF filter can be reduced to the DM capacitors.

To present a qualitative behaviour of the converter at the input terminals, let us consider first the simple equivalent circuit depicted in figure 3. It represents a VICOR converter connected to a primary source with short leads. Using as state variables the inductor current *il* and the capacitor voltage *vc*, the state equation is:

$$C\,\frac{dv_c}{dt} = i_l - \frac{P_c}{v_c}$$
$$L\,\frac{di_l}{dt} = E - i_l.r_l - v_c \qquad (1)$$

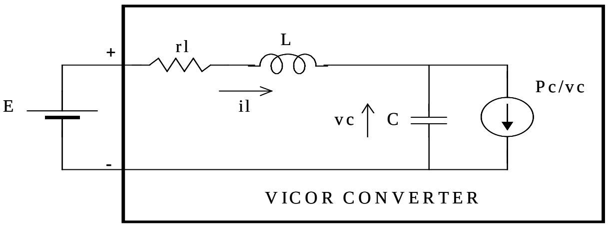
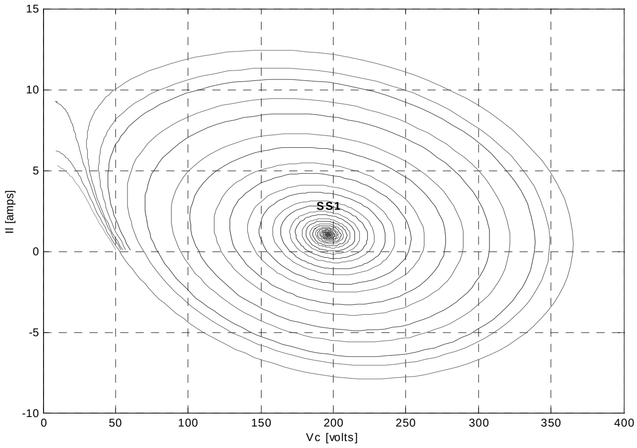


Figure 4: Model at the input terminals of the DC-DC converter.

This equation has two real valued equilibrium points if the condition $rl < E^2 / (4.P_c)$ is verified. Figure 4 shows the state portrait of eqn. 1. This picture shows there is a region of convergence around the equilibrium point SS1 if it is stable. The stability of this point is defined by the condition $rl > (P_c.L)/(C.v_c^2)$, where v_c is the capacitor voltage at equilibrium. The equilibrium point SS2 is not depicted in the figure, but it is located at low voltage and high current and, in general, is unstable. In the same plot, it is possible to see an unstable region near the origin of coordinates. Transient operating points falling into this region does not converge to the equilibrium point SS1 but escape at *vc* = 0.

Figure 5: Phase portrait of equation 1



To limit the operating region of the converter to the region of convergence of the stable equilibrium point, converters either include some limits into the dynamic range of the control circuit or disable the operation of the power transistor for low values of the input voltage. VICOR converters disable the unit if the input voltage value is outside of a voltage band around the equilibrium point (e.g. Vnom=300V, Vin=180-375V). In this case, the converter can still be modelled by equation 1 but including the condition, $Pc \neq 0$ if *vc* is between 180V and 375V, and $Pc = 0$ if *vc* is outside of this region.

As conclusion from this brief analysis, to analyse the stability of the system, the converter model can be simplified by a linearized model around the equilibrium point (small-signal analysis). The region of convergence can be estimated analytically or by simulation using a non-linear model of the converter. The linearized model of the converter at input terminal is characterized by a negative resistance of magnitude $r_n = -v_n / i_n$, where the v_n is the DC input voltage and i_n is the DC input current. This current depends of the load of the power converter and r_n can take different values according to the operating conditions.

Let us consider now the DC power distribution system composed by one AC/DC converter, a distribution line of 150 mts and *N* converter units connected to the end-point, as it was depicted in figure 1. Each DC-DC converter unit is composed by 2 VICOR converters, connected in parallel at the input. Only one input HF filter is used per unit as it was shown in figure 2. At the distribution bus, the system can be represented by the simplified block diagram showed in figure 6. The source sub-system contains the impedance of the AC mains, the AC/DC converter and the HV distribution cable. The load sub-system is composed by *N* DC-DC converter units. The source sub-system is stable when loaded by a resistor. Each DC-DC converter unit is stable if connected directly to a power supply.

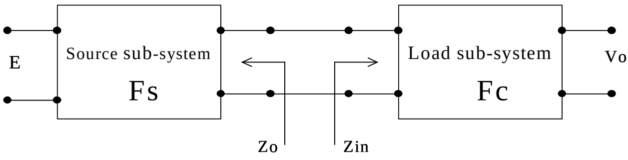


Figure 6: Simplified block diagram

Assuming the source sub-system has an input/output transference Fs and each DC-DC converter a transference Fc, the overall transference between any output voltage and input voltage is giving by.

$$\frac{v_{on}}{E} = \frac{Fs\ .\ Fc}{1+\frac{Zo}{Zin}} = \frac{Fs\ .\ Fc}{1+Tm}$$

where *Zo* is the output impedance of the source sub-system and *Zin* is the input impedance of the load sub-system . Due to both *Fc* and *Fs* are stable transference functions; the stability of the system is defined by the term (*1/1+Tm*) that represents the loading effect between the source and load sub-systems.

If |*Zin*| >> |*Zo*| for all frequencies, the loading effect is negligible. This condition can be difficult to achieve in all the frequency range. This rule prevents any noticeable interaction between source and load sub-systems and may be overly conservative. If |*Zo*| is larger than |*Zin*| a considerable loading effect exists. It does not necessarily imply a stability problem. In this case, either the Nyquist criterion or Bode based analysis can be applied to the gain *Tm* to determine the system stability [8][9].

Figure 7, in the upper plot, shows the Bode plot of the output impedance of the source sub-system and the input impedance of the load sub-system for different capacitance $C_D = C_{D1} + C_{D2}$ (fig.2). This capacitance is included to improve the LF noise filtering and improve the stability in the high frequency region (around point B). In that area, fig. 7 shows that T_m is equal to one and the phase is near 180°. Plots in figure 7 depict the load impedance for only one DC-DC converter unit connected to the bus. For increasing number of converters connected to the bus, the input impedance Z_{in} decreases, and the stability of the system becomes critical at low frequency (point A). At this frequency, there exists interaction between the AC/DC converter filter and the negative impedance of the DC-DC converters. In this case, to improve the stability margin is necessary to increase the damping of the AC/DC converter.

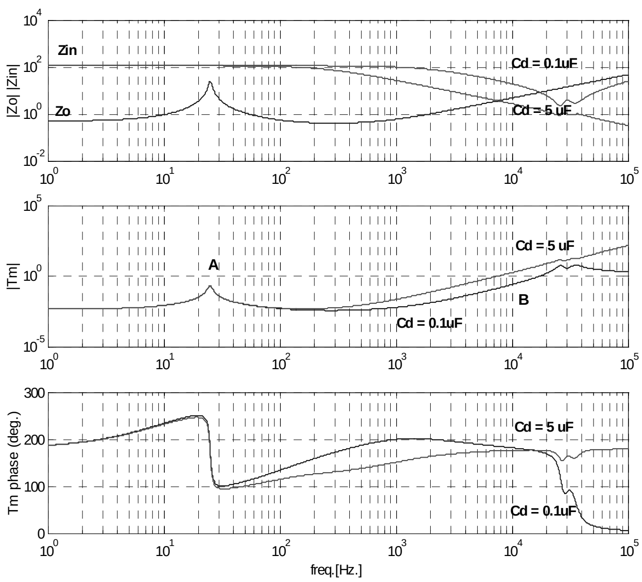


Figure 7: Bode Plot of **Tm**

V. CONDUCTIVE EMI INPUT FILTER

The noise generated by DC-DC converters depends strongly on the topology of the converter, layout design, parasitic elements, etc. To prevent EMI entering to the distribution cables, usually passive filters are inserted between the converter and the lines.

Filters can be considered as multi-port networks, where the input currents or output currents are linked by the condition $i_g = i_+ - i_-$ (figure 2), assuming there is not radiation in the frequency range of interest. For analysis and design those variable are decomposed into two orthogonal components the differential and the common mode components. These variables are defined as;

$$i_{DM} = \frac{i_+ - i_-}{2} \qquad i_{CM} = \frac{i_+ + i_-}{2}$$

The main consideration in the filter designing is to provide adequate attenuation to both EMI signal components using the smallest filter circuit. Additional important considerations are the filter damping and parasitic elements of filter components.

The methodology followed in designing both the input and output filters consisted in measuring the conducted EMI signal generated by the power converter at both the input and output, estimating the adequate attenuation to satisfy some standard and defining the filter attenuation or component values by simulation. Several measurements using a current transformer and a spectrum analyser in peak-mode have been performed on the input and output cables of vicor converters. Input currents were registered for individual units and also for both units connected in parallel at the input. Representative spectrums normalized to 50 ohms are depicted in figure 8. The upper plot shows the current noise of the positive input while the lower one, the input common mode current of the Vicor converter V300B12C250AL operating at *Vin=200V, Vout = 7.5V* and *Iout = 20A.*

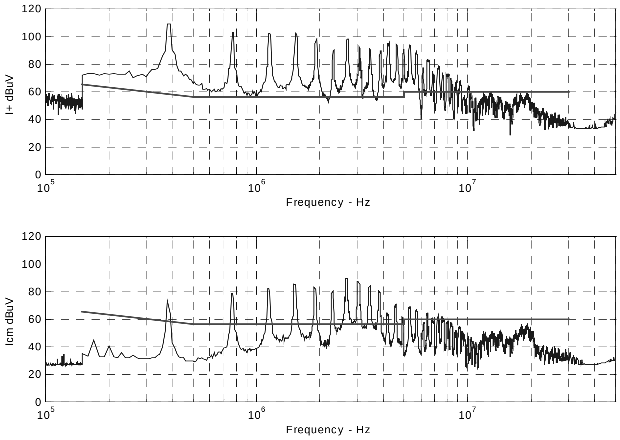


Figure 8: Current noise at input of the DC-DC converter

From these plots it is possible to understand the dominant component at low frequency (up to 2MHz.) is the differential mode component, while in high frequency both differential and common mode components have similar magnitude. Assuming the system has to complain with the European norm EU55022 (fig. 3), the attenuation required in the filter can be estimated from figure 8. It is necessary attenuations greater than 60dB at low frequencies for DM and noise reductions greater than 40dB in high frequency range for both DM and CM components. It is interesting to point out if a simple DM filter is used to attenuate the noise spectrum depicted in fig. 8, upper plot, the result after filtering will be similar to the noise spectrum depicted in the lower plot. The common mode components will remain unaffected and the system will not comply the standard.

There exists a vast variety of commercial high frequency EMI filters. Manufactures specify the insertion loss of these filters for DM and CM components covering the frequency range up to 30MHz. This information allows understanding the effect of parasitic elements in the attenuation reduction. It also allows defining simulation models to estimate the attenuation when the filter operates under different load conditions. Figure 9 shows the current noise after a HF filter and C_D=5uF is included at the input of the DC-DC converter unit. This plot is based on an estimation of the filter attenuation calculated by simulation.

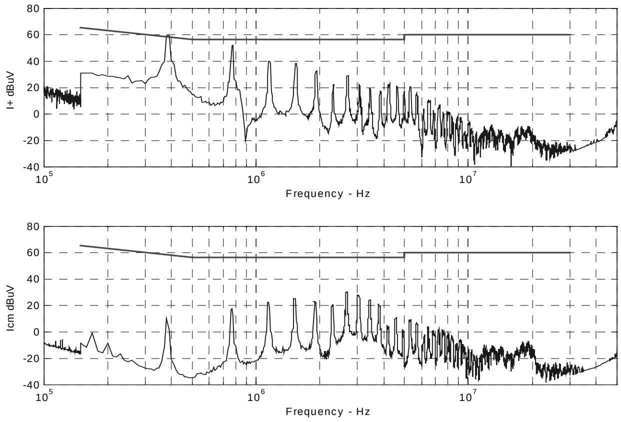


Figure 9: Current noise at the input after filtering

VI. CONCLUSIONS

Guidelines to design the EMI filters taking into account the level of attenuation required and the stability of the overall system have been presented. The design is based on model simulation of the converter, filter and measurements of the noise currents.

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