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Published in:
Proc. 10th International Symposium on High Voltage Engineering, Volume 6, Montreal, Quebec, Canada, 25-29 August 1997

Published: 01/01/1997

Document Version
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Link to publication

Citation for published version (APA):
EMC Analysis of Voltage Measurement Systems in High Power Laboratory

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Abstract
Measuring systems for voltages and currents in High Power Testing Labs are subject to large disturbances at power and at higher frequencies produced by the test setup. Several coupling paths for interference are analyzed to find appropriate measures for each path. The results can be generally applied to other voltage measuring systems.

1. Introduction
On request of KEMA High Power Laboratory (KHPL), we analyzed the EMC aspects of a voltage measuring system which consists of mixed R-C dividers installed in the 3 phases of the power supply. The existing system was of high EMC quality; nevertheless improvements could be recommended which were tested in the High-Voltage Laboratory at Eindhoven University. The mobile voltage dividers at KHPL could be adapted similarly.

![Diagram](image)

Fig. 1. Sketch of a voltage measuring system in a high-power laboratory, with three current loops indicated.

Three current loops are relevant for the voltage measuring system of Fig. 1:

a) the primary loop formed by the power source and the equipment under test (EUT). The high-voltage (HV) divider is connected close to the EUT.

b) the ground loop formed by the shield of the measuring cable grounded at both the low-voltage (LV) arm of the divider and at the measuring equipment.

c) the signal loop which transports the signal across the LV arm to the measuring equipment.

Loop a. Faraday's law states that a voltage between two points can be determined only if the path between the two points is also given. For transmission line a, a unique voltage can be defined in a plane perpendicular to the line. Consequently, the LV arm of the HV divider should be grounded under the position where the HV arm is connected. A ground connection of the divider LV arm to some far away 'reference' extends the measuring loop; magnetic flux variations and currents through distributed resistances may then contribute to the measured voltage.

Certainly at fast switching events, adjacent circuits may couple to the supply line of interest via stray capacitance and mutual inductance. This may cause a legitimate voltage to appear over the divider which the measuring system should faithfully reproduce. In addition, the distributed capacitance between adjacent circuits and the large HV arm ($C_s$ in Fig. 1) is of the order 1 - 10 pF and cannot be neglected [1]; the resulting interference voltage can be minimized by shielding, or by proper placement of the divider, or by proper design of the HV arm.

Loop b. A long cable connects the divider to the registration equipment in the control room (CR). The shield of the cable and the grounding system form a large loop, the 'common mode' (CM) loop in EMC terminology. If the CM loop is interrupted near the CR (e.g. at $A$ in Fig. 1), switching phenomena or fault conditions cause large voltages over the interruption. In the presence of these large CM voltages extensive precautions - floating electronics or optical links - are necessary to record the voltage over $Z_3$.

A more reliable solution is to prevent any CM voltage to appear in the CR. To this end, the signal cable shield is also grounded near the measuring equipment. A current $I_{CM}$ then flows in the CM loop, also at power frequency.
In order to protect the equipment, \( I_{CM} \) should be rerouted around the equipment, ideally by an EMC cabinet [2]. All cables for signal (s) and power (p) enter the cabinet via a single metal panel in Fig. 2. All cable shields are connected to that panel; other cable leads, e.g. for power, pass their CM current to the panel through filters (F); the safety ground (g) is also connected to the panel. The CM currents through all cables cross over at the outside of the cabinet and no CM current flows towards the equipment. This CM current routing is often more important than the shielding provided by the cabinet.

In an earlier study [3] we advised KHPL to transform the control room into a large EMC cabinet.

Loop c is the usual signal circuit or 'differential mode' (DM) loop, comprising the LV arm of the divider, the inner conductor of the signal cable with the shield as signal return, the termination in the CR and the measuring equipment. The disturbance coupling between the DM loop c) and the current \( I_{CM} \) in loop b) depends on the transfer impedance \( Z_{LC}^{'1e} \) (per meter) of the cable and on the termination of the cable at both ends. We express this coupling in an overall transfer impedance \( Z_1 \), the disturbance \( v_m \) due to \( I_{CM} \). 

2. Short cable model of disturbance coupling

In Fig. 3I the HV source \( V_{HV} \) is measured by a divider \((Z_1 > Z_2)\), which can be represented by its Thevenin equivalent at the cable input in the DM loop. The disturbance voltage \( I_{CM} Z_{LC}^{'e} \) is distributed over the length \( \ell \) of the cable. For wavelengths \( \lambda \) long compared to \( \ell \), the overall \( Z_1 \) can be split in two parts, \( Z_{11} \) and \( Z_{12} \): For a very short cable \( I_{CM} Z_{LC}^{'e} \ell \) can be localized in series with the cable shield, e.g. at A in Fig. 3I. The interference to signal ratio (ISR) over \( Z_3 \) due to \( Z_{11} \) is then

\[
\frac{I_{CM} Z_{11}}{V_{HV}} = \frac{I_{CM} Z_{11}^{'e} \ell Z_{11} + Z_2}{V_{HV}} Z_2
\]

\( Z_{11} \) is reduced when \( Z_2 \) increases. For a longer cable, but still \( \ell < \lambda \), a second effect sets in. The distributed voltage \( I_{CM} Z_{LC}^{'e} \) causes a current \( I_c \) through the distributed capacitance \( C_{LC}^{'e} \ell \) of the cable; \( I_c \) is shared by the impedances at both ends of the cable in parallel. The resulting part of the voltage over \( Z_3 \) becomes

\[
\frac{I_{CM} Z_{12}}{V_{HV}} = \frac{I_{CM} Z_{12}^{'e} \ell \omega C_{LC}^{'e} \ell Z_2}{V_{HV}} Z_2
\]

provided that \( |\omega C_{LC}^{'e} \ell Z_2| < 1 \), where \( Z_2 \) is the smaller of \( Z_2 \) and \( Z_3 \). This \( Z_{12}^{'e} \)-contribution to \( Z_1 \) is proportional to \( \ell^2 \). Such an \( \ell^2 \)-contribution has been discussed earlier [4].

3. Three systems

In the comparison of three measuring systems, we assume a cable with \( \ell = 60 \) m as at KHPL, and a resistive \( Z_{LC}^{'e} \) of 4.4 m\( \Omega \)/m for the frequency range of interest. The characteristic impedance \( Z_0 = 50 \) \( \Omega \) and the dielectric constant of the insulation inside the cable \( \epsilon_r = 2 \). The HV arm \( Z_1 \) always consists of \( R_1 = 4 \) M\( \Omega \) parallel to \( C_1 = 150 \) pF. Resistance \( R_{3a} \) terminates the signal cable into its characteristic impedance.

I: A first divider component \( Z_2 = Z_1/100 \) is placed under \( Z_1 \). The LV arm \( Z_3 \) in the CR acts as a second 1:100 divider stage. The rationale of this system I is described in [5]. In fact, the cable input effectively shunts \( Z_2 \); the value of \( Z_2 \) is not critical.

Fig. 3. Three voltage measurement systems.
II: $Z_I$ is grounded via a capacitor $C_Z = 0.22 \mu F$. A second cable [6] 'balances' the signal circuit at power frequencies; this cable is terminated by $R_e = Z_0$ to avoid resonances. Since the CM current in both cables are equal, a large reduction in the overall $Z_I$ results at power frequencies.

III: We combine the advantages of I and II. The impedance $Z_2$ is omitted. One signal cable suffices again.

Several versions of $Z_2$ are possible. The pass band for the intended HV signal should extend from d.c. up to several MHz. For system I and II, the signal attenuation can be trimmed to an elegant number $10^4$ by adjusting resistor $R_{3b}$, which is about 400 $\Omega$; the capacitor $C_3$ is $1.5 \mu F$. The small resistor $R_{3c}$ compensates the roll-off at high frequencies due to the time constant of $R_{3b}$ and $C_3$. In system III, $R_{3b}$ terminates the cable; the subsequent passive integrator ($R_{3b} = 10 \, k\Omega, \, C_3 = 60 \, nF$) contains only a small capacitor which can be selected for proper behavior at high frequency. The signal attenuation is given by $R_{3b}/R_1$.

4. Comparison based on $Z_I$

In the actual comparison we used a full transmission line (TL) approach [7] which is also valid at high frequencies. The ground loop b) is regarded as a terminated TL through which a current wave $I_{CM}$ flows travelling at the speed of light. This TL couples to the signal cable(s) via $Z'_w$. At low frequencies the TL results are in full agreement with those obtained by the simple formulas of Sect. 2.

![Fig. 4. The interference to signal ratio (ISR) for the three measuring systems. A cable of 60 m length, an $I_{CM}$ of 1 A, and a HV signal of 1 V are assumed.](image)

In Fig. 4 the calculated interference to signal ratio (ISR) is shown: the contribution $Z_{CM}$ to the voltage $V_w$ at the output (see Fig. 3) caused by an $I_{CM}$ of 1 A through the signal cable, in comparison with the contribution to $V_w$ of a HV signal of 1 V at the input of the divider. In system II we assumed $I_{CM} = 1$ A through each cable.

Due to the low $Z_2$, system I shows a high ISR, nearly independent of frequency. However, this system I has a better ISR than the simplest divider. When $Z_2$ would be lowered by another factor $10^2$, in order to obtain the full $1:10^4$ ratio by $Z_I$ and $Z_2$ alone, the ISR would worsen by the same factor $10^2$. Because of the high $Z_I$ at power frequency, system I does not allow grounding of the cable shield in the CR, which complicates signal handling.

System II and III show comparably low ISR at power frequencies, due to the balancing in system II, and due to the omission of $Z_2$ in system III. The cross-over frequency $f_1$ is given by $2/(2\pi R_1 C_1 \ell)$; at higher frequency $Z_2$ dominates over $Z_{CM}$. At $f_2 = 1/(2\pi R_1 C_1)$, $Z_1$ drops. The balancing in system II becomes ineffective at $f_3$ which cannot be given in a simple expression for the actual parameters. System II converges with system I beyond frequency $f_4 = 1/(2\pi R_1 C_2)$. System II and III allow the signal cable(s) to be grounded at both ends.

We measured the $Z_I$ of Systems II and III in the Eindhoven HV Laboratory for 20 m long cables, using the signal cable termination $Z_2$ of II in both systems. As Fig. 5 shows, calculated and measured amplitudes agree to within 15 percent. The rise of curve III above 20 kHz is caused by the small resistor $R_{3b} = 3.2 \, \Omega$ in the LV arm II. Other measurements (not shown) verified the $\ell^2$ dependence above $f_1$ for system III; for system II a more complicated behavior as function of length was expected and also found above $f_2$.

![Fig. 5. Calculated (\*) and measured $Z_I$ for system II (\x, left ordinate) and III (o, right ordinate) for a 20 m long cable.](image)
5. Selection of components

A chopped HV waveform presents the highest voltage across the LV arm elements: a 500 kV drop in 100 ns results in pulse current of 750 A which predominantly flows through 

The resistor \( R_{3a} \) should be selected for linear behavior during the pulse. The linearity requirements of \( R_{3a} \) are relaxed when a lower value of \( C_1 \) is chosen. We successfully tested system III with a well shielded compressed gas capacitor \( C_1 = 50 \text{ pF}, C_2 = 1.2 \text{ nF} \) [4]; the absence of \( R_1 \) can be compensated by an active integrator following \( Z_2 \).

Alternatively, a small parallel \( C_2 \) of 1 nF (dashed in Fig. 3III), and a series resistor \( R_{2a} \) of about 200 \( \Omega \) at B may be placed near the cable input. This still gives a reasonable ISR (see dashed line in Fig. 4), and resembles system II with a larger \( Z_2 \), certainly at power frequency since \( R_2 \) is removed.

6. Conclusions

Improvements with respect to EMC can be obtained with a HV divider component already present at KHPL. The principal LV divider arm \( Z_2 \) is placed at the end of the signal cable, near the registration equipment. Divider component \( Z_2 \) is omitted or largely increased in value, since a low \( Z_2 \) reduces the impedance seen by the cable input and increases the interferences coupled in. For sufficiently high \( Z_2 \), the second cable of system II can be removed.

With system II and III, a power frequency CM current of 10 A per (60 m) cable results in an interference signal equivalent to a HV input of 1 V. Such currents have indeed been observed at KHPL. The equipment is readily protected against this current by the EMC cabinet discussed in Sect. 1.

Additional measurements not reported here confirmed that stray capacitances between nearby circuits and the HV arm are the main source of interference now. This source remains the same for all three systems of this study.

It is often assumed that a \( Z_t \) coupling is proportional to the length of the cable. However, a \( f^2 \)-dependence exists above \( f_1 \). Metal conduits, braids or tubes around the cables divert the CM current from the cables. Even a shorter length of such additional grounded conductor is effective because of the \( f^2 \)-dependence.

Good EMC practice calls for grounding the signal cable at both ends. Proper selection, placement and connection of divider components ensure 1) a well defined HV voltage to be measured, 2) a good immunity with respect to the CM currents, and 3) a reliable protection of the registration equipment. Mobile dividers can be connected similarly.

7. Acknowledgements

This research was carried out on instigation of ir. A.L.J. Janssen (KEMA High Power Laboratory). The authors thank him for his generous support and the loan of the divider HV component. Ing. W. A. van der Linden (also of KHPL) kindly and fully informed us about his earlier measurements on system II.

8. References

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