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Feasibility Study of Adding a Common-Mode Choke in PLC Modem for EMI Suppression

K. Y. See, Senior Member, IEEE, P. L. So, Senior Member, IEEE, and A. Kamarul

Abstract—The feasibility of adding a common-mode (CM) choke in the analog front end (AFE) circuit of a power line communication (PLC) modem to reduce the CM noise coupling onto the power line is investigated. Based on a two-current-probe measurement approach, the CM and the differential-mode (DM) equivalent electrical models of a PLC modem are first developed. Both the CM and the DM attenuations due to the addition of a CM choke when the PLC modem is connected onto the power line network are then determined. Besides the CM noise attenuation, the impact of the CM choke on the PLC signal, which is DM in nature, is also studied.

Index Terms—Common-mode choke, electromagnetic analysis, electromagnetic interference, power system communication.

I. INTRODUCTION

While the power line network has been viewed as a convenient and inexpensive communication medium for data and voice transmissions, its imbalance nature leads to the generation of common-mode (CM) noise current in the power line network, which causes electromagnetic interference (EMI) radiation that might interfere with the existing wireless communications users [1]–[4]. In reality, one has no control over the imbalances of the power lines and the loads connected to them. Hence, the only possible way to control the EMI radiation is to ensure that the RF source (the PLC modem) has high CM impedance so that the CM current propagating through the power line network is kept to a low level as possible. With the aim of reducing the CM current in the power line network, the authors have initiated a feasibility study of adding a CM choke in the analog front end (AFE) circuit of the PLC modem. Although the use of CM chokes is reported in some PLC trials to reduce the EMI radiations, no formal in-depth study has been carried out [4]. Thus, this paper aims to carry out a systematic in-depth study of the effectiveness of a built-in CM choke in a PLC modem in reducing CM noise current in the power line network. The effectiveness of the CM choke in suppressing the CM current in the power line network depends not only on the CM impedance of the choke itself but also on the CM impedance of the source (the PLC modem) and the CM impedance of the terminating load (the power line network). Ideally, a CM choke would not affect the differential-mode (DM) signal generated by the PLC modem. However, the imperfect cancellation of high frequency magnetic fluxes of the two windings of the CM choke results in a finite DM attenuation, which will have an impact on the communication signal transmitted by the PLC modem. To study the effectiveness of using the CM choke in controlling EMI from the PLC network as well as its impact on the useful DM communication signal transmitted by the PLC modem, equivalent CM and DM electrical circuit models for the PLC system are developed. Based on a two-current-probe measurement approach, the CM and DM equivalent circuit models of any PLC modem connected to any power line network can be established. These models would allow us not only to evaluate the CM noise suppression performance of the PLC modem with the built-in CM choke but also to assess the effects of the choke on the useful DM signals.

II. POWER LINE COMMUNICATION SYSTEM MODEL

Fig. 1 shows the measurement setup for the study. The PLC modem is programmed to be able to transmit and receive signals continuously in a “loopback” test mode without using a receiver modem. The PLC modem is modeled as a combination of equivalent CM and DM signal sources. The DM signal source represents the intended communication signal transmitted by the PLC modem and the CM signal source represents the unwanted CM noise generated due to imbalance of the power line network. To ensure the repeatability of the feasibility study, the PLC modem is connected to the power mains through a line impedance stabilization network (LISN) [5]–[7], which serves two purposes: First, it terminates the PLC modem with stable, well-defined CM and DM power mains impedances. Second, it facilitates direct measurements of the conducted emissions emitted by the PLC modem. However, the LISN alone does not have the capability to discriminate the CM noise emissions from the DM signals. To overcome this problem, a CM-DM discrimination network is added to the output of the LISN so that both the CM and DM emissions from the PLC modem can be discriminated and measured independently. The design and construction of the discrimination network can be found in [8] and will not be discussed here.

With the measurement setup shown in Fig. 1, the effects of adding a CM choke on both the CM and DM emissions can be analyzed systematically. By adding a CM choke to the output of the PLC modem, the CM and DM equivalent circuits of Fig. 1 can be represented in Figs. 2 and 3, respectively.

The DM conducted emission measured by the LISN is the intentional communication signal and is denoted as $V_{signal}$. The CM conducted emission measured by the LISN is the unwanted noise and is denoted as $V_{noise}$. From the equivalent circuits, the
CM and DM attenuations due to the addition of a CM choke are given by (1) and (2), respectively

\[
A_{T,\text{CM}} = \frac{V_{\text{noise}}}{V^\prime_{\text{noise}}} \\
A_{T,\text{DM}} = \frac{V_{\text{signal}}}{V^\prime_{\text{signal}}}
\]

where \(V_{\text{noise}}\) and \(V^\prime_{\text{noise}}\) are the CM noises before and after adding the CM choke, respectively; and \(V_{\text{signal}}\) and \(V^\prime_{\text{signal}}\) are the DM signals before and after adding the CM choke, respectively. The CM and DM attenuations can be derived and expressed as

\[
A_{T,\text{CM}}(\text{dB}) = 20\log_{10} \left(1 + \frac{Z_{\text{inl,CM}}}{Z_{\text{LISN,CM}} + Z_{s,\text{CM}}}\right) \\
A_{T,\text{DM}}(\text{dB}) = 20\log_{10} \left(1 + \frac{Z_{\text{inl,DM}}}{Z_{\text{LISN,DM}} + Z_{s,\text{DM}}}\right)
\]

III. CM AND DM ELECTRICAL MODELS OF A CM CHOKE

A 3.2-mH CM choke (model CMV4.0) from Roxburgh, which is commonly used to attenuate the CM conducted emissions in power electronics applications, is chosen for the feasibility study. The CM and DM impedances of the choke are measured in the frequency range of 100 kHz to 30 MHz using the Agilent 4395 A Impedance Analyzer. Fig. 4 shows the measured CM and DM impedance magnitudes of the choke. For any CM choke, it is impossible to achieve perfect cancellation of the magnetic fluxes of the two windings on the same magnetic core. Thus, the nonzero DM inductance is resulted from such imperfect cancellation, which leads to the finite DM impedance shown in Fig. 4.

Based on the trends of measured impedance magnitudes with respect to frequency, the CM and DM equivalent electrical models of the choke can be extracted. The CM electrical model of the choke can be represented by a \(RLC\) parallel circuit with the following parameters: \(R_{\text{CM}} = 11.10\, \text{k}\Omega\), \(L_{\text{CM}} = 3.24\, \text{mH}\), and \(C_{\text{CM}} = 10\, \text{pF}\). The DM electrical model of the choke can also be represented by a \(RLC\) parallel circuit with the following parameters: \(R_{\text{DM}} = 3.850\, \text{k}\Omega\), \(L_{\text{DM}} = 27.8\, \mu\text{H}\), and \(C_{\text{DM}} = 6.89\, \text{pF}\).

IV. CM NOISE AND DM SIGNAL SOURCE IMPEDANCES

To estimate impacts of the CM choke on the CM noise and the DM signal, the CM noise source impedance and the DM signal source impedance of the PLC modem must be established first.
The two-current-probe approach is employed to determine the CM noise and the DM signal source impedances of the PLC modem [9]–[11]. This section briefly describes the measurement methodology.

A. Two-Current-Probe Measurement Methodology

Fig. 5 illustrates the basic setup of the two-current-probe approach to measure the unknown impedance \( Z_X \), where \( Z_X \) is connected to the high voltage power network. The measurement system consists of an injecting current probe, a monitoring current probe and a network analyzer. The two current probes and a decoupling capacitor \( C \) form a high-frequency coupler to avoid direct connection between the network analyzer and the high voltage power network. A pair of short wires with length \( d \) from the reference plane \( h \) to the reference plane \( b \) connects the coupler to \( Z_X \). Port 1 of the network analyzer induces a continuous wave (CW) signal in the closed loop through the injecting current probe. Port 2 of the network analyzer measures the resultant current in the closed loop through the monitoring current probe.

The injecting current probe can be modeled as an equivalent transformer circuit as shown in Fig. 6. \( V_{p1} \) and \( Z_p \) are the source voltage and the source impedance of the injecting signal source from port 1 of the network analyzer, respectively. With the injected signal, the injecting probe induces a voltage \( V_w \), which results in a current \( I_w \) circulating in the closed loop. \( L_p, L_w, \) and \( M \) are the primary self-inductance of the probe, the self-inductance of the wire in the probe volume, and the mutual inductance between the probe and the wire, respectively. \( V_{p1} \) and \( V_w \) can be expressed as follows:

\[
V_{p1} = (Z_p + j\omega L_p)I_p = j\omega MI_w
\]

(5)

\[
V_w = -j\omega MI_p + j\omega L_w I_w.
\]

(6)

Combining (5) and (6) and eliminating \( I_p \), we have

\[
V_w = Z_{M1}I_w - V_{M1}
\]

(7)

where

\[
Z_{M1} = j\omega L_w + \left( \frac{(\omega M)^2}{Z_p + j\omega L_p} \right)
\]

(8)

\[
V_{M1} = V_{p1} \cdot \left( \frac{j\omega M}{Z_p + j\omega L_p} \right).
\]

(9)

Equations (8) and (9) suggest that the injecting current probe at the reference plane \( h \) can be modeled by a Thévenin equivalent circuit as shown in Fig. 7. \( Z_{M2} \) is the reflected impedance in the loop due to the monitoring current probe.

From (9), the ratio \( V_{M1}/V_{p1} \), which depends on the properties of the injecting probe and its operating frequency \( \omega \), is given by

\[
K_R = \frac{V_{M1}}{V_{p1}} = \frac{j\omega M}{Z_p + j\omega L_p}.
\]

(10)

The typical wire length \( d \) between the reference planes \( h \) and \( b \) is much shorter than the wavelength of the maximum frequency of interest (10 m at 30 MHz) and therefore its transmission line effect can be ignored. With \( Z_{ip} \) being the impedance seen by the unknown impedance \( Z_X \) at the reference plane \( b \), \( V_{M1} \) can be redefined as

\[
V_{M1} = (Z_{ip} + Z_X)I_w
\]

(11)

where \( Z_{ip} = Z_{M1} + Z_{M2} + Z_C \). Substituting \( V_{M1} \) from (11) into (10), \( Z_X \) can be evaluated by

\[
Z_X = (K_R Z_{T2}) \cdot \left( \frac{V_{p1}}{V_{p2}} \right) - Z_{ip}
\]

(12)

where

\[
Z_{T2} = [V_{p2}/I_w] \text{ is the transfer impedance of the monitoring current probe and } V_{p2} \text{ is the voltage measured by the monitoring probe. The ratio of } V_{p1}/V_{p2} \text{ can be obtained through the S-parameters measurement using the network analyzer as follows:}
\]

\[
\frac{V_{p1}}{V_{p2}} = \frac{S_{11} + 1}{S_{21}}.
\]

(13)
The product \( K_R Z_{T2} \) is a frequency dependent coefficient that can be obtained by first removing \( Z_X \) and then measuring \( Z_{ip} \) using an impedance analyzer. \( Z_X \) is then replaced with a known precision resistor \( R_{std} \) (for example, a 100 \( \Omega \pm 1\% \) carbon film resistor) and \( V_{p2}/V_{p1} \) is measured again using the network analyzer. Finally, the coefficient \( K_R Z_{T2} \) can be obtained by

\[
K_R Z_{T2} = \frac{Z_{ip} + Z_{std}}{(V_{p2}/V_{p1})Z_X = Z_{std}}.
\]

With \( K_R Z_{T2} \) and \( Z_{ip} \) determined, the two-current-probe setup is ready to measure any unknown impedance \( Z_X \). After measuring \( V_{p1} \) and \( V_{p2} \) using the network analyzer, \( Z_X \) can be found based on (12) and (13).

### B. CM and DM Source Impedances of the PLC Modem

Using the two-current-probe approach, Figs. 8 and 9 show the setups used to measure the CM noise source impedance \( Z_{s,CM} \) and the DM signal source impedance \( Z_{s,DM} \) of the PLC modem, respectively. The Tektronix CT-1 (5 mV/mA, bandwidth 25 kHz to 1000 MHz) and CT-2 (1 mV/mA, bandwidth 1.2 kHz to 700 MHz) current probes are chosen as the injecting and monitoring current probes, respectively. The Agilent 4395A Network Analyzer is employed for the S-parameters measurements.

For the CM impedance measurement, the two current probes and two “Y” class 0.1 \( \mu F \) capacitors (one for live-to-earth connection, and the other for neutral-to-earth connection) form the CM coupling circuit to avoid any direct connection to the power mains. For the DM impedance measurement, the two current probes and two “X” class 0.1 \( \mu F \) capacitors (both connected from live to neutral) form the DM coupling circuit.

The impedance \( Z_L \) is first measured without the PLC modem connected to the power line network, and then \( Z_T \) is measured with the modem connected to the network and in the active mode. Therefore, the source impedance of the PLC modem can be determined by

\[
Z_S = \frac{Z_T Z_L}{Z_L - Z_T}.
\]

### V. IMPACTS OF THE CM CHOKE

Based on the earlier measurements, the CM and DM equivalent circuit models of the PLC modem terminated with the LISN are shown in Figs. 11 and 12, respectively.

Given the values in Figs. 11 and 12, the CM and DM attenuations due to the insertion of the CM choke are calculated and plotted in Fig. 13. Interestingly, the CM choke seems to have a larger impact on the DM signal, since the DM attenuation is higher than the CM attenuation across the full frequency band. The CM attenuation remains relatively constant at around 10–12 dB.
Fig. 11. CM circuit model of the PLC modem terminated with the LISN.

Fig. 12. DM circuit model of the PLC modem terminated with the LISN.

Fig. 13. Calculated CM and DM attenuations due to the CM choke.

Fig. 14. CM noise before and after the CM choke is inserted.

Fig. 15. DM signal before and after the CM choke is inserted.

dB in the frequency range of 5–25 MHz whereas the DM attenuation can achieve attenuation of as high as 30 dB at around 9 MHz, with at least 15 dB at the other frequencies. A closer look reveals that the lower CM attenuation is expected due to the high-impedance nature of the CM noise source impedance of the PLC modem. Hence, the CM choke must provide much higher impedance than the noise source impedance in order to have a more significant impact on the CM noise suppression. On the other hand, the finite DM impedance due to the imperfect CM choke, though its magnitude is small, causes larger impact on the DM signal because of the low-impedance nature of the DM source impedance.

To further confirm the findings, the CM and DM conducted emissions measured by the LISN, with the help of CM-DM discrimination network, are shown in Figs. 14 and 15, respectively.

Fig. 14 shows the measured CM noise spectrums before and after the CM choke is inserted into the AFE circuit of the PLC modem. It can be seen that the CM noise in the frequency range of 5 MHz to 20 MHz is suppressed by 10 to 12 dB as predicted earlier by the CM equivalent circuit model. Fig. 15 shows the measured DM signal spectrums before and after the CM choke is added to the AFE circuit of the PLC modem. It can be seen that the PLC signal is attenuated by 15 to 30 dB throughout the PLC operating frequency range of 5 MHz to 20 MHz as predicted by the results derived from the DM equivalent circuit.

VI. CONCLUSION

The feasibility of adding a CM choke in a PLC modem for CM noise suppression has been studied. Both the theoretical models and the measured results have demonstrated that the equivalent CM and DM source impedances of the PLC modem have a strong influence on how well a CM choke performs in suppressing noise emissions in the power line network. Due to the high-impedance nature of the CM source impedance of the PLC modem, there is a certain limit on the CM noise attenuation that a CM choke can achieve. On the other hand, the finite DM impedance, which is due to the imperfection of the CM choke, has a much larger impact on the intentional DM signal because of the low-impedance nature of the DM source impedance of the PLC modem.

Hence, adding a CM choke in the AFE circuit of a PLC modem is not a feasible solution to reduce the CM noise in the power line network. Further work will be carried out to consider other alternatives so that large isolation barrier against CM noise can be offered without affecting the intentional PLC.
signal, for example, by replacing the existing isolation transformer in the AFE circuit of the PLC modem with an optical coupler unit.

REFERENCES


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