A BIFILAR APPROACH TO POWER AND DATA TRANSMISSION OVER COMMON WIRES IN AIRCRAFT

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Abstract

Since digital control, monitoring and diagnostics of various mechanical, hydraulic, or electric functions have found their ways into aeronautical applications, there is an increasing demand for data communications. Local area networks and field bus solutions meeting aeronautics requirements have become standard. However these systems add considerably to an aircraft's wiring harness complexity and weight.

Transmitting data over power lines (Powerline Communications – PLC) is proposed as a remedy against the progressive increase in wiring harness complexity. In a PLC approach dedicated wiring for data transmission may be completely removed and modem, coupling and filtering components can be integrated into the aircraft application equipment resulting in a solution providing a single connector for power and data.

The power distribution for a significant amount of the systems in an aircraft is based on a single wire method in which the metal chassis is used for the current return path. Such a wiring solution is disadvantageous for PLC in achieving EMC standards compliancy and in regards to ingress of noise due to crosstalk.

An alternative approach is therefore proposed to aeronautical onboard PLC that replaces the single wire by a double wire (bifilar approach), providing a homogenous and well defined symmetric transmission line (differential mode) for data, but maintaining the asymmetric mode with a common ground return path for the distribution of power (common mode). This solution improves the performance of a PLC based data network dramatically and is also the key to achieving compliance with existing EMC norms. It will be shown in this article that these benefits may outweigh the drawbacks of the required double wire cabling.

Introduction

Based on results obtained from, among other sources, the European Union (EU) Power Optimized Aircraft (POA) project, electrical systems are replacing conventional hydraulic and pneumatic systems in order to develop the More Electric Aircraft (MEA) or even All Electric Aircraft (AEA) [1-2]. The disadvantage of MEA/AEA is that the transfer to electrical systems could result in significantly more wires leading to considerable weight, complexity and space allocation increases.

One of the possible solutions to mitigating the increase in wires is to integrate separate power and data distribution networks into a single network providing both data and power transmission. Currently, two such solutions are being investigated in the EU project TAUPE (Transmission in Aircraft on Unique Path wirEs [3]) using either Powerline Communications (PLC) in order to enable data transmission over the power distribution network or Power over Data (PoD) in order to transmit power over data cabling. This article will focus on specific parts of the PLC solution.

The goal of the TAUPE project is to provide a fully optimized avionic architecture for power and data transmission on unique path wires. For the PLC solution, two different reference applications are being investigated: the Cabin Lighting System (CLS) and Cabin Communication System (CCS). These reference applications were selected as they are representative both in terms of data traffic as well as wiring harness complexity for a wider variety of non-flight critical aircraft (A/C) systems. The development of the PLC solution has been aided through extensive numerical simulations of propagation channel characteristics [4], measurements on a test bench representative of an A/C wiring harness [5] and integration into a full demonstrator (Cabin Mock-up at EADS-Innovation Works in Ottobrunn, Germany).

Technologies and standards for PLC are in a very mature state for in-home and, to a lesser extent, automotive applications, however its use in A/C applications has only received minimal attention (see [6] for an overview of previous work). These standards may also principally be applied in aeronautics applications. Adapting existing PLC technologies for use in an A/C is unfortunately not straightforward. A PLC solution for use in an A/C may suffer from a number of drawbacks including:

- *Adverse propagation channel*: complex wiring harnesses with multiple branches and dynamic loads lead to a frequency selective and (slow) time varying channel.
- *Noise*: Ingress noise is generated from various sources and is further complicated through crosstalk in complex wiring bundles.
- *EMC compliance*: EMC emissions standards in civil A/C (RTCA/DO160 [7]) are very restrictive in their limits for unwanted emissions. By convention, a spectrum allocation, i.e. declaration as intentional emissions, for a wired technology (PLC) is not permitted, thereby limiting the allowed transmission levels of the PLC signal.

This article begins with a description of the PLC technology including a general architecture for use in A/C applications. A detailed description of the bifilar approach is then presented followed by an overview of various measurement results which have been performed on bifilar networks. Finally, the topic of wire fault detection with the bifilar approach is discussed including an innovative solution for resolving that issue.

PLC Technology

Using PLC technology in a power distribution network, a modulated high frequency carrier signal is superimposed over the existing power signal, e.g. 115 VAC/400Hz or 28 VDC. PLC technology generally allows for communications over any shielded or unshielded wired networks which do not meet the requirements for high frequency applications in terms of delay spread, frequency flatness and noise. This is the major differentiating point between PLC and other wire line technologies which require a dedicated wiring network such as Ethernet.

PLC technologies can be generally separated into two categories: narrowband systems and broadband systems. Narrow band solutions typically operate in the frequency band below 500 kHz in the USA or below 150 kHz in Europe and provide maximum data rates of only a few hundred kbps.

On the other side are the broadband technologies which operate in the frequency band between 1 and 30 MHz with newer standards (see IEEE P1901) supporting transmission up to 50 MHz. These technologies typically provide maximum raw data rates of 200 Mbps. Aside from a higher data rate, broadband PLC solutions can provide robustness against frequency selectivity and narrow band noise through frequency diversity, resilience to impulsive noise and low latency. As these aspects are critical for the complex wiring networks and systems in the A/C, a broadband technology has been selected for use within the TAUPE project.

The PLC technology used within the TAUPE project is based upon the European standard OPERA which was developed within two EU funded FP6 projects. The physical layer is based upon OFDM providing 1536 subcarriers within a 10, 20 or 30 MHz channel, depending on transmission mode. Two different bit loading modes are supported: an adaptive mode in which the bit loading is dynamically adapted between 2 – 10 bits/symbol (QPSK – 1024 QAM) based on real-time SNR measurements and a robust HURTO (High performance Ultra Redundant Transmission mOde) with a high level of redundancy and forward-error correction. A raw data rate of up to 205 Mbps or 150 Mbps at the application layer can be supported.

At the medium access control layer a master-slave logical topology is defined in which the master node is responsible for the channel access allocation of all nodes in the network. Multiplexing and channel access is based on a time division concept. The channel access allocation from the master is dynamically distributed through the use of a virtual token. The token designates the next node allowed to transmit (all other nodes must delay transmission) and the maximum transmission time. At the end of a transmission, the token is returned to the master. The OPERA standard provides a QoS mechanism in order to influence the allocation of the token based on the traffic type. The exact algorithm for the allocation of the token is left as a proprietary solution for the technology provider.

PLC System Architecture in Aircraft

The conventional approach used in A/C systems is to provide power and data distribution on separate networks as is shown in Figure 1. The power network is typically multi-tiered with a complex wiring harness topology (multiple branches) providing point-to-multipoint distribution of the power signal to application devices. Due to the complexity and large number of systems in an A/C, the cross section of a wiring harness bundle may include over 100 wires from multiple branches and/or systems. Data networks may be point-to-point or point-to-multipoint field buses providing low or high bandwidth communications. This means that each application device must provide two separate interfaces in order to access the power and data networks[1].

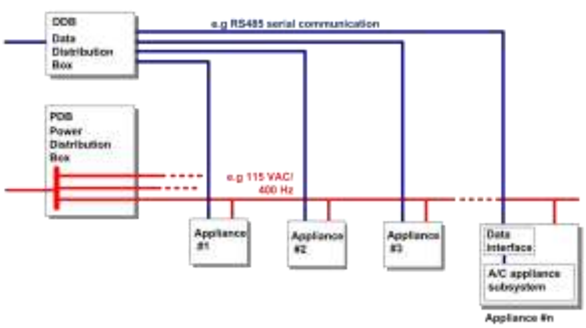

Figure 1: Conventional approach for power and data transmission in an A/C

In a PLC approach, dedicated wiring for data transmission may be completely removed and the necessary additional modem, coupling and filtering components can be integrated directly into the application equipment resulting in a solution providing a single interface for power and data (see Figure 2). The PLC signal coupler is used to combine/split the power and data signal through either capacitive or inductive coupling. The filter is used to stabilize the load impedance as well as to suppress noise generated in the power supply system or in any other part of the application equipment.

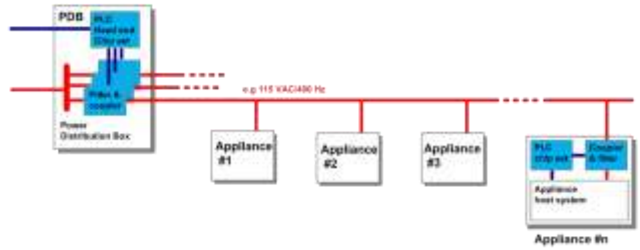

Figure 2: PLC approach for power and data transmission in an A/C

Furthermore, an optimized PLC architecture takes advantage of the multi-tiered or branched nature of the power distribution network in order to increase the reusability of the limited PLC bandwidth. As previously mentioned, the PLC signal bandwidth is limited to 30 MHz which allows for approx. 200 Mbps raw throughput per PLC cell which must be shared by all users in that cell. As transmission range and bandwidth would not be sufficient for supporting A/C-wide systems with hundreds of application devices such as the CLS, a cellular approach has been defined. In the cellular approach master PLC modems are integrated at key branching locations in the network, e.g. the secondary power distribution boxes (SPDB). With proper filtering within the SPDB, neighboring PLC cells can be isolated from conducted emissions; thereby allowing a large reuse of the limited available bandwidth throughout the A/C. PLC signal ingress from neighboring cells through crosstalk may hinder this re-use, however this can be mitigated through the bifilar approach as will be described in the following section.

Bifilar Approach

Disadvantages of the Monofilar Approach

A majority of the power distribution networks in the A/C are based on a single wire (monofilar) method in which the metal chassis is used for the current return path. The major problem of using a monofilar power distribution network for PLC is related to its single wire nature. A general single wire network is shown in Figure 3. A single wire power distribution has the advantage that it is a simple and

[1] Some application devices integrate data and power into a single connector, however they still provide two logically separate interfaces.

cost effective solution providing a low resistance return path as well as weight savings.

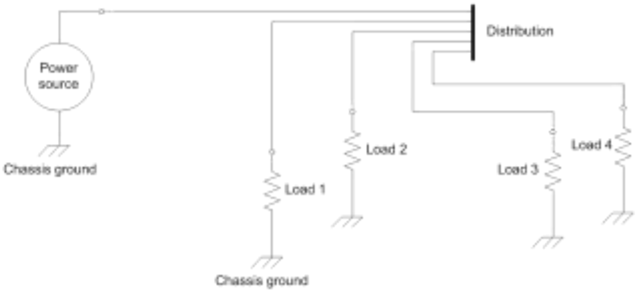

Figure 3: Single wire power distribution network with return path via chassis ground

Regarding their use for communications at frequencies up to 30 MHz, such networks appear unsuitable as they are characterized by an asymmetric transmission line structure with undefined characteristic impedance resulting from variations in the cross-sectional geometry due to varying height over ground, branching at sub-distributions, and the effect of the surroundings in wire bundles.

Assuming the bundling of wires as is typical in A/C, the asymmetric lines provide little cross-talk attenuation since electric and magnetic fields of different wires in the same bundle are largely congruent (see Figure 4). Furthermore, in terms of EMC aspects, monofilar networks lead to relatively strong radiated fields (egress), unfavorable conditions in regards to existing EMC norms limiting conducted unwanted emissions in terms of common mode (CM) currents as well as little protection against radiated high frequency fields (ingress).

While most PLC technologies in use today are designed to cope with considerable delay spread and frequency selective fading, other channel impairments like cross-talk, noise, interference egress and ingress may still lead to loss of communication performance and reliability.

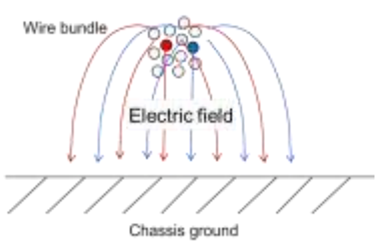

Figure 4: Electric field distribution of two different wires in a bundle

Common Mode Suppression

According to the conducted emissions section of the RTCA/DO160 norm for civil aeronautics applications [7], a current measurement is defined in which the current clamp is placed over the single wire in a monofilar harness. This means that, for a PLC system operating on a monofilar network, the PLC signal is measured directly without the benefit of any CM suppression.

On the power distribution network, the PLC technology operates in a frequency band which is seen as unwanted RF emissions regarding EMC. Therefore, if a PLC communication system is to be integrated into an A/C, it must comply with the relatively strict levels for conducted and radiated emissions. Other equipment operating on the same power network must also comply with the same levels as the PLC equipment. Even when filtering is integrated into the PLC equipment, noise from adjacent equipment/systems due to crosstalk in complex bundles, could lead to an insufficient SNR transmission margin.

Alternative Approach

Due to the previously mentioned drawbacks, an alternative, *bifilar*, approach to PLC onboard A/C is proposed which replaces the single wire by a (preferably twisted) twin wire. Power distribution will use the twin wire in CM or asymmetric mode with the return path via chassis ground as in the classical scheme. Thus, AC or DC currents induced by power sources will be, in the ideal case, split into equal halves (see Figure 5) allowing use of wire with a smaller copper cross section to gain back some of the extra harness weight and space that is inherent to the twin wire approach. As PLC operates with low signal voltages, there are only relaxed requirements in regards to insulation between the two wires. This may additionally pay off in mass savings, provided that insulation material is predominant and assuming a novel wire technology in which the two conductors are embedded in a common insulation. The shortened end at the bifilar wiring termination points lends itself well to the use of an inductive (current) coupling method by means of a differential mode (DM) transformer as shown in Figure 5. Alternatively, capacitive (voltage) coupling with a DM choke towards the shortened end may be used.

Since AC or DC currents for power delivery are CM, their magnetic fields ideally cancel inside the ferrite core of the DM coupler or DM choke as the windings (currents) corresponding to the two wires of the balanced line are in opposite direction (see I_a and I_b in Figure 5). So assuming that these AC or DC currents have equal strength as stated above, there will ideally be no core biasing. This allows generally smaller core sizes to be used, i.e. reduced size and weight. Coupler design furthermore becomes an important aspect as any asymmetry in the coupler may convert system extrinsic CM noise into DM noise or it may convert PLC DM signals into CM signals that leak out to the network. This will also impact EMC characteristics of the system. Asymmetries or current imbalances may not only be generated within the coupler, but also in the wiring network. Therefore, a set of measurements investigating these aspects in a bifilar network has been made and the results are presented in the following section.

One may argue that this concept makes a PLC solution redundant and any twisted pair single wire-line communications technology may do the job, e.g. existing field bus standards, Ethernet, AFDX, HomePNA, xDSL, etc. This is however not true since the ramified topology of the power distribution network and thus the multi-path propagation phenomena will still exist even with the proposed solution. A PLC technology resilient to signal delay spread and frequency selective attenuation is still required.

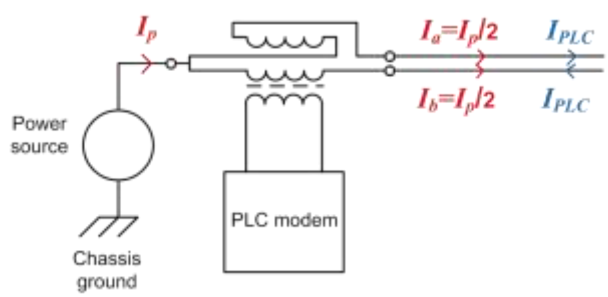

Figure 5: Currents in the bifilar approach

The advantages of the bifilar approach are summarized below. *Crosstalk is reduced* as the coupling due to mutual inductance and capacitance between the victim bifilar pair and the disturber bifilar pair or monofilar wire in the same wiring bundle is less than that between two monofilar wires.

The bifilar system allows the *PLC modems to operate with a higher transmission level* as benefits can be gained with respect to the DM to CM conversion ratio. With existing EMC current measurement concepts, the current clamp would be placed around both wires in the bifilar pair. In the ideal case, this would result in a complete cancellation of the measured PLC signal as the differential currents flow in opposite directions, i.e. the ratio of DM current to CM current or Common Mode Conversion Ratio (CMR) due to the PLC signal would be infinite. However, due to impedance asymmetries in the bifilar wiring network, e.g. at connectors, branch points, etc., some of the DM current from the PLC signal will be converted into CM current. This means that the effective transmission power will still be limited in order to be compliant to the applicable CM EMC limits. However, the effective transmission power may be increased above those limits by a factor equal to the CMR. A statistical measurement of the CMR on the available bifilar test bench is presented later in this article.

Radiated emissions levels will also be reduced as the majority of the PLC signal exists as a DM current and the radiation from the bifilar twisted pair is minimal. The majority of the radiation will occur due to the relatively large loop created between harness and ground (A/C chassis) for CM current.

A further advantage of the bifilar approach, albeit with a minor impact, is in terms of the *PLC signal transmission*. As previously mentioned a monofilar network will provide a highly undefined characteristic impedance towards ground and neighboring wires of a bundle. However, it has been shown through both simulations and measurements that the average gain in terms of the transfer function between two ports of the wiring network (S_{21}) is minimal across the PLC frequency band. In general, the transfer function over the bifilar network did show less frequency dependent variance. Figure 6 shows an example of this difference. The figure compares the S_{21} measurement made between the same ports of two identical – in terms of topology – networks, one bifilar and one monofilar. The final advantage of the bifilar approach exists for *wire fault detection* which is discussed separately later in this article.

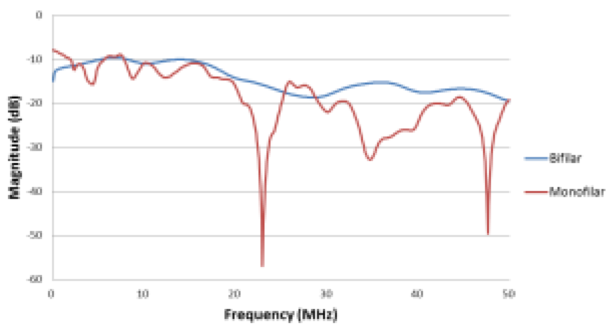

Figure 6: Example of the transmission on a monofilar vs. bifilar network

Although a number of advantages have been presented, the main advantage can be summarized in terms of the gain in SNR from the CMR (signal level) and crosstalk (reduced noise) which will be quantized in the following section. The bifilar approach is, however, not without its potential disadvantages. Splitting the single wire into a pair of wires may have a negative impact through increased weight, harness volume as well as integration and manufacturing complexity compared to a monofilar system. It also rules out a retrofitting approach for integrating PLC into existing A/C. Within the TAUPE project, a detailed assessment including different variations of bifilar cabling (untwisted pair, twisted pair, flat cable, etc.) was performed investigating propagation characteristics and industrial aspects such as weight, volume, manufacturing complexity and costs. In terms of propagation characteristics, the results were heavily in favor of the bifilar approach as the SNR with the monofilar approach was shown to be insufficient for supporting reliable communications for the reference applications [4]. The increase in weight, volume and manufacturing costs for the bifilar approach compared to the monofilar approach was found to be acceptable while still allowing the overall PLC solution to provide significant gains compared to existing separate data/power network systems[2].

[2] Exact comparison figures are still under evaluation and will be published at a later date.

Measurement Results

As described in the previous section, the main advantage of the bifilar over the monofilar approach is the gain provided for SNR which is the most critical factor in any communications system. This gain can be defined by two components:

$$G_{bifilar} = G_{CMR} + G_{crosstalk},$$

where $G_{bifilar}$ denotes the SNR gain in dB for the bifilar vs. the monofilar approach, G_{CMR} the gain in dB of allowed transmission power spectral density (p.s.d.) due to the differential mode-to-common mode ratio (CMR), and $G_{crosstalk}$ the gain in dB due to the reduced cross coupling in a bifilar vs. a monofilar network.

This section will present measurements results which have statistically quantized this gain. Performance in terms of EMC emissions levels cannot be directly quantized as emissions are influenced by a number of different factors. Here, the advantage will be shown by presenting results of civil avionics conducted EMC measurements.

Current imbalance, crosstalk and CMR measurements were performed on the Low Power Test Bench (LPTB) developed by Safran Engineering Services in Villemur-sur-Tarn, France. The LPTB [5] has been designed to be representative of an A/C wiring harness for the target applications in terms of transmission characteristics, CM/DM currents and crosstalk. RTCA/DO160 EMC measurements for conducted and radiated emissions were conducted at the National Aerospace Laboratory (NLR) EMC facilities in Marknesse, Holland.

Power Supply Current Imbalance Measurements

Assuming that AC or DC power supply currents have equal strength as stated above, there will ideally be no core biasing in a DM bifilar power line coupler. Thus, smaller core sizes may generally be used without risk of saturation. This is desirable in regards to components weight and space requirements.

In real bifilar networks however, some supply current imbalance due to wiring resistance asymmetry is to be expected. In order to determine the extent of the current imbalance in a bifilar wiring network and to optimally design the bifilar power line coupler, a set of measurements was made on the

LPTB. In these measurements, the normalized power supply current imbalance as defined by

$$\lambda_d = \frac{|I_a - I_b|}{|I_a + I_b|}$$

was determined at each port of the LPTB. All ports were terminated with respect to CM with a load resistance which was much larger than the measured wiring resistances to guarantee equity of current flow into all network branches when injecting a DC current at the main SPDB port. An example test setup to measure the differential power supply current is shown in Figure 7. A DC power supply was used and measurements were made by injecting a high representative current (20-30 A) into the network. The maximum normalized current imbalance was found to be 1.9%. Therefore, even in the worst case, the current on each wire of the bifilar pair can be considered equal and no significant measures are necessary in order to compensate for the imbalance. This finding can be explained by the fact that wire resistance predominates contact resistance of intact terminals by several orders of magnitude. This is also true for short wire sections.

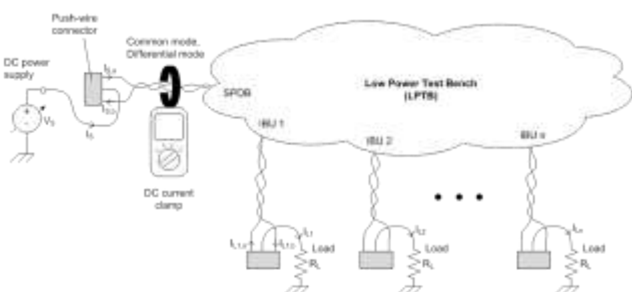

Figure 7: Set-up to measure differential power supply current

Loose, oxidized or charred terminal connections or broken wire may lead to a strong current imbalance exceeding design limits (ratings) of a weight-optimized power line coupler and of weight optimized wiring. Such defective connections represent a potential danger to the A/C safety, particularly since conventional circuit breakers would not trip in such events. In the last section of this article it will be shown how this apparent shortcoming in detecting the current imbalance of a weight-optimized bifilar PLC system can actually be turned into an advantage.

Crosstalk Measurements

In order to determine a statistical coupling factor which could be expected between neighboring wires in a wiring harness, a number of measurements were performed on the LPTB. The LPTB consists of four independent networks: short line (SL) bifilar, short line monofilar, long line (LL) bifilar and long line monofilar. Both short line wiring networks run in parallel with each other as can be said for both long line wiring networks. Only certain sections of the short line and long line networks run in parallel with each other. Considering that a number of A/C systems may exist within a wiring harness, monofilar and bifilar wiring may co-exist in a single harness. Therefore, three different cases for crosstalk could be considered: bifilar to bifilar, monofilar to monofilar and monofilar to bifilar. One could assume that for future systems in A/C all bifilar powerlines would be properly conditioned through filtering of the devices on the bifilar powerline, but monofilar lines not part of the PLC system would not have this conditioning. Therefore the coupling of noise from the monofilar powerline onto the bifilar powerline would be the most critical case regarding communication performance and the most interesting for comparison with the existing monofilar to monofilar case.

The LPTB enables all three of these cases to be tested. For the crosstalk measurements, the source was always located on one network (either SL bifilar or SL monofilar) and the "victim" was on a different network than the source. The transmission scattering parameter (S_{21}) was measured using a network analyzer. Each port of the network analyzer was connected to the LPTB using a low-loss, highly symmetric coupler or directly to a BNC connector for a bifilar or monofilar network port, respectively. Furthermore, each port at which measurements were not made was terminated with a purely resistive load. Figure 8 shows an example measurement setup for the case of measuring bifilar to monofilar crosstalk.

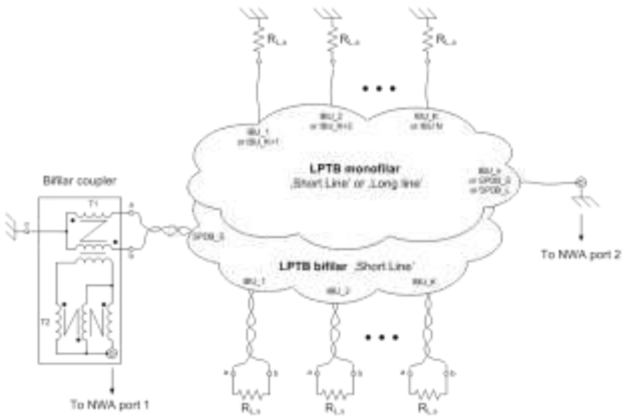

Figure 8: Crosstalk measurement setup

Measurements were made at a number of different port combinations in order to generate a sufficient statistic including worst case near end crosstalk. An example measurement directly comparing the three different crosstalk cases is shown in Figure 9. It is important to remember that the OPERA based PLC signal will be from 2-32 MHz. Therefore, in order to properly compare the bifilar approach to the monofilar approach it is important to look at the improvement in crosstalk performance with the total collection of measurements within this frequency range and not just to draw conclusions from maximum or minimum values within this range.

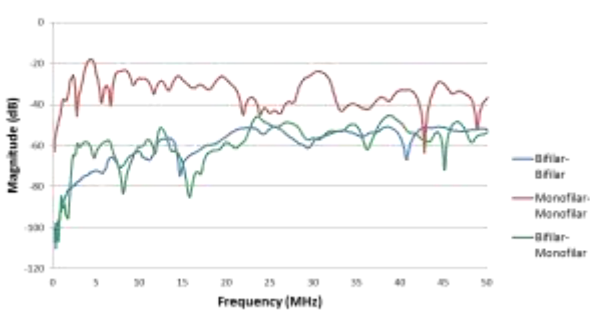

Figure 9: Example crosstalk measurement

For this purpose a histogram showing the improvement in terms of crosstalk performance between the bifilar-monofilar crosstalk and the monofilar-monofilar crosstalk has been generated for four different frequency ranges and is shown in Figure 10. As can be seen, there is a significant improvement in terms of crosstalk for the bifilar approach within the frequency range of interest. Even for the worst case bifilar-monofilar crosstalk case, the average improvement was found to be approximately 28 dB over the monofilar approach. Looking directly at the measurement results, it is obvious that the crosstalk improvement is less at higher frequencies (> 20 MHz). However, the results clearly show that for two-thirds of the frequency range of interest, the average improvement is above 30 dB.

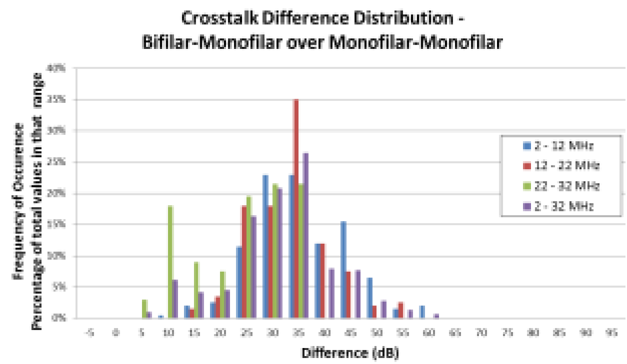

Figure 10: Crosstalk improvement Bifilar-Monofilar compared to Monofilar-Monofilar

Common Mode Conversion Ratio

Any asymmetry in the bifilar wiring system is a potential cause to convert DM current into CM current. CM currents are responsible for EM conducted and radiated emissions, thus determining the EMC of the PLC equipment when installed in a real network. Measurements have been performed to obtain statistical data on the network's CMR and to derive a DM current limit which is equivalent to a p.s.d. limit for the PLC equipment when connected to the nominal line impedance. Operating PLC at this limit in a real A/C bifilar wiring network will ensure that both conducted emissions (CM currents) and radiated emissions (electric field) are below defined limits for a high percentage of cases.

An ensemble of measurements has been collected on the bifilar networks of the LPTB with all ports terminated by a well-defined impedance. The reason for this is based on the assumption that both the DM impedance and CM impedance of all A/C appliances (PLC or non-PLC) connected to a bifilar wiring network will be standardized in the future as shown in Figure 11. Thus, the bifilar network can be assumed fully impedance conditioned in regards to both DM and CM. This conditioning only applies to equipment (PLC or non-PLC) located on a bifilar powerline, i.e. all equipment in the A/C must not be conditioned. This may mean in the end that a future bifilar standard will specify the PLC coupler and the CM impedance conditioning circuit.

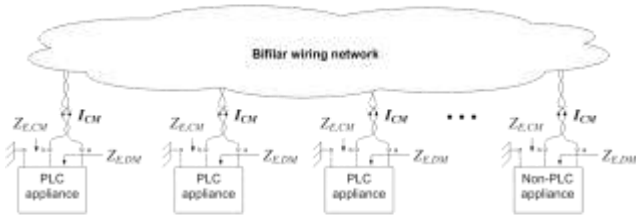

Figure 11: Impendence of a future bifilar wiring network

The ensemble of measurements was collected by performing a "near end" S_{21} measurement using a network analyzer at each port of the SL and LL bifilar network. Here near-end means that S_{21} was measured at a point close (<5cm) to the bifilar coupler at which the DM current was injected at the PLC port. This is opposed to "far-end" measurements in which the current probe would be placed at points further away from the DM current injection port. The near end measurements are statistically speaking the worst case, i.e. present the smallest CMR, and therefore only near end measurements are used for the statistical ensemble. This assumption was confirmed through a number of measured samples. The near end measurement set up is shown in Figure 12. All other ports of the network were terminated with bifilar couplers developed especially within the TAUPE project. Furthermore, the PLC port of each bifilar coupler was terminated with a 50 Ohm resistor and each coupler was grounded to the ground plane of the LPTB. This creates the required well-defined impedance condition on the network.

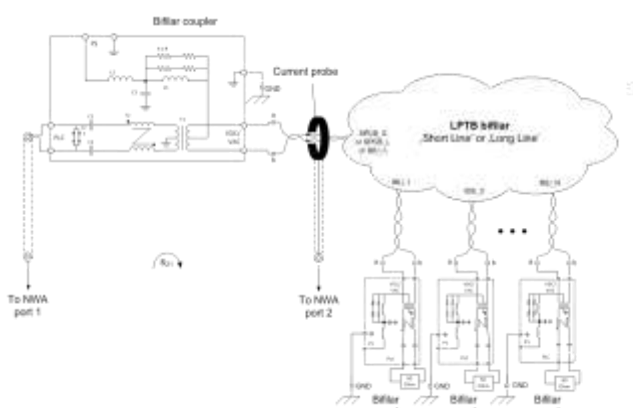

Figure 12: Setup of near end CMR measurement

The CMR has been defined as follows:

$$CMR(f) = \frac{I_{CM}(f)}{I_{DM}(f)@R_{DM}},$$

where $I_{DM}(f)@R_{DM}$ denotes the DM current as measured under nominal loading conditions at frequency f. This loading condition that approximately matches to the modem's source impedance has been defined as: R_{DM} = 100 Ohms. According to this definition, CMR can be also understood as the measured CM current normalized to the square root of the available p.s.d. of the PLC signal source. As the normalization is the same for the ensemble of measurements, CMRs reflect the measured CM currents in absolute terms, regardless of the actual DM currents.

Using this definition and measurement method, the ensemble of normalized CM measurements as shown in Figure 13 has been obtained. The general trend of the measurements shows that the CMR is frequency dependent and increases with increasing frequency (CMR in dB is negative!). In regards to the statistical nature of CM conversion in real networks and in accordance with commonly applied EMC product certification policies, namely the 80/80 rule (cf. [8]), the 80% percentile has been found adequate to define the characteristic CMR of a bifilar network. In order to determine the 80% percentile which is the CMR value for which 80% of the measurements were either less than or equal to that value, a relative cumulative histogram was generated and is shown in Figure 14. To show the frequency dependent nature of the CMR, the relative cumulative histogram is shown for five different frequency ranges. According to the measured statistical ensemble, the 80% percentile point for the CMR for the frequency range of interest for OPERA technology (2-32 MHz) has been determined to be -23 dB.

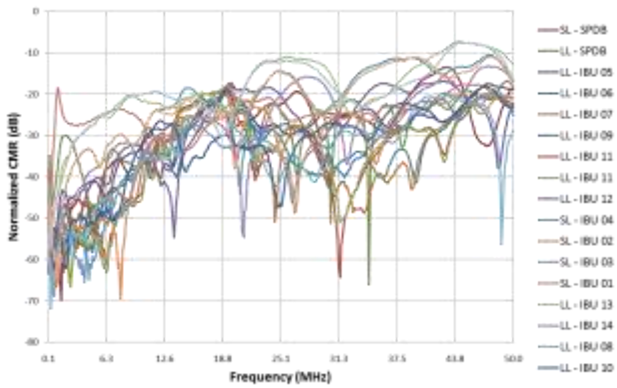

Figure 13: Ensemble of normalized CM currents as measured at different ports of the LPTB

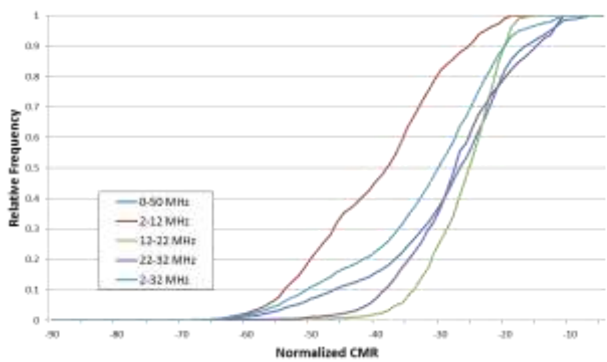

Figure 14: Normalized CM currents - relative cumulative histogram

EMC Compliance Tests

Within the TAUPE project, conducted and radiated emissions tests were performed according to section 21 of the RTCA/DO-160E standard [7]. The DO160E test setup for conducted emissions was extended in order to support a bifilar PLC system as shown in Figure 15. The Equipment Under Test (EUT) now only provides a single interface for power and data according to the PLC approach. As the PLC modem in the EUT will not transmit a representative PLC signal on its own, a stimulating PLC modem is integrated into the test setup (located outside the shielded enclosure) in order to provide a suitable communications sink for the EUT's transmitted PLC signal. Representative data traffic was generated between the EUT and the stimulating modem. A bifilar coupler is inserted between the EUT and the standard Line Impedance Stabilization Network (LISN) to couple the signal from the stimulating modem onto the bifilar wiring harness. In order to measure the CM current the measurement current probe was placed around the pair of wires in the bifilar wiring harness at a distance in accordance with the standard DO160E setup. All other aspects of the test setup were made in accordance with the DO160E standard.

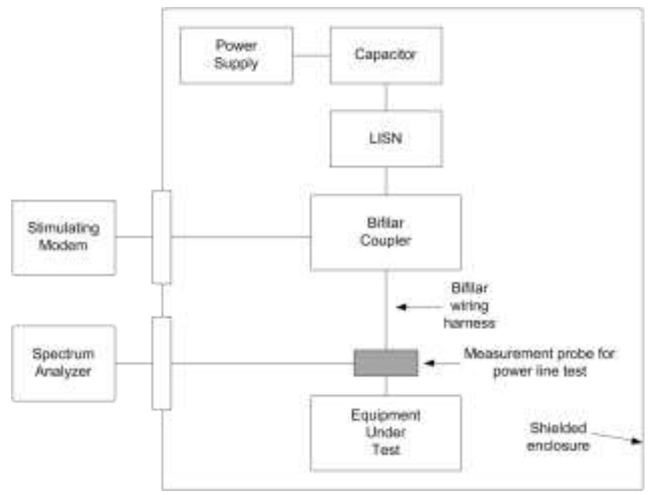

Figure 15: Modified DO160 conducted emissions test setup

During testing the PLC modem in the EUT was configured to transmit at the maximum available p.s.d. of -50 dBm/Hz and with all OFDM carriers at the same level in the frequency range from 2 to 30 MHz. Carriers above 30 MHz were masked out. The result of the measurements for 28 VDC bifilar PLC equipment is shown in Figure 16 and Figure 17. The measured interface has been designated as a category M interconnecting bundle interface. Therefore the limit level shown in red in those figures is that for interconnecting bundles. However, as can be seen, the measured levels would still be below the more restrictive power line interface limit (20 dBuA in the range between 2 – 30 MHz). The conducted emissions measurements were performed on two further types of PLC equipment developed within the TAUPE project with similar pass results.

EMC radiated emissions test results are currently under internal review so that the results are not available at the time this article was prepared.

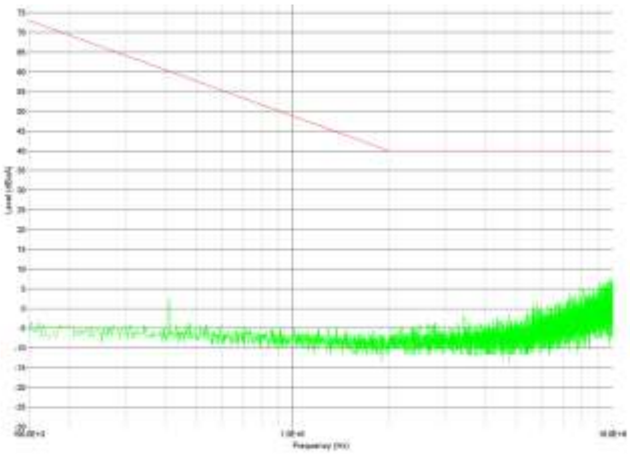

Figure 16: 115VAC PLC equipment DO160E conducted emissions measurement – 2-10 MHz

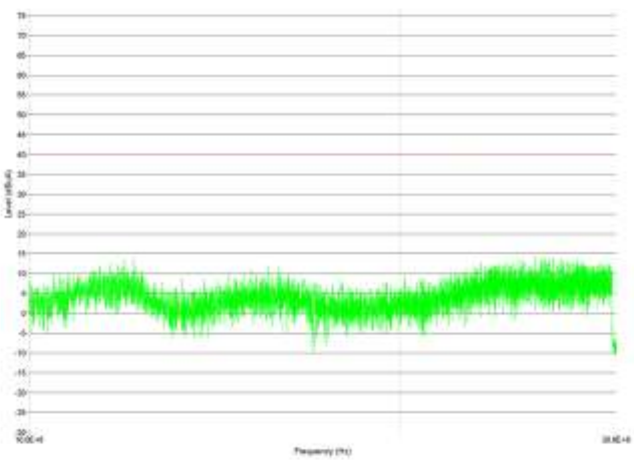

Figure 17: 115VAC PLC equipment DO160E conducted emissions measurement – 10-30 MHz

Bifilar Wire Fault Detection

In normal conditions (intact wiring), currents on a bifilar pair will split into halves with only a very minor imbalance, since the total wire path resistance will be largely dominated by the wire's resistance and not that of connectors, branches, etc. A problem that is inherent to the bifilar approach arises from the fact that a single broken wire or an increased contact resistance, e.g. due to a loose terminal connection, will disturb the current balance. This may have the following secondary effects:

- Increase of current flow through the yet intact connection. In an extreme case, single wire current may exceed the rated current by up to 200%.
- Saturation of the power line coupler transformer leading to degraded performance of the PLC system or even the complete loss of the communication link.
- Conversion of an increased portion of the PLC DM injected current into CM leading to increased radiated emissions

Conventional circuit breakers that simply detect the sum current would not trip in such an event. Therefore, a special means to reliably detect wire faults leading to current imbalance is required. This can make a virtue out of necessity in the sense that the bifilar, thanks to its inherent redundancy, can enable a means to detect almost any kind of wire faults including arc faults; even those which may not be reliably detectable in a conventional monofilar power distribution system.

The current state-of-the-art in arc fault detection is the relatively new Arc Fault Circuit Interruption (AFCI) technology. Using AFCI, electrical circuits are monitored for events that are indicative of potentially unsafe wiring conditions which could result in fires or loss of electrical circuit functionality. AFCI technology has been used in households since the early 1990's. However, the use of AFCI technology in an A/C provides a number challenges [9] including, among others:

- Support for the variable frequency (200 Hz to 800 Hz) AC signals and DC (28VDC) used in A/C. Frequency dependent detection algorithms will be adversely affected.
- Differentiating between the normal steady state and transient A/C load conditions. This actually turns out to be the key challenge in arc fault detection within A/C as active or new types of loads in an A/C can lead to insufficient performance or failure of the detection algorithm.

Current sensing in each wire of the bifilar is proposed in order to provide the required accuracy and reliability. Two current sensors are inserted in each wire as shown in Figure 18. A slight change in the conducting or insulating properties in one of the conductors or both will instantly lead to a change of the corresponding current, which, when correlated to the current in the other conductor, means that arc faults can be detected in a sensitive and robust manner. For example, in Figure 18, I_a would be correlated with I_b. If the correlation result proved to be above a certain threshold, then a fault event would be detected. In the event of a wire fault including an arc fault, the two current waveforms will always differ. The advantage of this method is that this threshold can be relatively low compared to typical AFCI algorithms as no margin must be allowed for transient load effects or other masking effects. Also, new loads or fault types can easily be introduced into the system as the correlation and detection threshold are always relative to actual conditions and not pre-defined values. This optimized detection threshold is believed to be very sensitive (detecting minimal arc faults, e.g. series arcing) and robust resulting in a lower probability of nuisance trips. It can also be anticipated that the bifilar approach will, per se, reduce the probability for series arcing as to enable a series arc both wires have to be broken.

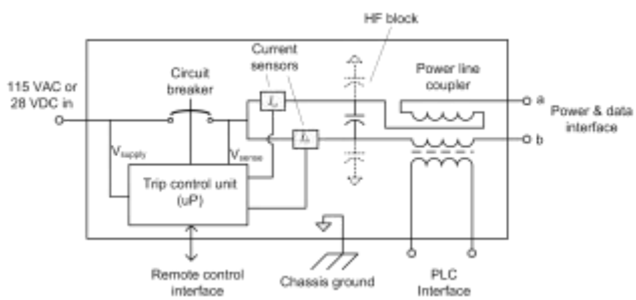

Figure 18: PLC enhanced bifilar circuit breaker

The current sensors could be based on the Hall Effect or Giant Magneto-Resistance (GMR) Effect which are able to sense both AC and DC currents (115 VAC/400 Hz and 28 VDC). Because any current-carrying wire or PCB trace produces a magnetic field, magnetic sensors are useful for sensing current. They also provide galvanic isolation because they make no contact with the current-carrying conductor. The basic concept using a ferromagnetic core is depicted in Figure 19. Since Hall Effect and GMR Effect may be temperature dependent and non-linear, a closed-loop field compensation method typically applies. Micro-sensors for PCB mounting are normally coreless but may be more susceptible to extraneous fields. Therefore, these sensors generally require calibration and special precautionary measures to reduce their susceptibility to magnetic interference from adjacent circuitry.

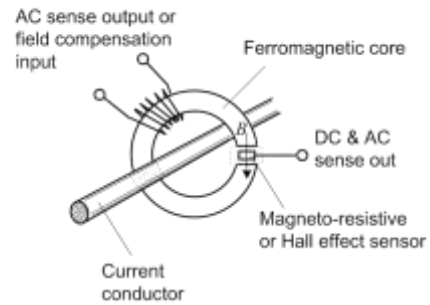

Figure 19: Basic concept of an AC & DC current sensor

The device that actually breaks the circuit when tripped by the trip control unit may be a solid state or classical electro-mechanical switch. The circuit breakers may also provide a data interface for remote control, monitoring and diagnostics. Finally, the system may also provide a means to maintain communication via power line in case of a single wire fault by altering coupling to a CM transmission e.g. using capacitive coupling and a robust transmission mode. Using a CM transmission mode may be acceptable in an emergency case.

Conclusion

A concept for a bifilar or twin wire approach for implementing PLC over single wire power distribution networks in A/C has been presented. The classical PLC approach for single wire distribution has proved to not provide an acceptable solution in regards to performance and EMC compliancy. The main advantages of the bifilar approach are reduced crosstalk, increased transmission p.s.d. and reduced conducted and radiated emissions. Measurements have shown that the expected gain in SNR compared to a monofilar approach will be on the order of 50 dB thanks to the differential mode transmission. Also, EMC measurements have shown that even with a high transmission p.s.d. of -50 dBm/Hz, compliancy with the RTCA/DO160 limits for conducted emissions can be achieved. Both of these aspects are critical points for the future acceptance of PLC technology in avionics applications. Furthermore, an innovative potential solution to wire fault detection within bifilar distribution networks has been described. This solution has to potential to provide detection of wiring and arc faults with increased sensitivity and robustness compared to existing state-of-the-art solutions.

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