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Critical Investigation of Common-Mode Radiation Mechanism from Power Line Communication Network

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Symbols

l : length of wire antenna (meter)

λ : wavelength (meter)

a : thickness of wire antenna (meter)

I : current (Amps)

I_0 : constant current (Amps)

A : Vector magnetic potential (Wb m^{-1})

F : potential function (Volts)

E : Electric field (V/m)

H : Magnetic field (A/m)

Chapter 1

INTRODUCTION

1.1 Motivation

Internet services have been widely used in the commercial, residential and educational communities. According to the annual surveys conducted by the Infocomm Development Authority (IDA) of Singapore on Infocomm usage in households in Singapore between the year 2000 and 2004 [1], it showed that broadband internet adoption within the residential community alone in Singapore is widespread. The surveys further reflected a growth in broadband subscription among the household users in Singapore. Broadband access had doubled from 8% in 2000 to 17.7% in 2001. The surveys also indicate that more than half of the nation's population is connected to the Internet in their daily lives for work, entertainment and educational purposes, and this figure is expected to increase over the next few years.

With the increase in broadband users in Singapore, Internet applications such as online information retrieval, online banking, online job searches and applications, online entertainment and education are fast becoming popular. And as global competition intensifies with the massive free flow of trade and information, the need to have access to instantaneous, up-to-date information within the residential and business communities in Singapore becomes more critical than ever. With the impending deregulation and liberalization of the telecommunication industry in Singapore and worldwide, new players entering the market are beginning to investigate how they can compete vigorously and effectively with the existing telecommunication companies in providing a full range of basic telecommunication services nation-wide especially in broadband services which do not fall under the monopoly rights granted to the dominant Public Basic Telecommunication Services (PBTS) operator, the Singapore Telecom (SingTel). With the introduction of facilities-based competition before service-based competition by the Telecommunication Authority of Singapore (TAS) in 2000 [1], service providers are

expected to invest in the construction and development of high-quality and advanced telecommunication infrastructure, which would in turn provide the necessary foundation to generate a nationwide broadband-ready network and thus, enhancing Singapore international broadband connectivity. Therefore, new players entering the market at this stage are expected to be committed in developing and advancing Singapore's telecommunication infrastructure.

1.2 Broadband Power Line Communication Systems

Broadband over Power Lines (BPL), which is also known as power line internet, is the use of the technology to provide broadband Internet access through ordinary power lines. The system can transmit voice and data by superimposing modulated analog signals over the standard 50 or 60 Hz alternating current. A computer (or any other communication device) would only need to plug a PLC modem into any outlet in an equipped building to have access to high-speed Internet access. Broadband PLC offers obvious benefits over regular cable or digital subscriber line (DSL) connections in such a way that the availability of extensive power line infrastructure would allow more people in more locations which have access to power supply to have access to the Internet as well. Also, such ubiquitous availability would make it much easier for other consumer electronics equipment, such as video or audio systems, to be connected to the network.

Thus, with the introduction of the power line communication (PLC) system into the telecommunication industry, the local distribution will inevitably be a very competitive arena, where many utilities could take advantage of their vast, in-place wiring infrastructure to gain competitive advantage by offering new broadband Internet services in addition to electric power and building brand recognition. With the proper technology, the infrastructure can also serve as a high-speed communications medium over the "the first hundred feet" to the residence. Through the use of the PLC system, electrical utilities can supply both electric power and a pipe for high-speed, reliable communications traffic, including Internet access. Utility companies can further enhance their utility services in providing high-speed 'last mile' connectivity to Internet Service Providers (ISPs), which

do not own the necessary infrastructure to reach their customers. For new non-dominant telecommunication entrants, the issue of local access - the 'last mile' connectivity to customers' homes or offices - remains the key limitation. As Singapore Telecom (SingTel), which owns most of the last-mile infrastructure to end-users, currently dominates the local broadband market, all conventional ISPs have to rely on SingTel for that last mile access to the customer's premises. This technology provides new Telco a 'last mile' alternative infrastructure without having to incur heavy expenses for digging and laying additional cables. They will find PLC a more convenient and less expensive option as compared to the traditional laying of telecommunication wires to their customers' premises and in-house Local Area Network (LAN) wiring.

1.3 Potential Applications

Utilizing existing power lines as a communication is both convenient and economical to provide broadband access. Two major promising areas where researchers in academia and organizations are trying to use the PLC technology are the Last Mile Solution [2] and Indoor Networking [3].

1.3.1 Last Mile Solution

Across the world researchers in academia and organizations are still working on various aspects of the PLC technology to use the technology as a "Last Mile" solution for providing broadband access. The internet service provider will be linked to the local distribution transformer. The local transformer supply power to few tens of houses over the low-voltage power lines and the same LV lines would be utilized as information backbone to link houses to the internet service provider to have access to Internet. Another benefit of the PLC technology is that it is compatible with existing technologies like fibre optics, WiMAX or WiFi. For instance, WiMax technology could be used to transmit information from the Internet service provider to the local distribution transformer and the local transformer LV power lines could be used to transmit information to all the houses. Utilizing the long LV power lines is a convenient and economical method to provide broadband access, as illustrated in Fig.1.1 [2].

Fig 1.1: PLC Technology as a Last Mile solution

1.3.2 Indoor Networking

Another potential application of PLC technology is to setup an Indoor Network over the existing power lines. The convenient and economical PLC technology will be extremely beneficial to have broadband access anywhere within the house, for multimedia communication as well as for automation control, as shown in Fig 1.2. PLC technology is highly appropriate to cater to the needs of Smart home in the near future [3] as the current the technology can support speed as high as 200Mbps (recent PLC chipset by Intellon supports data rate upto 200Mbps) and can reliably communicate over indoor power-line networks [4].

Fig 1.2: PLC Technology for setting up Indoor Network

1.4 PLC Technology

Power line network is originally devised for distribution of power at 50-60Hz. The use of this medium for communications at radio frequency (RF) presents some technical challenges. Power line networks are usually made of a variety of conductor types, joined almost at random, and terminating into loads of varying impedance. Such a network has an amplitude and phase response that varies widely with frequency. Because of the power-line channel's response with respect to frequency at some frequencies, the signal may arrive at the receiver without much attenuation, while at other frequencies the signal may be severely attenuated. Furthermore, the channel characteristics can also vary with time as the load on the network changes. Power line networks are also affected by interference. Electric appliances with brush motors, switching power supplies and halogen lamps produce noise that can reduce the reliability of communication signals. Due to high attenuation over the power line, the noise is also location dependent. Apart from these, ingress sources such as amateur radio transmission can render certain frequencies unfit for communication. HomePlug 1.0 products overcome these challenges by using an adaptive approach that uses robust transmission technique combined with sophisticated forward error correction (FEC), error detection, data interleaving, and automatic repeat request (ARQ) [5].

1.4.1 Home plug Physical Layer

Orthogonal Frequency Division Multiplexing (OFDM) is the basic transmission technique used by the HomePlug. OFDM is well known in the literature and in industry. It is currently used in DSL technology, terrestrial wireless distribution of television signals, and has also been adapted for IEEE's high data rate wireless LAN Standards (802.11a and 802.11g). The basic idea of OFDM is to divide the available spectrum into several narrowband, low data rate subcarriers. To obtain high spectral efficiency the frequency response of the subcarriers are overlapping and orthogonal, hence the name OFDM. Each narrowband subcarrier can be modulated using various modulation formats. By choosing the subcarrier spacing to be small the channel transfer function reduces to a simple constant within the bandwidth of each subcarrier. In this way, a frequency selective channel is divided into many flat fading sub-channels, which eliminates the

need for sophisticated equalizers. The OFDM used by HomePlug is specially tailored for power line environments. It uses 84 equally spaced subcarriers in the frequency band between 4MHz and 21MHz. Cyclic prefix and differential modulation techniques (DBPSK, DQPSK) are used to completely eliminate the need for any equalization. Impulsive noise events are overcome by means of forward error correction and data interleaving. HomePlug payload uses a concatenation of Viterbi and Reed-Solomon FEC. Sensitive frame control data is encoded using turbo product codes [5].

1.4.2 Home Plug MAC Layer

The choice of Medium Access Control (MAC) protocol provides a different set of challenges. Home networks should be able to support a diverse set of applications ranging from simple file transfer to very high QoS demanding applications such as Voice-over-IP (VoIP) and Streaming Media. The Home Plug MAC is built to seamlessly integrate with the physical layer and addresses these needs. Home Plug MAC is modeled to work with IEEE 802.3 frame formats. This choice simplifies the integration with the widely deployed Ethernet. Home Plug MAC appends the Ethernet frames with encryption and other management before transmitting it over the power line. A segmentation and reassembly mechanism is used in cases where the complete packet cannot be fit in a single frame [5].

1.5 Electromagnetic Compatibility

Power lines were designed to supply low frequency (50 Hz or 60 Hz) AC power and not intended for RF communication purposes. However, by selecting an appropriate frequency band from 1MHz to 30MHz in which level of noise on the power line is low and the impedance of the power-line network is relatively invariant [6] and with the use of advanced communication techniques, it is possible to communicate over the power lines in the 1-30 MHz band. Because of the mature techniques, communication over power lines was made possible at data rates as high as 200 Mbps. However, communicating over power lines in the frequency range between 1 to 30 MHz gives rise to radiated emission from the power lines. If the emissions levels are higher than the

electromagnetic compatibility (EMC) regulatory limits, the radiation from power lines will interfere with electronic devices to cause them to malfunction. It can also interfere with radio receivers to degrade quality of signal reception.

In a study conducted in China, a realistic test bed was developed and radiated emission from the test bed was measured when a pair of 200 Mbps modems communicated over the test bed, as shown in Fig. 1.3. Fig 1.4 shows the measured radiated emissions from the trial which had exceeded the EMC regulatory limits specified by US FCC and German NB30 and therefore indicates a high likelihood of interference in the HF band from the power line [7]. Other measurement data collected from many field trials [8]–[15] in the United States, Europe and other Asian countries have also concluded significant level of emissions from PLC network in the frequency from 1 to 30 MHz.

Fig 1.3: Realistic Test bed to evaluate radiated emission due to communication over Power lines

Fig 1.4: Radiated Emission from the Test bed

In another study conducted in November 2004, radiated emissions due to communication over power lines were measured in the Swiss city of Solothurn. Emissions from Homeplug based modems were measured in 5 single dwellings and in 5 multiple dwellings located in rented blocks. In order to get statistically conclusive results in all, more than 4,400 measurements were taken using an automated measurement system specially designed for this purpose. The measurement locations were distributed statistically inside the house on the different floors and on the ground outside. It was ensured that all interior fittings were also taken into account in the distribution. The distance to the walls as well as any metallic objects was kept strictly to 1 m. A measurement location density of at least 1 per 10 m² was envisaged inside the building. The distance between measurement locations was set at a minimum of 3 m. Fig. 1.5 gives an indication of the indoor distribution concept [16].

Fig 1.5: Floor plan of the house in the building

Fig. 1.6 shows the statistical maximum, minimum and medium level of emissions from the power lines when the Homeplug based modems were communicating. Maximum level of electric field emission was found to be as high as 70 dBuV/m, which exceeded the US FCC limit and German NB30 limit.

Fig 1.6: Comparison of the PLC radiated interference level with the FCC and NB30 limit inside buildings.

Degradation of the signal to noise ratio of the radio signals due to high levels of emissions from the power lines was also measured inside the buildings. Fig. 1.7 shows the degradation of the radio signal's signal to noise ratio. Such degradation meant poor quality of radio reception hence dissatisfaction to users of amateur radio and resistance from amateur radio operators to allow widespread use of PLC technology.

Fig 1.7: Degradation of the S/N ratio related to the peak value of the PLC carrier inside buildings

1.5.1 EMC Standards

While isolating PLC system signals from background or equipment noise can be achieved by appropriate filtering techniques, it will be necessary to limit radiation from PLC networks so that the primary users of wireless services remains unaffected. One of the possible ways to accomplish EMC between PLC and the wireless services is to control the radiated fields from power lines below some specified limits. Many international standards have been developed to control radiated emissions below 30 MHz in the HF band. These standards, however, vary from one country to another since the power distribution networks have different configurations in different countries especially between the United States and Europe. Thus, the EMC regulations developed for one country may not be suitable for the other. For example, the regulating administration for telecommunications and posts (RegTP) in Germany has adopted NB30 [17] for the radiation of telecommunications services in the frequency range 9 kHz to 3 GHz, while the Radio Communications Agency in the United Kingdom has defined MPT1570 [18] as its current standards for telecommunication systems operating in the frequency range of 9 kHz to 30 MHz. If one were to make a comparison between the standards in these two countries (refer to Fig. 1.8), it could be observed that the limiting level defined by UK's MPT1570 is generally about 20 dB below the German RegTP's recommendation. The

UK's MPT1570 and German NB 30 low limits ensures strict restriction in the PLC band (1MHz to 30MHz) so that amateur radios which operate from 3MHz to 30MHz can be used by organizations such as broadcasters, military including NATO, diplomatic services, NGOs, civil aviation, ports and dock authorities, short range devices, safety of life service, radio astronomers as well as radio amateurs and short wave listeners without any degradation in information due to operation of PLC [19]. Under such a strict regulation, utilities and other infrastructure owners will never be interested in investing manpower and money in upgrading their facilities to provide Internet services nationwide through PLC technology. Further comparisons with the FCC Part 15 [20] regulations in Fig. 1.8, which is currently being adopted by the United States for its PLC systems, further highlight the disadvantages imposed by the regulations adopted by both Germany and UK. Therefore, it is hardly surprising that the development of high speed PLC equipment is enormously more progressive in the United States than anywhere else in Europe.

Fig. 1.8 Electric field limits for radiation from wire-bound communication for three different countries

With major standardization organizations for PLC system such as the HomePlug are adopting the FCC Part 15 as their EMI regulatory standards. Development of PLC systems capable of processing and handling data rates as high as 10 Mbit/s as specified in the Homeplug Specification version 1.0 is no longer impossible in the United States. In fact, the HomePlug announced in 2005 that its specification for the next version,

HomePlug AV (Audio/Video) [21], designed for transmission of High Definition Television (HDTV) data and Voice over Internet Protocol (VoIP) has finally been approved unanimously by the board of directors of the alliance. If successfully implemented, the HomePlug AV would accelerate the development of PLC systems capable of processing and handling data rates as high as 200 Mbits/s. On the other hand, with the current stringent regulations imposed in both Germany and UK, such a rapid progress for high-speed PLC networking seems doubtful even for PLC systems with data rates of only 1-2 Mbit/s. However, relatively high limits of US FCC, shows that US is interested in deployment of high speed PLC systems especially in indoors[20].

1.5.2 EMC Research in PLC

Many researchers have put in effort to characterize the radiated emissions associated with PLC networks, ranging from theoretical characterizations to experimental assessments. These researchers not only sought to understand the behavior of radiated emissions from the PLC network but also aim to contribute to the regulatory harmonization of the EMC standards for broadband PLC usage. These were driven largely by the desire to reduce the testing burden for affected PLC products by removing the need for redundant testing. PLC modems are often designed to transmit signals of reasonably high power in order to compensate transmission losses in the power lines. However, this leads to higher level of radiated energy emitted by the power lines. Thus, for most PLC modem manufacturers, it would be important to have clear and easy-to-measure limits of voltage to be fed into the power lines. Most regulations, however, do not care for this injected voltage, but the possible radiation emitted. In order to bridge this gap, field tests have been performed [13]–[15] to investigate the relationship between the voltage levels of signals fed into the power line network and the resulting levels of radiated electric and magnetic fields. A transfer function, frequently referred to as the “mains decoupling factor”, has been proposed to define such a relationship. Unfortunately, this method of characterization of electromagnetic fields could only provide estimation for the level of EMI radiation emitted by any arbitrary symmetrical input signal injected into the PLC network but is unable to provide further useful information, such as the effects of the different network

configurations, cabling arrangements, method of signal coupling, and varying environmental conditions on radiated electromagnetic fields. It is well-known that the emissions from the PLC network originate from the so called common-mode (CM) high frequency current flowing through live, neutral and earth bundle [22] but no comprehensive study has been carried out to explain the mechanism behind the generation of these emissions from the PLC network. To lower emissions from the PLC network, differential excitation between live and neutral and earth and neutral is proposed as a solution [23] but it only works well for balanced network (impedance of between live and earth is equal to that between neutral and earth). However, in most cases, one has no control over the impedance balance of the power line network.

1.6 Objective and Contributions of the Thesis

PLC technology can only gain acceptance if radiated emission from power line network is well controlled to meet the EMC regulatory limits in the respective countries. Although it is well known that radiated emission from the power line network is contributed mainly from the common-mode (CM) current on the power lines, the mechanism of the generation of CM current is rather complex and not well understood. Hence, the objective of the thesis is to carry out an in-depth study of the causes of CM current in the PLC System so that appropriate solutions can be devised to lower radiated emissions from PLC system to satisfactory levels.

Major contributions of the thesis are summarized as follows:

1. Detailed analysis of the CM coupling mechanism from PLC modem to power line that gives rise to CM current over the power lines and practical solutions to suppress the CM noise from the PLC modem to the power lines.
2. On a full-wave electromagnetic simulation tool, a realistic RF current probe model is developed and its accuracy is verified against measurements. The modeled current probe allows accurate prediction of CM current flowing in the power cable bundle that consists of live, neutral and earth wires.

3. Using the modeled current probe, impacts of asymmetry of power lines and unbalanced terminating loads on CM current over the PLC network are studied and analyzed.

1.7 Organization of the Thesis

The thesis is divided into six chapters.

Chapter 1 introduces the latest development of PLC technology and its market potential.

The EMC issues of PLC technology are also addressed.

Chapter 2 provides the theoretical background of the causes of CM current on the power lines that are used for PLC purposes. The radiation mechanism is also explained.

Chapter 3 investigates the CM coupling from the source (PLC modem) to the power lines. Based upon the understanding of coupling mechanism, effective solutions are proposed and implemented to lower emissions from PLC system.

In Chapter 4 a realistic RF current probe is developed using 3D full-wave electromagnetic simulation software (Computer Simulation Technology, CST [24]) to facilitate accurate prediction of CM current over the power cable bundle. The modeled current probe's accuracy is validated with experimental results.

Using the RF current probe model developed in Chapter 4, Chapter 5 studies the impacts of power line asymmetry and the imbalanced loads on CM current on power lines. Both simulation and measurement results from a realistic test bed are collected to study these impacts.

Finally, Chapter 6 concludes the thesis and suggests future works that are worth exploring.

Chapter 2

RADIATED EMISSION FROM PLC SYSTEM

In the previous chapter, radiated emission from PLC network has been identified as a major issue that prevents the widespread acceptance of PLC technology. Due to the coupling from source and imbalance nature of the power line network at high frequency, the net current flowing through the power line bundle consisting of live, neutral and earth line, referred to as common-mode (CM) current, is not zero. According to the antenna theory, the non-zero high frequency CM current flowing through the power line bundle gives rise to the radiated emissions from the power line network that carries the PLC signal. In this chapter, the mechanism of the radiated emission due to CM current over the PLC network will be briefly described.

In the case of a straight wire of length l ($l \ll \lambda$), the relationship between a current flowing through the wire I_0 , and the fields in the far-field region ($kr \gg 1$) are given by the following expressions [25]:

$$\left. \begin{aligned} E_\theta &= j\eta \frac{kI_0 l e^{-jkr}}{4\pi r} \sin \theta \\ E_r &= E_\phi = H_r = H_\theta = 0 \\ H_\phi &= j \frac{kI_0 l e^{-jkr}}{4\pi r} \sin \theta \end{aligned} \right\} kr \gg 1 \quad (2.1)$$

where

λ is the wavelength of the wave propagating in free space;

E_r, E_θ, E_ϕ are electric fields in the spherical coordinate system in the r, θ, ϕ directions, respectively;

H_r, H_θ, H_ϕ are magnetic fields in the spherical coordinate system in the r, θ, ϕ directions respectively;

r is the distance between the center of the wire and observation point in space in the far-field region;

l is the length of wire antenna;

k is the wave number; and

η is the free-space intrinsic impedance ($120\pi \Omega$).

2.1 CM current in PLC system

Due to the coupling from the source and imbalance nature of the power line network, the resultant current flowing on the whole power cable bundle gives rise to the so called CM current which with reference to direction of the current flowing in live, neutral and earth wires, as shown in Fig 2.1 is equal to $I_L - I_N - I_E$. For the CM current concerned, the live, neutral and earth lines of the power cable bundle can be considered as an equivalent wire antenna which radiates electromagnetic fields in accordance with the Equation (2.1).

Fig 2.1: Physical interpretation of Common-mode (CM) current

Based on several literature searches, the main causes of CM current on the power lines are summarized as follows [22-23, 26-29]:

1. **Source:** High frequency noise from the source (PLC modem) couples to the power line via any path which has low CM impedance and the noise induces CM current over the power line.
2. **Propagation Path:** Due to geometrical asymmetry of live-to-earth and neutral-to-earth of the power lines, some high frequency current flowing through the earth line does not cancel out with the currents through live and neutral lines and therefore leads to non-zero CM current through the power line bundle.
3. **Imbalance Loads:** When live-to-earth and neutral-to-earth load impedances are not equal (imbalance), unequal currents flowing through live and neutral results in finite

current flowing through earth and this causes significant CM current to flow in the power line bundle.

Fig 2.2: Detailed model of a basic PLC Network

Since the level of generated CM current is dependent on all the three above-mentioned factors, the CM current generation mechanism can be rather complex. To briefly explain the CM current generation mechanism in PLC network, Fig 2.2 shows a detailed electrical model of a basic PLC network consisting of PLC modems as transmitter and receiver, the power line as propagation medium and the electrical appliances connected to the power network as loads. The transmitting modem (TX) has a differential voltage source (V_{DM}) between its live and neutral with output impedance Z_{TXDM} . Similarly, the receiving modem is represented only by differential impedances, Z_{RXDM} between its live and neutral. TX excites a differential signal while the receiving modem receives the signal across live and neutral. Both the transmitting and receiving modems are not physically connected to the earth line. But at high frequency, the parasitic capacitances within the two modems provide coupling path between the modems and the earth line (the unwanted impedances due to parasitic capacitances are shown as Z_{TXCM} and Z_{RXCM}). Also, there are mutual couplings between the live, neutral and the earth wires, which are due to mutual inductance and capacitance between the three lines. In the frequency range from 1MHz to 30MHz inductive mutual couplings between the lines are more dominant compared to mutual capacitive couplings.

Due to these couplings, the equivalent electrical modem of the transmitting modem can be represented by two differential voltage sources of $(V_{DM}/2)$ and two source impedances of $Z_{TXDM}/2$, as illustrated in Fig 2.2. In addition, a CM voltage source (V_{CM}) is connected in series with the two differential voltage sources, to represent the CM noise present.

At low frequency, the transmitting modem mainly sees a low impedance path between live-to-neutral (electrical appliances) compared to the impedance between live-to-earth and neutral-to-earth, when the electric loads and the receiving modem are connected to the power lines. Hence, at low frequency, current from the source is mainly drawn by the low impedance path between live-to-neutral. However, at high frequency the impedance between live-to-earth and neutral-to-earth are comparable to that of live-to-neutral, due to the parasitic effects within the electrical appliances. Therefore the high frequency current drawn from the source is influence by all the three impedances.

Ideally, a PLC modem excites differential signal between live and neutral and is electrically isolated from the earth. For such a scenario, even when there is a CM noise source, there is no CM current because the CM impedance between modem and earth is infinite.

Fig 2.3: Power and Data Interface in a Typical PLC Modem

However, in reality, the parasitic impedances, Z_{TXCM} and Z_{RXCM} , within the modems cause CM path between the PLC modem and the earth line to appear. Fig 2.3 shows a power and data interface in a typical PLC modem. In the modem, the data path and AC

side of power supply are commonly connected to the live and neutral of the power line and are in close proximity to the power line. The power supply converts the AC power to the DC power for the modem's circuitry. The modem's circuitry runs on a high speed clock and generates high frequency noise at the secondary coil of the power transformer. Due to the parasitic capacitance between the primary and secondary windings of the power transformer, which at high frequencies, provides finite CM impedance path for the high frequency noise to bypass the transformer and induce CM current on the power line. The induced CM current in turn gives rise to CM radiated emissions [26-27].

In addition, the PLC modem has an isolation transformer to couple the information signal to the power line without being physically connected to the high voltage power lines. The isolation transformer allows useful DM information signal to pass through without any attenuation. However, it also has parasitic capacitance between its input and output terminals. Similarly, at high frequencies, the parasitic capacitance, which may not have sufficiently high impedance, can provide another path for CM noise from the modem to propagate to the power line and induce CM current over the power line. The induced CM current in turn gives rise to additional CM radiated emissions.

Other than unwanted CM noise coupling from the PLC modem to the power line, CM current can also be generated when the DM signal injected between the live and neutral wires gets converted to CM current along the power line [28-29].

In the ideal situation the following conditions are all met:

- The source is perfectly balanced (source is purely differential without any common-mode component).
- Both modems' impedance are balanced (impedance in series to modem's live and neutral is $Z_{DM}/2$).
- The power cable geometry is symmetrical from the source to the load (mutual inductances M_{LN}, M_{LE}, M_{NE} are equal and coupling capacitors C_{LN}, C_{LE}, C_{NE} are equal hence there is symmetrical coupling between the three lines).
- And the loads are also perfectly balanced ($Z_{LE} = Z_{NE}$).

And in the ideal scenario when all the conditions all met, the source experiences a power-line communication network with symmetric/balanced coupling whose input impedances between live-to-earth and neutral-to-earth are equal. Due to the equal input impedances, current drawn from the two voltage sources ($V_{DM}/2$) and current flowing through live and neutral are equal and totally opposite in phase. Therefore, the current flowing through the live-to-earth and the current flowing through neutral-to-earth cancel out each other. As there is no current through the earth wire, the overall net current through live, neutral and earth lines bundle is zero. Because of the net zero current, radiated emission from the perfectly balanced and symmetrical power line is zero. To clearly understand the mechanism of emissions from the balanced ($Z_{LE} = Z_{NE}$) and symmetric (mutual inductances and coupling capacitors among the three wires are equal, $M_{LN}=M_{LE}=M_{NE}$ and $C_{LN}=C_{LE}=C_{NE}$) power-line network, fullwave simulation software CST[24] is used and magnetic fields around the live, neutral and earth conductors is computed. Fig 2.4 shows the magnetic fields around each wire in the balanced load and symmetric power line network. As the currents flowing on the live and neutral lines are equal and opposite in direction, the magnetic fields generated by the live and neutral lines are of equal intensity and oppose each other. As the loads are balanced, insignificant current will flow in the earth line. Hence, the resultant magnetic field around the whole cable bundle is rather small and it indicates that CM current on the whole cable bundle is also small. Therefore, CM radiation from the symmetrical power network with balanced load is rather insignificant.

Fig 2.4: Canceling Magnetic Fields emitted @ 30MHz emitted by Live and Neutral Lines
(Balanced Case)

However, in reality the cross-sectional geometry of live, neutral and earth lines are not perfectly symmetrical as, for example, the separation distance between live-to-earth and neutral-to-earth lines are not exactly equal. Also, the live-to-earth terminated impedance (Z_{LE}) and neutral-to-earth terminated impedance (Z_{NE}) are not equal too. Due to these conditions the input impedances seen between the live-to-earth and neutral-to-earth may not be equal. Due to the inequality in the input impedances, the current drawn from the voltage sources flowing through live and neutral lines may not be equal and may not be totally opposite in phase. Also due to the inequality in coupling between the live-to-earth and neutral-to-earth respectively, currents in the two loops do not cancel out completely, and this results in significant current on the earth line. Therefore, for the unbalanced and the asymmetric case, net current through the live, neutral and earth lines bundle will not be zero. Because of this non-zero CM current, radiated emission from the PLC network can be significant if the CM current is high. To understand the mechanism of emission for the unbalanced ($Z_{LE} \neq Z_{NE}$) and asymmetric case (mutual inductances and coupling capacitors among the three wires are not equal, $M_{LN} \neq M_{LE} \neq M_{NE}$ and $C_{LN} \neq C_{LE} \neq C_{NE}$), fullwave simulation software is used and magnetic field around the live, neutral and earth conductors is computed. Fig 2.5 shows the magnetic fields around the three wires in the unbalanced load and asymmetric power line network case.

Fig 2.5: Non Canceling Magnetic Fields emitted @ 30MHz emitted by Live and Neutral Lines (Asymmetrical and Unbalanced Case)

As the currents flowing on live and neutral lines are not equal, the magnetic fields generated by the live and neutral lines do not cancel out completely. Also, the unbalanced loads and asymmetry of the power line results in finite current flowing through the earth

wire. Hence, the resultant magnetic field around the whole cable bundle is significant and it indicates a significant CM current flowing on the whole cable bundle. Therefore, significant CM radiation is expected under the situation of unbalanced load and asymmetric power-line network.

2.2 Concluding remarks

In this section, the causes of the CM current in the PLC network and the radiation mechanism from power line were explained. The radiated emissions were attributed to the incomplete cancellation of the currents flowing through the live, neutral and earth lines. In reality, high frequency signal can couple from the source to the power line due to parasitic effects as well as the power line is not perfectly symmetrical and the loads are usually imbalanced in nature. All these give rise to non-zero CM current, which in turn gives rise to significant radiated emissions from the PLC system.

Chapter 3

GENERATION OF COMMON-MODE CURRENT BY COUPLING FROM SOURCE

As explained in Chapter 2, in a typical PLC modem, the data path and the power transformer of the power supply are commonly connected to the AC outlet's live and neutral terminals as shown in Fig 3.1. The power transformer steps down the AC voltage for the regulator to convert it into DC voltage for the modem's internal circuitry. The high frequency DM information signal however is received and transmitted through an isolation transformer and a coupling capacitor (X2) as shown in Fig 3.1.

Fig 3.1: System diagram of a typical PLC modem

The parasitic capacitance between primary and secondary windings of the power transformer and the isolation transformer provide a path for the CM current over the power line. In this chapter, using a commercial PLC modem as a test case, the CM coupling paths from the modem [26-27] to the power line will be investigated to confirm our explanation as given in Chapter 2. With better understanding of the generation of CM current due to coupling from the PLC modem, some practical solutions will be proposed and implemented on the modem to isolate such CM coupling paths from the power lines.

3.1 Design of PLC Test Bed

To investigate into CM current generation due to high frequency noise coupling from the source to the power-line, a PLC test bed as shown in Fig 3.2, is designed to investigate into the generation of CM current over power line by means of CM impedance path in the PLC modem.

Fig 3.2: Experimental PLC Test Bed

On the PLC test bed, two modems (Aztech 14Mbps modem based on Intellon's PLC Chipset) with a communication bandwidth of 4 MHz to 21 MHz, one for transmitting and another for receiving, are connected through a 3 m long power cable consisting of the live, neutral and earth lines. Both modems are programmed to communicate continuously using a software provided by the commercial modem manufacturer. The PLC test bed is not connected to the AC Mains so that generation of CM current can be studied in a controlled scenario without any unnecessary complexities and without any unwanted interference from the real power line network. Since the PLC test bed is not powered by AC power, the transmitting and receiving modems are powered by a 9V battery. The 9V battery is connected to the modem's voltage regulator to supply power to the modem's internal circuitry.

Fig 3.3a shows the measured [30-33] live-to-neutral, live-to-earth and neutral-to-earth impedances of the actual power line network. These three impedances vary between 10 Ω and 200 Ω across the frequency range of interest. To achieve the impedance characteristic

close to the actual power-line network, appropriate loads are connected along the PLC test bed at 1 m intervals. Both Loads 1 and 2 are balanced loads of $200\ \Omega$ resistors, which are connected between live-to-earth and neutral-to-earth. Load 3 is an unbalanced load with a $150\ \Omega$ resistor connected between live-to-earth and a $15\ \Omega$ resistor connected between neutral-to-earth. With Loads 1, 2 and 3 and the receiver modem, the measured PLC test bed impedances between live-to-neutral, live-to-earth and neutral-to-earth are shown in Fig. 3.3b. Although it is impossible to resemble the actual power line network, the impedance variation between $20\ \Omega$ and $200\ \Omega$ is realistic enough for the study carried out in the thesis.

Fig 3.3 (a): Impedance of PLC Test Bed with Receiver Modem; (b) Impedance of PLC Lab's Power Network

To investigate the generation of CM current, the CM current flowing through the live, neutral and earth lines, and the radiated emissions from the PLC test bed are measured. CM current flowing through the live, neutral and earth bundle is measured with a clamp-on RF current probe (Schaffner CSP8425-1 with a bandwidth of 100 MHz) at the center of the 3 m PLC test bed. Radiated emissions from the test bed are measured using a rod antenna (EMCO 3301B Active Rod Antenna with a bandwidth of 50 MHz) at a distance 3 m away from the horizontally laid power lines. Radiated emission measurement is conducted in a 10 m semi-anechoic chamber housed in Electromagnetic Effects Research Laboratory (EMERL), situated in the university, as shown in Fig 3.4.

Fig 3.4: Experiment Setup in Semi-anechoic chamber in EMERL

3.2 Analysis of PLC Modem

The commercial broadband PLC modem used in the study is analyzed in detail to understand the CM current coupling path from the modem to the power line. With understanding, effective design techniques can be implemented on the modem to lower the CM current induced over the power line. Fig 3.5 shows the commercial broadband PLC modem under study. The main components of the broadband PLC modem are the digital circuitry, power transformer and the isolation transformer, as indicated in Fig. 3.5.

Fig 3.5: Commercial Broadband PLC Modem

The block diagram of Fig. 3.5 is shown in Fig 3.6.

Fig 3.6: High Frequency Noise Coupling

Although the primary and secondary coils are isolated from each other, there is a finite parasitic capacitance between the primary and secondary coil of the power transformer. To measure the parasitic capacitance, the transformer is taken out from the PLC modem. The two ends of the primary coil are shorted and two ends of the secondary coil are also shorted. The impedance between the two shorted coils is measured using an impedance analyzer (HP 4395 with a bandwidth of 500 MHz). Fig 3.7 shows the measured impedance between the two coils. It is about 7 k Ω at 1 MHz but falls to 400 Ω at 20 MHz. The impedance characteristic with increasing frequency shows a 20 dB per decade reduction, which indicates the impedance is capacitive in nature. The parasitic capacitance between the primary and secondary coils of the power transformer is found to be 10 pF based on the measurement result. At high frequency, the parasitic capacitance provides a relatively low impedance path between the PLC modem and the isolated earth line.

Fig 3.7: Impedance of power transformer's parasitic capacitance

Since the primary coil of the power transformer is connected to the power line, the parasitic capacitance offers a low impedance path at high frequency for the high frequency signal to propagate over the power line. Hence, the high frequency induced CM current over the power line [26-27]. Fig 3.8 shows the measured CM current over the power line in the PLC test bed. For the case when the power transformer is inside the modem, the CM current is found to be 25dB μ A at 21 MHz and nearly negligible at 4 MHz. Since the power transformer's parasitic capacitance has been identified as a low impedance path for the CM noise to propagate to the power line, the power transformer is removed from the modem. With absence of the power transformer, the modem receives its DC power from a 9V battery. Fig 3.8 shows that when the power transformer is removed from the modem, the measured CM current has reduced to about 10 dB lower compared to the case when power transformer is inside the modem. Hence, it confirms that the parasitic capacitance of the power transformer provides the CM propagation path for the high frequency noise to propagate from the modem to the power line.

Fig 3.8: CM Current Comparison: Modem with and without Power transformer

Similarly, Fig 3.9 shows that when the power transformer is removed from the modem, about 10dB reduction in radiated emissions is also observed at high frequencies as compared to the case when power transformer is inside the modem.

Fig 3.9 Radiated Emission Comparison: Modem with and without Power transformer

The strong correlation between higher CM current and higher level of radiated emissions for the case when power transformer is inside the modem indeed confirms that its parasitic capacitance is an important factor for the high level of CM radiation.

As mentioned earlier, in the broadband PLC modem, there is another interface between the modem's circuitry and power line. The wideband DM data signal transfers to and from the power line via the isolation transformer and the X2 coupling capacitor. The isolation transformer serves to couple the DM signal to the power line without directly connected to the high voltage AC mains. It also has a parasitic capacitance between its input and output terminals. The impedance between the primary and secondary windings of the isolation transformer is also measured using the one port impedance analyzer (HP 4395A with a bandwidth of 500MHz). Through the measurement, it shows that the impedance is about 200 k Ω at 1 MHz and reduces to 10 k Ω at 20 MHz, as shown in Fig 3.10. The parasitic capacitance of the isolation transformer is found to be about 1 pF between its input and output terminals.

Fig 3.10: Impedance of parasitic capacitance between isolation transformer's input and output terminals

Hence, the isolation transformer has much smaller parasitic capacitance than that of the power transformer. Anyway, at 20 MHz, it still provides an alternative CM path for the CM noise to propagate to the power lines.

In order to effectively block CM noise from propagating via the isolation transformer to the power line, it is necessary to increase the CM impedance of the path via which the CM noise propagates. Therefore, to increase the CM impedance seen by the high speed circuitry, an effective CM choke is inserted in series to the isolation transformer. The CM choke provides additional CM impedance to the isolation transformer without affecting the useful differential signal in the frequency range from 1 MHz to 30 MHz. Low DM impedance is desired so that DM signal can pass through it without much attenuation and extremely high CM impedance is essential so that CM noise can be effectively attenuated before it couples to the power line.

The EPCOS's 100 μ H CM choke (Part Number: B82789C104N2) is chosen because it has a low DM and high CM impedance, as shown in Fig 3.11a and Fig 3.11b, respectively. The 100 μ H CM is inserted in the modem, between the output of the isolation transformer and X2 capacitor, as shown in Fig 3.12.

Fig 3.11 (a): DM impedance of CM choke; (b) CM impedance of CM choke

Fig 3.12: PLC Modem with added CM choke

Fig 3.13 shows that when CM choke is inserted in series to the isolation transformer, the CM current over the power line drops by a further 5 dB, especially at high frequency compared to the case when no CM choke is connected in the modem. Radiated emission results in Fig 3.14 show that adding the CM choke lowers the level of radiated emission by 5 dB at high frequencies, which is consistent with the measured CM current result. The reduction in CM current and level of emissions for the case when the 100 μ H CM choke is added to the isolation transformer again has proven the parasitic capacitance of

the isolation transformer, though very small in value, could still contribute to higher CM radiation from the power line.

Fig 3.13: CM current Comparison: Modem with only Battery and with CM choke inside

Fig 3.14: Radiated Emission Comparison: Modem with only Battery and with CM choke inside

Fig 3.15 shows the final modifications done on the PLC modem. The power transformer is removed from the modem and the 100 μ H CM choke is added between the isolation transformer and the X2 capacitor.

Fig 3.15: Modifications to PLC modem
(Removal of power transformer and addition of CM choke)

Fig 3.16 compares the radiated emission results for three cases:

- Modem with power transformer;
- Modem without power transformer; and
- Modem without power transformer and with CM choke.

Fig 3.16: Radiated Emission Comparison for cases: Modem with, without power transformer and with CM choke inside.

A reduction of about 20 dB in radiated emissions is clearly observed after implementing all the proposed modifications on the commercial PLC modem. The significant reduction has clearly shown that the proposed modifications work very well to reduce CM radiation from the power line.

However, removing the power transformer is not a practical modification. Hence, a practical way to suppress CM coupling through the power transformer is to add another effective CM choke in series with the power transformer as shown in Fig 3.17. It will serve to block high frequency CM noise from propagating to the power line and to lower emissions from the PLC the network.

Fig 3.17: Proposed Practical Solution

3.3 Concluding Remarks

In this chapter, the CM path within the PLC modem was investigated. A realistic PLC test bed was designed to investigate possible CM coupling paths available in a broadband PLC modem. Analysis of the broadband PLC modem clearly showed that the inherent parasitic capacitances of the power transformer and the isolation transformer are the main causes of these coupling paths. Therefore to increase the CM impedance of the coupling paths within the modem, it was proposed to add the CM chokes in series with the power transformer as well as the isolation transformer. The proposed solutions proved to be effective and had demonstrated significant reduction of radiated emissions' level by 20 dB, especially at high frequencies.

Chapter 4

MODELING OF CURRENT PROBE

As mentioned in the earlier chapters, radiated emissions from power lines is caused by the CM current flowing through live, neutral and earth wires bundle. Since, CM current is strongly correlated to the radiated emissions from the power line bundle, it is important to understand generation of CM current flowing through the power line bundle as it will provide insights to design effective solutions to lower CM current as well as radiated emissions from PLC network.

To clearly understand the physical phenomenon which gives rise to CM current along the power-line network, it is necessary to model the power-line network in full-wave simulation software. As the actual CM current on the whole cable bundle will be measured by a clamp-on current probe, for ease of comparison, a full-wave current probe's model is suitable. According to Faraday's law, AC current flowing through a conductor emits field which cuts through a conductive coil and induce a voltage across the coil [34]. Based on this principle model of a realistic RF current probe can be used to accurately predict CM current in the power-line bundle consisting of live, neutral and earth wires, by simulating the "clamping" of the current probe onto the power cable bundle. With this prediction approach, the impact of power network's imbalance and asymmetry can be estimated accurately without the actual experimental setup. The RF current probe's model is developed using full-wave electromagnetic simulation software, CST [24] (Computer Simulation Technology) and its accuracy is validated against measurement results.

4.1 Current Probe Model

Fig 4.1: Typical RF Current Probe

Fig. 4.1 shows a commercially available RF current probe for CM current measurement [35-38]. The magnetic core of the probe has an outer diameter of 10 cm and inner diameter of 3.2 cm. To facilitate clamping the current probe onto a cable, the commercial current probe is made of two semi-circular cores with coil around each core. To simplify modeling of the current probe, it is modeled as a single circular core of outer diameter 10 cm with a window diameter of 3.2 cm. The magnetic core is made of material of reasonably high relative permeability so that it has the sensitivity to detect very small high frequency currents. Typically, magnetic core of a wideband current probe is made of Zinc-Manganese ferrite whose relative permeability is about 1,000. Therefore, the relative permeability (μ_r) of the modeled current probe is chosen to be 1,000. The number of turns around the core also affects sensitivity and bandwidth of the current probe. Usually, the number of turns is between 15 and 24. As a compromise between good sensitivity and reasonable bandwidth, 20 turn coil is chosen for the model. Fig. 4.2 shows the actual model of the current probe, designed based upon the above-mentioned parameters.

Fig 4.2: Physical Model of the Current probe

For modeling, CST uses a time-domain based Finite-Difference Time-Domain (FDTD) technique. In the FDTD technique the whole simulation volume including the structure is meshed into regular (square/rectangle) cells and the necessary parameters are computed at each cell [39,40]. Cells size should be much smaller (about 10 times) than the wavelength of the propagating wave so that the parameters (E & H fields) do not change drastically from one cell to another cell. Also because the cells are regular in shape in order to mesh a circular structure, the cells at the circular boundary have to be fine enough so that the structure's round boundaries can be closely modeled as round curvatures [41]. For PLC, highest frequency of operation is 30MHz therefore wavelength of the propagating wave would be approximately 10 m and hence for FDTD technique cell's size should be at least 1m. But because the current probe is about 10cm in diameter in order to model it's round curvature properly, it is meshed finely using cells of 1 mm, 3 mm and 1 mm in the x, y and z axes, respectively as shown in Fig 4.3a & b. The current probe is placed in an air-filled simulation volume which measures 0.5m by 0.3m by 1m in x, y and z axes, respectively. The 1m dimension in the z axis is necessary because a ground plane is modeled at 1 m away from the current probe to represent a distant ground plane in real situation. The whole simulation volume including the current probe is meshed using a total of 861,300 cells.

Fig 4.3 (a): Top View of Current Probe; (b) Zoomed View of Quarter Current Probe; (c) Side View of Current Probe

4.1.1 Transfer Impedance and Transfer Function of Current Probe

Fig 4.4: Current Probe Calibration Model

Current flowing through the conductor emits changing magnetic field which induces voltage across the probe's terminating load and current through the probe's coil. Therefore, in order to the predict current flowing through the conductor, it is important to

evaluate the parameter which relates the current through the conductor to the voltage induced across the probe's terminating load (transfer impedance) and the parameter which relates the current through the conductor to the current induced in the probe's coil (transfer function).

To obtain the transfer impedance and transfer function of the current probe, the modeled current probe is placed around a modeled conducting loop as shown in Fig. 4.4. The rectangular conducting loop is 10 cm by 25 cm and is excited by a constant current source. As the conductor is modeled using the perfect electric conductor (PEC), a $1\ \Omega$ resistive load is specified in the loop to avoid violation of infinite current in the electromagnetic modeling software. For convenience, the loop is excited by a 1 A current source so that transfer function and the transfer impedance of the modeled probe can be computed with reference to 1 A directly, without further adjustment. Fig. 4.5 shows the simulated current in the loop, which stays nearly constant at 1 A across the frequency range of interest from 1 MHz to 30 MHz.

Fig 4.5: Current through Loop

Fig 4.6 shows the current transfer function of the modeled current probe. It is found to be between 0.05 and 0.055 and is acceptable because once current flowing through the probe's coil is known, the transfer function can be used to compute the current through the conductor. Hence, the transfer function conveys that 1 A current in the conductor induces about 0.05 A in the probe's coil.

Fig 4.6: Current Transfer Function

With the current transfer function, the actual current flowing through the conductor which is sensed by the current probe can be calculated using the following expression:

$$I_{conductor} = \frac{I_{cp}}{Tf_{cp}}$$

where $I_{conductor}$ is the predicted current flowing through the conductor, I_{cp} is the current in the current probe's coil and Tf_{cp} is current probe's transfer function.

The transfer impedance of the modeled current probe is about 1.3Ω ($2.3\text{dB}\Omega = 20 \times \log [1.3 \Omega]$) as shown in Fig 4.7, which is comparable to the transfer impedance of commercially available current probe and therefore is acceptable. Once the modeled current probe is characterized from 1 MHz to 30 MHz with its transfer impedance, current through a conductor can be predicted with good accuracy. Approximately 1.3 V is induced in the probe's coil by the 1 A current flowing through the conductor.

Fig 4.7: Current Probe Transimpedance

Thus current flowing through the conductor can also be calculated using the current probe's transfer impedance using following expression:

$$I_{conductor} = \frac{V_{cp}}{Z_{cp}}$$

Where V_{cp} is the voltage induced across current probe's 25Ω load and Z_{cp} is the current probe's transfer impedance.

4.2 Current Probe Model Validation

To validate the RF current probe's model using the full-wave simulation tool [22], a simplified monopole is fabricated and is also modeled using the full-wave software. The previously modeled current probe is used to predict the current flowing through the monopole's wire and the predicted current is compared with measured current flowing through the fabricated monopole.

Fig 4.8: Monopole Antenna Design, (a) Top View ; (b) Side View

The description of the fabricated monopole is shown in Fig 4.8. The ground plane is made of copper of size 20 cm by 20 cm. At the middle of the ground plane, a SMA connector is mounted on the ground plane and a wire of diameter 0.71 mm and length 30 cm is soldered to the centre pin of the connector. The monopole is excited through the SMA connector with a $2 V_{rms}$ input sinusoidal voltage with respect to the ground plane. The voltage is kept constant at $2V_{rms}$ in the frequency range from 1 MHz to 30 MHz and is supplied by a signal generator (HP E4433B with a bandwidth of 4 GHz). The voltage

excitation gives rise to the current flowing through the wire of the monopole. The current is measured along the wire at different locations (1 cm, 15 cm and 29 cm away from the ground plane) with a RF current probe (Tektronix CT6 with a bandwidth of 2GHz).

Based upon the dimensions of the fabricated monopole, a 3D model of the whole monopole antenna is developed using CST, as shown in Fig 4.10. The modeled monopole has a 20 cm by 20 cm copper ground plane whose conductivity is specified to be 5.0×10^7 S/m. At the centre of the ground plane, monopole's wire of diameter 0.71 mm and length 30 cm is fed through a SMA port. It is also modeled as copper wire of conductivity of 5.0×10^7 S/m. The wire is excited through a SMA connector by a constant voltage of $2V_{rms}$, with respect to the ground plane from 1 MHz to 30 MHz. Fig 4.9 shows the details of the modeled SMA connector. The SMA feed to the wire is 0.112 mm in diameter and it is surrounded by PTFE substrate of relative dielectric constant of 2.33 and diameter of 4 mm.

Fig 4.9: SMA Feed (Top View)

The current flowing through the monopole is predicted at the three different locations by placing modeled current probe at the three locations (1 cm, 15 cm and 29 cm away from the ground plane), as indicated in Fig 4.10.

Fig 4.10: Monopole Antenna Model, (a) Top View ; (b) Side View

The monopole and current probe are modeled with the Finite-difference Time-Domain (FDTD) technique by meshing them using fine cells of 1 mm by 3 mm by 1 mm in the x, y and z axes, respectively, so that round and small structures can be modeled properly as illustrated in Fig 4.11. The whole structure is placed in an air-filled volume which measures 23 cm by 36 cm by 23 cm, in the x, y and z axes, respectively, as shown in Fig 4.12. The whole simulation volume including both the monopole and the current probe in the given volume is meshed using a total of 940,000 cells.

Fig 4.11 (a): Top View of Monopole and Current Probe; (b) Side View of Monopole and Current Probe

Fig 4.12: Monopole and current probes in air-filled simulation volume

4.3 Experimental Validation

The measurement and simulation results are given in Fig. 4.13. The maximum deviation between measured and predicted CM current is within 3 dB. As the measurement uncertainty of the spectrum analyzer is about ± 2 dB and current probe also has a ± 2 dB tolerance, the deviation of 3 dB is considered to be acceptable for good agreement between predicted and measured CM currents. Hence, the modeled current probe model is reasonably accurate and can be employed to predict CM current along any structure, including bundle of wires for the case of power-line network.

Fig 4.13: Comparison of Measured and Simulated Current flowing through Monopole

4.4 Concluding Remarks

In this chapter, a 3D model of a RF current probe is developed to predict CM current along any conducting structure. Based on a fabricated monopole, current probe model is validated experimentally. Good agreement between the predicted current and measured current proved that developed current probe's model can be used for predicting CM current generated over the power line network in the next chapter.

Chapter 5

GENERATION OF COMMON MODE CURRENT ON POWER LINES

When CM current in the frequency range from 1 MHz to 30 MHz flows through long power lines in a PLC system, it causes the long power lines to radiate as an efficient wire antenna. As verified in the Chapter 3, the emissions from the power lines are strongly correlated to the CM current flowing through the power line bundle consisting of live, neutral and earth lines. As mentioned earlier, the CM current is generated not only due to couplings from the source (PLC modem) to the power line, but also due to factors such as imbalance in the live-to-earth and neutral-to-earth impedances and the physical asymmetry between live-to-earth and neutral-to-earth [22-23, 28-29] of the power line. In this chapter, these factors and their impacts on the generation of CM current over the power line bundle are investigated.

5.1 PLC system Test Bed

Fig 5.1: Design of the PLC Test Bed

In order to facilitate the study on the generation of CM current for the cases such as balanced loads, imbalanced loads and asymmetric power lines, a realistic PLC test bed is designed, as shown in Fig 5.1. Usually, the imbalance at the source can be ignored because the commercial PLC modem is designed to be balanced in the frequency range of interest. The coupling from the modem due to the parasitic capacitance is not considered in the study as the effects have been investigated in the previous chapter. Also, the effects due to couplings from source can be isolated by adding carefully selected chokes.

The transmitting and receiving modems (Aztech 14Mbps modem based on Intellon's PLC Chipset with a bandwidth from 4MHz to 21MHz) are programmed to communicate continuously over the 3 m long power cable using the software provided by the modem manufacturer. The PLC test bed is not connected to the AC Mains so that the effects that affect the measurement, such as unwanted interference from the real power line network, can be eliminated. Since the PLC test bed is not powered by the AC power, the transmitting and receiving modems for all the test cases are powered by the 9V batteries.

Along the 3m test bed appropriate loads are connected to represent realistic indoor environments. In realistic indoor environments, many devices are connected to the AC mains but not all of them are in switched on condition. In electrical terms, devices which are switched on have low impedance connection between their and the main's live, neutral and earth. Hence, balanced devices which are plugged into the mains and are switched on do not cause impedance imbalance between live-to-earth and neutral-to-earth. However balanced devices which are plugged into the mains socket but are not turned on would exhibit low impedance between neutral and earth and high impedance between live and earth. Hence, the balanced devices which are plugged but are not turned on, cause an impedance imbalance between live-to-earth and neutral-to-earth. Also, some of the electrical appliances may not be balanced in nature with their impedance between live-to-earth and neutral-to-earth not being equal, such as the impedance imbalance of a typical oven, as shown in Fig 5.2 (refer to impedance measured using Two-Current Probe Method in [30-33]). On the PLC test bed, balanced load scenario is emulated by connecting 15 Ω resistive loads between live-to-earth and neutral-to-earth, whereas

imbalanced load scenario is emulated by connecting a 1.5 k Ω resistor (representing high impedance connection) between live-to-earth and a 15 Ω resistor between neutral-to-earth (representing low impedance connection). Three such loads are connected along the test bed at 1 m intervals to resemble a case of a real power network with many devices connected to it. The CM current is measured at the midpoint of the 3 m long test bed using a RF clamp-on current probe (Schaffner Chase CSP-8425-1 with a bandwidth 100 MHz).

Fig 5.2: Impedance Imbalance between Live-to-Earth and Neutral-to-Earth for an Oven

5.2 Physical model

The 3D model of the power cable in the test bed is developed with the fullwave EM simulation software, CST, based upon the following physical parameters:

- The 3m long power cable consists of copper live, neutral and earth wires. The cable is placed 1 m above a ground plane to represent a real situation where a metallic ground plane is not in close proximity to the power lines.

Fig 5.3: Core diameter of the Power Line and Wire-to-Wire Separation Distance among the power lines

- The wire diameter is defined to be 1 mm and wire-to-wire separation distance is specified to be 5 mm, as shown in Fig 5.3.

Fig 5.4: Excitation Current on Live Line

- Transmitting modem is modeled by a balanced differential current source between live and neutral. Fig 5.4 shows the measured current from the PLC modem, which is of different level at different frequency band. The current in the frequency range from 4MHz to 21MHz is the signal current whereas current in the frequency bands 1MHz to 4MHz and 21MHz to 30MHz is the spurious current and therefore

the level of spurious current is much lower compared to the level of signal current. As the signal current level from 4MHz to 21MHz is much higher than spurious current, the signal source is only modeled as a current source of amplitude 900uA (p-p) and simulation is carried out only in the frequency range from 4MHz to 21MHz.

Fig 5.5 (a): Impedance seen between modem's live and neutral terminals; (b) Impedance seen between modem's live and earth & neutral and earth

- Receiving modem's input impedance between its live and neutral is shown in Fig 5.5a is measured using two-current probe method [30-33]. The modem's impedance between live-to-neutral varies between 40 Ω and 90 Ω . As an approximate model to the modem, 60 Ω is chosen in our PLC test bed for ease of simulation. The receiver modem is modeled with a 60 Ω resistor between live and neutral and connected at the end of the power cable.
- For the balanced load case, 15 Ω resistive loads are connected between live and earth and neutral and earth. For the imbalanced load case, a 1.5 k Ω resistive load is connected between live and earth and a 15 Ω resistive load is connected between neutral and earth.
- To study the impact of asymmetry of power lines, the asymmetry in the power line network is modeled by separating the neutral wire 10 mm away from the earth wire and keeping the live wire 5 mm away from the earth wire. The separation distances are maintained along the entire 3 m power cable.

The PLC test bed's complete model is shown in Fig 5.6. The previously developed current probe is employed to predict the CM current through the power line bundle for the three cases, namely balanced loads, imbalanced loads and asymmetric power lines. The modeled current probe is “clamped-on” at the mid-point of the 3 m test bed.

Fig 5.6: Physical Model of the Designed Test Bed

Fig 5.7 (a): Top View of PLC test bed; (b) Side View of PLC test bed

Fig 5.8: PLC test bed structure in air-filled simulation volume

The whole PLC test bed is modeled using the FDTD technique. The PLC test bed and the current probe are finely meshed by 1 mm, 30 mm and 2 mm cells in the x, y and z axes, respectively, as shown in Fig 5.7 to properly model the round and small structures. The whole structure is placed inside an air-filled simulation volume, which measures 1.12 m, 4.19 m and 1.63 m, in the x, y and z axes, respectively, as shown in Fig 5.8. The whole volume including the test bed and current probe structure are meshed by 2.42 million cells.

5.3 Balanced and Symmetric Case

A balanced and symmetric case is when impedances between live-to-earth and neutral-to-earth line are equal, and the power lines cross sectional separations are equal from each other. Usually a well designed electric appliances have their live-to-earth and neutral-to-earth impedances almost equal. Therefore, when a device is plugged into AC mains and turned on, then there is a low impedance connection between device's and AC mains' live, neutral and earth wires therefore the load will be seen as balanced. In the model, the low impedance connection for the balanced case is represented by connecting 15 Ω load resistors between live-to-earth and neutral-to-earth.

Fig 5.9 shows the predicted currents flowing through the live, neutral and earth wires in the frequency range from 4MHz to 21MHz. For the balanced and symmetric case, the current flowing in the live and neutral are equal in magnitude and totally opposite in phase. It is expected because the balanced source (transmitting modem) sees equal impedances between live-to-earth and neutral-to-earth. Also, the power line is symmetrical and no DM current to CM current conversion is taking place. And because of currents flowing in the live-to-earth loop and neutral-to-earth loop cancel out completely almost zero current flows in the earth wire, as shown in Fig 5.9 it is at least 60 dB lower than the currents in live and neutral wires.

Fig 5.9a Current through Live, Neutral and Earth Line (Balanced and Symmetric Case)

Fig 5.9b: Phase Comparison of current through Live and lines
(Balanced and Symmetric Case)

Since current flowing through live and neutral are equal in magnitude and totally opposite in phase and there is negligible current flowing through the earth, the CM current flowing through the whole power line bundle is very low, as shown in Fig 5.10.

Fig 5.10: CM Current Comparison (Balanced and Symmetric Case)

On a balanced and symmetric network, because the currents flowing on the live and neutral lines are equal and opposite in direction, the magnetic fields generated by the live and neutral lines are of equal intensity and oppose each other as shown in Fig 5.11. As the loads are balanced insignificant current flows in the earth line. Hence, the resultant magnetic field around the whole cable bundle is rather small and it indicates that CM current on the whole cable bundle is also small. Therefore, CM radiation from the symmetrical power network with balanced load is rather insignificant.

Fig 5.11: Magnetic Fields Emitted by Power Lines at 20MHz
(Balanced and Symmetric Case)

5.4 Imbalanced and Symmetric Case

Usually the electrical appliances are balanced in nature with their live-to-earth and neutral-to-earth impedances almost equal. However, when the balanced electrical appliances are plugged into the AC mains and are not turned on, then there is a high impedance connection between the device's and AC mains' live wire and a low impedance connection between the device's and AC mains' neutral and earth wires. Therefore, when plugged devices are not turned on then the impedances seen between live-to-earth and neutral-to-earth will not be equal. Such imbalance in live-to-earth and neutral-to-earth impedances can be significant, especially at high frequency. Using an oven as a sample (plugged to the AC mains but not switched on), it is found that the impedance imbalance between live-to-earth and neutral-to-earth can be as much as 100 times, with low impedance as low as $10\ \Omega$ and high impedance can be as high as $1\ \text{k}\Omega$ in the frequency range of interest. Hence, the high and low impedance connection for the unbalanced case is represented in the model by connecting a $1.5\ \text{k}\Omega$ resistor between live-to-earth and a $15\ \Omega$ resistor between neutral-to-earth.

Fig 5.12a: Current through Live, Neutral and Earth (Imbalanced and Symmetric Case)

Fig 5.12b: Phase Comparison of current through Live and Neutral lines (Imbalanced and Symmetric Case)

For the imbalanced and symmetric case when loads connected to live-to-earth and neutral-to-earth are not equal, currents flowing through live-to-earth loop and neutral-to-earth loop are not equal in magnitude and are not totally opposite in phase, as shown in Fig 5.12. Therefore, the currents in the live-to-earth and neutral-to-earth loops do not completely cancel out, and results in significantly higher current flowing through the earth wire, as shown in Fig 5.12a, as compared to the case for the balanced loads (Fig 5.10).

As the currents in the live and neutral do not cancel out completely and significant current flows through the earth, high CM current flows through the power line bundle is expected, as indicated in Fig 5.13a. Fig 5.13 shows the CM current results for the balanced and unbalanced test bed. The difference for the balanced and unbalanced cases is about 20 dB on average for the measurement results. The predicted CM currents for both the balanced and unbalanced cases also show similar trend. Hence, in general, the measured and predicted CM currents from 4MHz to 21MHz are in reasonably good agreement.

Fig 5.13: (a) Measured CM Current Comparison; (b) Predicted CM current Comparison

For the unbalanced and symmetric case, because the currents flowing on live and neutral lines are not equal, the magnetic fields generated by the live and neutral lines do not cancel out completely as shown in Fig 5.14. Also the unbalanced loads results in finite current flowing through the earth wire. Hence, the resultant magnetic field around the whole cable bundle is significant and it indicates a significant CM current flowing on the whole cable bundle. Therefore, significant CM radiation is expected under the situation of unbalanced load.

Fig 5.14: Magnetic Fields Emitted by Power Lines at 20MHz (Imbalanced and Symmetric Case)

5.5 Asymmetrical Power Lines and Balanced Case

Fig 5.15: Core diameter of the Power Line and Asymmetrical power lines

In real situations live, neutral and earth lines are laid individually through a plastic conduit pipe, therefore the lines may not be totally equidistant from each other. In other words the live, neutral and earth lines are an asymmetrical network. Such asymmetry can cause the DM current to be converted to CM current on the power line. To study the impact of power line asymmetry on CM current, the asymmetry is introduced in the model by placing neutral line 10 mm away from earth line, with the live-to-earth distance maintained at 5 mm, as illustrated in Fig 5.15. Balanced loads of $15\ \Omega$ resistors are connected between live-to-earth and between neutral-to-earth.

Fig 5.16a: Current through Live, Neutral and Earth Line (Asymmetrical Case)

Fig 5.16b: Phase of the Current through Live and Neutral lines (Asymmetrical Case)

Fig 5.16 shows that the current flowing through the live and neutral is almost equal in magnitude and opposite in phase due to the balanced loads. However, due to the asymmetry, the mutual couplings from live to earth and from neutral to earth are not equal. Due to this asymmetry, some finite current in earth wire is resulted, as shown in Fig 5.16. Fig 5.17 shows that the CM current is about 10 dB higher as compared to that for the balanced case.

Fig 5.17: CM current generated due to asymmetrical lines

For the asymmetric power-line network with balanced loads, because the currents through live and neutral are equal and opposite in phase, the fields generated by the live and neutral lines are equal in magnitude and oppose each other as shown in Fig 5.18. But due to the asymmetry there is a finite current flowing through the earth wire. Hence, the resultant magnetic field around the whole cable bundle is significant and it indicates a significant CM current flowing on the whole cable bundle. Therefore, significant CM radiation is expected from asymmetric power-line network.

Fig 5.18: Magnetic Fields generated at 20MHz by asymmetrically placed lines

5.6 Impacts of Various Factors on CM Current

Fig 5.19: CM Current Comparison

The impacts of balanced loads, imbalanced loads and asymmetric power line on the CM current have been studied. For ease of comparison, Fig 5.19 shows the CM current on the power cable bundle for the three cases. Using the ideal case of balanced loads and symmetrical power line network case as a reference, the imbalanced loads case is the major contributing factor of CM current generation, and is about 20 dB higher than the ideal case. Whereas the case of an asymmetric network is the next dominant contributing factor which generates 10dB higher CM current as compared to the ideal case.

In summary, imbalanced load is the most dominant factor that gives rise to significant CM current and high level of emissions. CM current generated by the coupling from the source (PLC modem) was lowered by implementing CM coupling suppression techniques on the commercial PLC modem, but the solutions are unable to lower the CM current generated over the power lines due to the imbalanced loads.

In reality, long power line network will have asymmetry and the loads connected to it are likely to be imbalanced. Both of these factors will give rise to significant CM current and high level of radiated emissions, and therefore, it adds complexity to suppress CM radiation from a real PLC network.

One possible and practical solution would be to add DM filters within the electrical appliances so that these imbalanced loads “appeared” to be balanced, at least in the PLC operating frequency band. It will add to the product’s cost but it may be justifiable if significant reduction in emissions is achieved.

In order to explore the possibility of lowering CM current for the imbalanced loads case, a PLC test bed with imbalanced load and filter is designed as shown in Fig 5.20. In this study, the power lines are tied together so that impact of asymmetry of power cable can be neglected in this case. Suitable loads are connected at 1 m intervals along the 3 m test bed. Load 1 (200 Ω resistors are connected between live-to-earth and neutral-to-earth), Load 2 (an imbalanced oven) and Load 3 (150 Ω between live-to-earth and 15 Ω between neutral-to-earth) are connected.

Fig 5.20: PLC Test Bed Design with imbalanced oven and EMI filter

Oven is chosen as one of the loads, because as shown in Fig 5.21a, it has a realistic impedance imbalance between its live-to-earth and neutral-to-earth. And because the oven is imbalanced, when it is connected to the PLC test bed, the overall impedance characteristic of the PLC test bed also becomes imbalance between live-to-earth and neutral-to-earth, as shown in Fig 5.21b.

Fig 5.21 (a): Impedance Imbalance of oven; (b) Impedances of the PLC test bed with oven

To ensure that the transmitting and receiving modems see a relatively balanced network even when imbalanced oven is connected to the PLC test bed, a filter is now connected to the AC power inlet of the oven. The DM filter components will block the DM signal current from flowing to the imbalanced oven in the frequency range from 1 MHz to 30 MHz. An EMI filter (CORCOM's 6A, Model 6EP3) as shown in Fig 5.22a is chosen for the study, as it provides sufficient DM attenuation in the frequency range from 1 MHz to 30 MHz, as shown in Fig 5.22b (the attenuation is measured with respect to 50 Ω) and hence will provide a high DM impedance between the PLC test bed and the imbalanced oven.

Fig 5.22 (a): EMI Filter Design; (b) EMI Filter Attenuation Factor

Fig 5.23 shows that before the filter is added to the oven, significant CM current is measured due to the imbalanced nature of the oven at high frequency. The measured CM current is as high as 50 dB μ A. Fig 5.24 shows that measured emissions level is also significantly higher with the imbalanced oven, and emission is as 60 dB μ V/m, which is about 10 dB higher than the FCC's limit of 50 dB μ V/m.

When the mentioned filter is added to the imbalanced oven, due to the high DM impedance (line-to-line) presented (solid line in Fig. 5.22b), the oven with the filter appears as a balanced load to the PLC network. Hence, the CM current due to imbalanced load is now reduced significantly, as indicated in the measured CM current and radiated emission results. The reduction can be as high as 30 dB, especially at high frequency. Radiated emissions drop to about 30 dB μ V/m, which is 20 dB lower than the FCC's limit.

Fig 5.23: CM current Comparison: Imbalanced Oven without and with Filter

Fig 5.24: Radiated Emissions Comparison: Imbalanced Oven without and with Filter

The significant reduction in the measured CM current and radiated emissions proves that the proposed technique of adding a filter with high DM impedance within the imbalanced electrical appliance can be an effective way to reduce CM radiation from the PLC network. The filter used in the study is rather costly. A simple DM choke with high DM attenuation should be able to achieve similar level of reduction in the radiated emissions.

Addition of a filter with high DM impedance is shown to suppress CM current and radiated emissions generated due to the presence of imbalanced loads, however the filter may not be able to provide such a high suppression if the CM current is generated because of asymmetry of power-line network. But assuming a symmetric power-line network is reasonable because in Singapore, the power-lines are tied tightly together and are laid in the buildings through a conduit pipe.

Moreover, addition of a filter with high DM impedance in the electronic products will not affect the PLC operation as well as appliances' operation. Also it would suppress interference caused by the conducted current from the product and from neighboring appliances.

5.7 Concluding remarks

In this chapter, with the help of full-wave 3D EM model of a PLC test bed, impacts of balanced loads, imbalanced loads and asymmetric power line on CM current over the power line were investigated in details. Comparison of the CM current for the three cases highlighted that load imbalance is the major contributing factor that gives rise to significant CM radiation from the power lines.

One of the feasible methods to lower the emissions from PLC network due to imbalanced loads is to connect an effective DM filter at the power inlet of the imbalanced loads so that, the PLC network will see relatively balanced loads in the PLC operating frequency range. The technique was tested and verified on a PLC test bed with an imbalanced oven and CM current and emissions were lowered by nearly 30 dB.

Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

PLC Technology is a convenient and economical alternative for broadband access, multimedia communication and home automation. However the existing PLC technology has issues which are hindering its commercialization and widespread use. One of the main issues is the significant level of CM radiation emitted from the PLC system, which interferes with radio receivers and electronic devices operating in the HF band. Numerous field trials have shown that the emission levels, on the average, are about 20dB higher than the FCC limit of 50dBuV/M. Although these field trials have shown consistent high levels of radiated emissions from the PLC network, no comprehensive in-depth investigation and study have been carried out to understand the fundamental radiation mechanism of the PLC system.

In this thesis, the CM current generation over the power line at high frequencies due to CM noise coupling from source, impedance imbalance and asymmetric power lines are explained. Firstly, using a commercial broadband PLC modem as a case study, the parasitic capacitances of the power and the isolation transformers have been identified as the high frequency CM paths that provides path for the high frequency noise from the PLC modem to couple to the power line. The coupled high frequency noise in turn induced CM current over the power lines. To lower CM current generated by these couplings, effective design techniques were implemented on the modem to provide good isolation of the high frequency noise from propagating to the power line. Through experiments using the PLC test bed, the proposed techniques lowered the CM current and emission levels by about 20dB.

Once the CM coupling path from the source was resolved, the next step was to investigate the conversion of DM signal current to CM current along the power line in the presence of impedance imbalance and asymmetric power line. To study generation of

CM current over the power line, a 3D model of a current probe based upon commercial current probe's mechanical and electrical specifications was developed with a full-wave simulation software. The current probe model was validated experimentally using a monopole antenna as a test example.

Using the developed current probe model and the PLC test bed model, CM current over the power line due to imbalance loads and asymmetric power line was studied. Using the ideal balanced loads case as a reference, the simulation and experimental results showed that imbalanced loads play a dominant role in generating CM current over the power lines. In reality, the loads connected to power lines are imbalanced in nature. One of the feasible solutions to suppress CM current generated due to imbalanced load was to connect a DM filter at the power inlet of the imbalanced load. The filter would provide a high impedance connection between the PLC network and the imbalanced load so that the transmitting and receiving modems see a relatively balanced PLC network, which would emit lower level of emissions compared to the imbalanced PLC network. To study the effectiveness of adding the DM filter to the imbalanced load in lowering the radiated emissions, a filter was added to an oven on a PLC test bed. Measurement of CM current and radiated emissions showed that when the filter was added to the imbalanced load, the CM current and radiated emission level, especially at high frequency, dropped by nearly 30 dB. With such a significant reduction, it has been shown that with careful design and planning, CM radiation from PLC network can be lowered to meet the FCC limit.

6.2 Future Work

The solutions, which were proposed in the thesis to suppress CM radiation from the PLC network, have to be incorporated into cost-effective practical designs. Further work has to be conducted in realistic indoor settings so that the effectiveness of the proposed solutions can be assessed critically.

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List of Publications

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Biography

Manish Oswal received the B.Eng. degree in Electrical Engineering from National University of Singapore in 2003. After graduation he has been working with Nanyang Technological University as a Research Engineer. He worked in collaboration with overseas Universities and Institutes on EMC projects and also provided EMC consultation to the customers in the private and public sectors. Currently, he is pursuing his M.Eng. Degree in Nanyang Technological University, Singapore. His main research interests are in Electromagnetic Compatibility (EMC) and Communication engineering.