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Coupling for Power Line Communication: A Survey

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Abstract—The advent of power line communication (PLC) for smart grids, vehicular communications, internet of things and data network access, has recently gained ample interest in industry and Academy. Due to the characteristics of electric power grids and regulatory constraints, the effectiveness of coupling between the power line and PLC transceivers become a very important issue. Couplers devices used to inject or extract data communication signals into or from (Alternating Current or Direct Current) power lines are very important components of a PLC system. There is, however, an obvious gap in the literature for a detailed review of existing PLC couplers. In this paper, we present a comprehensive review of couplers, which are required in narrowband and broadband PLC transceivers. Prevailing issues that protracts the design of couplers and consequently subtended the inventions of different types of couplers are clearly described. We provide, also, a useful classification of PLC couplers based on the type of physical couplings, voltage levels, frequency bandwidth, propagation modes, and a number of connections. This survey will guide researchers, and designers alike, into a quicker resourcing when studying coupling in narrowband and broadband PLC systems.

Index Terms—Power line communication, coupling, impedance matching, electric power system.

I. Introduction

The use of power cables for data communication purposes known as Power Line Communication (PLC) dated back to the early 1910s when Major George Squier of US Army demonstrated the transmission of analog voice signals (multiple telephony channels) over a pair of power cables to support the operation of distribution power system by electric utilities. At that time, this type of analog data transmission was called wired wireless [1]. The period from 1910 to 1930 was characterized by the introduction of some technologies which involve the transmission of telephone signals through power cables.

PLC has since moved from the little-known technology in the 30s to a competitive technology of the 21st century. As a consequence, coupling issues have become more relevant.

Essentially, couplers are devices that inject data signals into electric power cables. These power cables could be alternating current (AC) or direct current (DC) power lines and the signals of PLC transceivers are subsequently coupled to the power line via a coupling circuit. In the case of power lines used to transmit AC power, the coupling circuit also has to filter out the AC mains signal. On the other hand, the coupling circuit simply has to block the DC mains voltage of the DC electric power grids.

During the late 1970s and early 1980s, new investigations to characterize electric power grids as a medium for data communication showed a higher potential in the range of frequencies between 5 kHz and 500 kHz [2]. Some years later, it was demonstrated that, given some constraints (transmission power and distance), the frequency range from 9 kHz to 30 MHz could be used [3]. Currently, there research and development efforts are focusing on the use of electric power grids in the frequency band between 0 and 500 MHz.

Moreover, PLC systems can be distinguished based on two classes of frequencies: narrowband and broadband. Usually, narrowband PLC refers to data communication over the frequency band between 0 and 500 kHz [4]. On the other hand, broadband PLC covers the frequency band between 1.7 MHz and 500 MHz and high-speed data rate [5]–[7].

It is important to mention that the main focus on PLC technologies is to provide data communication over AC and DC electric power grids. The use of PLC technologies over the DC bus in distributed energy generation, airplanes, automobiles, and trains reduce wiring complexity, weight, space requirement and ultimately installation cost of telecommunications infrastructure. Thus, the PLC technologies eliminate the need for extra wires dedicated for data communication reduces the total vehicle weight increases the efficiency, lowers the number of electric wires and reduces problems when passing wires through dashboard and instrumentation panels. It decreases cost and complexity of cable connectors and raises the cost-benefit relation to any new device requiring extra wiring [8]. Therefore, the investigation of low-cost couplings is of utmost importance for such kind of vehicles.

The electric power systems have the advantage of being a ubiquitous infrastructure [9]. Also, no changes in the installed power cables infrastructure are necessary to implement the PLC system. As a result, the payback can be quicker with reduced capital expenditures. PLC networks can be used as a backbone of data communication networks and considered as a technology for replacing, completing, serving or interconnecting with other data networks. The cost of PLC systems is moderate for long-term purposes, especially when compared to the conventional data network systems. For example, the replacements of these power cables are not comparable in cost

with the replacements of the conventional data communication system devices such as cables, switches, and outlets [10].

Reviewing the literature about PLC technologies, measurement [11], [12], characterization [13], and modeling, as well as the development of techniques, to improve the performance of the PLC systems at the physical and link layers [14]–[17]. As a result, there are a number of technical contributions providing understanding into how PLC system works and pointing out challenging issues related to the advancement of the PLC technology. Although there is a plethora of literature on the general PLC systems, such volume is presently not similarly available for coupling techniques in PLC systems. Hence, the relevance of this survey.

In the literature, antenna coupling was the first type of coupling used with the electric power grid due to its simplicity, cost, and easy installation. However, impedance mismatching with the power cables, which reduces the transfer of energy between the power cable and the antenna, motivated investigations which resulted in the introduction of capacitive couplers [1], [18]. It is interesting to note that one century later, researchers are reinvestigating the use of antennas to introduce the so-called PLC wireless system [19], [20]. In the sequel, inductive coupling was introduced. Due to the characteristics of inductive couplings, such as electromagnetic isolation between the power cable and the PLC transceiver, they have been successfully applied in Medium Voltage (MV) based PLC systems because they can be installed with the power line alive. On the other hand, their usage in Low Voltage (LV) electric power systems was not widely adopted due to the high insertion loss. For LV levels, capacitive coupling is common due to its low cost and simplicity. More recently, resistive PLC couplers have gained some interest due to their low cost and simple circuitry features [21].

Above all, coupling is a very important issue in PLC system since the dynamism of electric power systems at High Voltage (HV), MV and LV levels and, as a consequence, the lack of perfect impedance matching at the point of connection with the PLC transceiver in time and frequency domains may result in remarkable insertion loss and signal distortion [22].

In this context, this work aims to present a comprehensive review on coupling for PLC systems. With this in mind, firstly, we discuss important issues related to the design of PLC couplers, such as printed circuit board (PCB) design, insertion loss and return loss, galvanic isolation, impedance matching, analog filtering, protection and performance due to the type of components, costs and complexities. Secondly, we present a classification of couplings which considers the type of physical coupling (capacitive, inductive, resistive, and antenna), the voltage levels (HV, MV, and LV), the type of voltages AC or DC, the frequency band (narrowband and broadband), the type of signal propagation (common mode (CM) or differential mode (DM)) and the number of connections. Additionally, we highlight future tendencies and critical issues which must be pursued to introduce PLC couplers which will comply with the constraints imposed by the electric power systems and fulfill the needs and demands associated with the novel generation of PLC system.

The remaining parts of this work are organized as follows:

Section II briefly and concisely addresses the main issues for designing PLC couplers; Section III discusses a classification of PLC couplers based on a comprehensive review of this subject; Section IV highlights open problems and future trends for advancing the design of PLC coupling devices; and, finally, concluding remarks are stated in Section V.

II. DESIGN OF A PLC COUPLER: IMPORTANT ISSUES

The coupling of PLC transceivers with electric power grids is considered to be a difficult task to be accomplished mainly because the access impedance (impedance at the point of connection) changes with frequency and time due to the dynamism of loads connected to electric power grids. Also, the low impedance of power cables, which is desired for reducing technical losses associated with the energy delivery yields a problem because the usual coupling devices are designed to have access impedance equal to 50 Ω or 75 Ω.

The design of a PLC coupler considering impedance matching, flat frequency response to minimize distortions, efficient electrical protection against transients, and low cost have been the major challenges in recent years. To carry out such design, several issues must be addressed in order to come up with a PLC coupler which may be useful for the target application. In this context, it is necessary to understand all main issues that must be taken into account to correctly design a PCB, such as to measure S scattering parameters for quantifying insertion and return losses, to provide galvanic isolation, to deal with impedance matching, to design the analog filters with passive components, and to choose the appropriate electric protection scheme. These relevant issues are briefly described in the following subsections.

A. Printed circuit board design

The electrical characteristics of the PCB used to physically mount and connect the components of the coupling device significantly impact on the coupling performance [23]. In [24], the author showed that the transmission line properties of signal traces in the PCB is considerably changed when multiple circuits or components are connected to a given signal trace. Characteristics such as impedance mismatching and skin effect usually result in an increase of the conductor impedance as the frequency rises.

Moreover, as frequency increases parasitic elements may impact the design of the PCB of PLC couplers, and their modeling for circuit simulation and design become relevant [25]. In a high-frequency circuit, it is simple to visualize how a long thin track of a printed circuit will behave as an inductor, and a large pad over a ground plan will behave as a capacitor, and performance degradation may occur due to the crosstalk among tracks [26]. In [27], the authors discussed the impedance mismatching in the connections among tracks, capacitors, pathways, stubs, and welds.

In [28], high-frequency transmission line effects were studied and a fundamental concept called electrically long trace was defined. If a distance from transmitter to receiver exceeds $\lambda/20$, where λ is the wavelength in meters, or terminate the transmission line in its characteristic impedance when the

one-way propagation delay of the PCB track is equal to or greater than one-half the applied signal rise/fall time, then the PCB should be treated as a transmission line and a routing topology should be created to match the trace impedance of a PCB. To match impedance line in a PCB, several techniques are available for designing a transmission line structure. There are two techniques that are most frequently used to control trace impedance, stripline, and microstrip. In stripline, the transmission lines exist on internal routing layers and require a minimum of 3 board layers (2 ground planes and a routing layer). The insulating material of the substrate forms a dielectric. The width of the strip, the thickness of the substrate and the relative permittivity of the substrate determine the characteristic impedance of the strip which is a transmission line. The use of microstrips is a popular method, used to provide trace controlled impedance when microwave frequency is taken into account. Microstrip lines are exposed to both air and dielectric material referenced to the planar structure. Fig. 1 shows a microstrip transmission line structure, where T is the thickness of the track, W is the width of the track, and h is the distance between signal track and the reference plane.

The stripline technique has the advantage of greater isolation of transmission lines and bandwidth, lower radiation loss. Better isolation and good electromagnetic shielding can be achieved but the stripline technique has the disadvantage of complex and expensive in fabricating it, tuning or troubleshooting is complex and stripline trace width is smaller compared to a microstrip line of same impedance and height. Microstrip has the advantage of dielectric losses are less (when using identical materials), cheaper and easier to manufacture and the location of traces on the top and bottom layers leads to easier debugging [29].

Characteristic impedance Z_0 of microstrip is also a function of the ratio of the height to the width W/h (and the ratio of width to height h/W) of the transmission line. The characteristic impedance Z_0 of a microstrip is calculated by [30]

$$Z_0 = \left(\frac{87}{\sqrt{\varepsilon_r + 1.41}} \right) \ln \left(\frac{5.98h}{0.8W + T} \right) \Omega \qquad \text{for} \quad 15 < W < 25 \text{ mils} \tag{1}$$

or

$$Z_0 = \left(\frac{79}{\sqrt{\varepsilon_r + 1.41}} \right) \ln \left(\frac{5.98h}{0.8W + T} \right) \Omega \qquad \text{for} \quad 5 < W < 15 \text{ mils}, \tag{2}$$
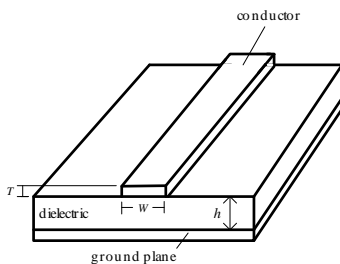

Fig. 1: A PCB microstrip transmission line.

where ε_r denotes the dielectric constant of the PCB material.

To implement a ground plane, one side of a double-sided PCB is made of continuous copper plate and used as ground.

The theory behind this is that the larger the amount of metal, the lower resistance is obtained. An analytical method for characterizing the impedance behavior of the ground planes in the frequency domain is presented in [31]. The importance of maintaining a low impedance large area ground plane is critical to all analog circuits today. The ground plane not only acts as a low impedance return path for decoupling high-frequency currents but also it minimizes electromagnetic interference (EMI) emissions [32].

To make full use of PLC couplers for data communication purposes or in order to analyze the impedance matching it is important to know how signals propagate on a PCB to obtain low insertion loss in a microstrip transmission line.

B. Insertion loss and return loss

Assuming that the two ports use the same reference impedance then the insertion loss (I_L) is the magnitude of the S_{21} scattering parameter, in dB:

$$I_L(dB) = -20\log_{10}|S_{21}|, \tag{3}$$

where S_{21} represents the gain of voltage transferred from Port 1 to Port 2 [33], which is often used to shown the frequency response of passive circuit which is supposed to be linear and time-invariant [34]. Insertion Loss is defined as the drop in power as a signal enters in the two port networks. This value not only includes the reflected incoming signal but also the attenuation of the component and is the ratio between output power and input power [35].

The return loss (R_L) is the magnitude of the S_{11} scattering parameter, which represents the reflection coefficient, because it describes what fraction of an incident wave traveling is reflected back to the input port. In other words, the S_{11} scattering parameter is a measure of how close the source and input impedances are matched. The R_L is given by

$$R_L(dB) = -20\log_{10}|S_{11}|. \tag{4}$$

In order to measure S_{12} and S_{11} scattering parameters, the impedances of a vector network analyzer (VNA) are matched to $50~\Omega$, the passive PLC coupler is considered as a two-port network and, as a consequence, we characterize it through its scattering matrix, as shown in Fig. 2 [36]. In Fig. 2, the $Z_{network}$ represents the impedance of electric power network at the connection point, Γ_{in} and Γ_{out} represent the reflection coefficients of PLC coupler and $Z_{network}$, respectively. Finally, Z_2 represents the impedance of port 2 - 2' of the PLC coupler. With knowledge of the scattering parameters, we can completely characterize PLC coupler and precisely quantity the distortion introduced by the PLC coupler in the transmitted signal.

C. Galvanic isolation

Galvanic isolation is usually necessary when two or more electric circuits are connected, but their grounds may be at different potentials. Also, it is an effective approach of breaking ground loops by preventing undesirable current flowing between two distinct circuits sharing a ground conductor. Moreover, it protects transceiver circuits and people from
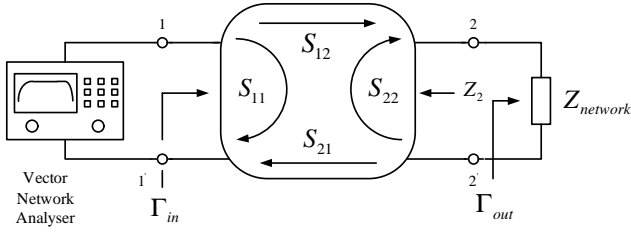
Fig. 2: Measurement of scattering parameters.

shocks and short-circuits. Regarding the PLC coupler, a radio frequency (RF) transformer is normally responsible for the galvanic isolation [37] between the transceiver and the power line. Also, as discussed in [38]–[40], it can be applied to impedance matching purposes through the transformation ratio $1{:}N$ between the primary and secondary windings of the transformer, where N denotes the turns ratio of secondary to the primary windings.

In [41], it was shown that an RF transformer has some non-ideal and characteristic properties which must be observed, such as the maximum magnetic flux density in the core to avoid non-linear effects, frequency band specification, impedance levels/winding ratio, maximum voltage levels, maximum power and currents, skin effect, number of strands, number of turns, leakage inductance, enlarging of leakage inductance, magnetizing inductance, and distortion of signal in secondary winding.

In [37], a model of an RF transformer was proposed and analyzed by Kazimierczuk. Fig. 3 depicts such model. It consists of ideal transformer, magnetizing inductance L_M, core-loss shunt resistance R_C, leakage inductances L_{lP} and L_{lS}, winding resistances R_P and R_S, and stray capacitances C_P and C_S. The stray capacitances models the effect of turn-to-turn capacitance, layer-to-layer capacitance, winding-to-winding capacitance, winding-to-core capacitance, winding-to-shield capacitance, core-to-shield capacitance, and the capacitance between the outer winding and surrounds circuitry [42]–[45].
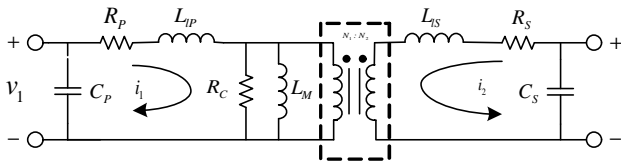

Fig. 3: Model of RF Transformer.

In order to determine the bandwidth of an RF transformer low frequency and high frequency are analyzed. For a low frequency of an RF transformer, the magnetizing impedance is calculated by $j\omega L_m \backslash\backslash R_C$. The values of L_M and R_C are determined by the core material and the cutoff frequency can be calculated by the core material with high relative permeability. High-frequency cutoff is attributed to intra-winding capacitance (C_P, C_S) and series leakage inductance (L_{lP},L_{lS}), core and conductor losses (R_P,R_S). To achieve a high value of frequency the stray capacitance (C_P, C_S) and leakage inductance (L_{lP},L_{lS}) should be reduced.

D. Impedance matching

The impedance matching between the PLC coupler and power cable at the connection point is a challenging task to be accomplished due to the time-frequency varying nature of the loads connected to the electric power grids [46]–[48]. Due to the wide range of values that the impedance at the connector point (access impedance) can assume when the frequency and times vary [49]–[51], it definitely must be brought to the center of discussion when designing a PLC coupler. In fact, the lack of impedance matching may considerably reduce the transmission power [52]–[58] even though impedance matching is ensured within the PCB of the PLC coupler.

Impedance matching techniques for narrowband PLC couplers were proposed in [58], [59]. The impedance matching technique based on the change of the tap of an RF transformer was outlined in [60]. In [61] the authors described a technique for measuring the impedance at the connection point of an electric power grid to feed a microcontroller, which is capable of switching a bank of capacitor [62] aiming to eliminate the reactive component of the access impedance. The complexity of this technique increases if the number of capacitors in the bank increases. Moreover, the resolution of the variation step depends on the number of branches of the bank of capacitors. Then, [58], [63], [64] proposed a new circuit, which is capable of adapting the impedance changing the series inductance and the turns ratio of the RF transformer. Transformerless coupling circuits and impedance adaptation for narrowband PLC, with a view of simplifying the design and minimizing costs of a PLC transceiver, were discussed in [65], [66].

Impedance matching techniques for broadband PLC were discussed in [67], [68]. These works addressed an optimization method to calculate the values of the parameters of 5th order band pass filters for matching the access impedance. Moreover, [58] focused on another design method that is capable of offering an optimization procedure to synthesize broadband impedance matching circuits for the equalization of the power transfer gain in a wide frequency band. The method is based on a parametric representation of the driving impedance of the broadband impedance matching circuit, which is optimized by means of a meta particle swarm optimization method [69].

Impedance matching to improve the maximum power transfer of transmission/reception of signal into/from power line cable becomes an important and challenging issue. Different design of impedance matching circuit has been studied in the literature. Frequency and time dependencies of access impedance, which renders adaptive matching circuits to be developed are the major challenge of PLC coupler.

E. Analog filtering

In a typical PLC coupler design, analog filtering is performed by a cascade of a high-pass filter and a low-pass filter, in this order, and their combination results in a passband filter. The design of an equivalent passband filter is not recommended because the purposes of designing the high-pass and low-pass filters are totally different. In fact, the former aims to block the high power mains signal [70], while the latter limits the upper edge of frequency bandwidth to comply with

the analog to digital conversion [71]. Fig. 4 shows a typical capacitive single input single output (SISO) PLC coupler, where T_1 is an RF transformer, C_{BLOCK} is a high-pass filter and L_1, L_2, C_1 up to C_5 constitute low-pass filter.

The design of the high-pass filter is very simple because it is realized with a capacitor with a reasonable working voltage and a self-resonant frequency higher than the maximum mains frequency. On the order hand, the low-pass filter is more sophisticated and can be realized with a Butterworth, Chebyshev, or an elliptic filter. Usually, the choice is in favor of an elliptic filter due to the sharpness of its frequency response [72]–[75]. However, a careful analysis of the low-pass filter must be carried out when multi-carrier scheme based on discrete Fourier transform (DFT) is used because it can increase the effective delay spread of the channel between the digital-analog converter (DAC) of the transmitter and the analog-digital converter (ADC) of the receiver. Moreover, a practical approach for reducing the order of a low-pass filter is to concatenate of a low-order high-pass filter (less selective) together with a 2nd or 3rd order notch filter with notch frequency located in the stopband. Additionally, the analog filter can be used to mitigate interference from radio signals (AM, FM, and TV) [76], [77]. The order of the analog filter can be determined by the designer according to the desired selectivity but if the order of an analog filter increases the insertion loss increases. Therefore, a rule of thumbs is to keep the analog filter order bellow or equal to six.
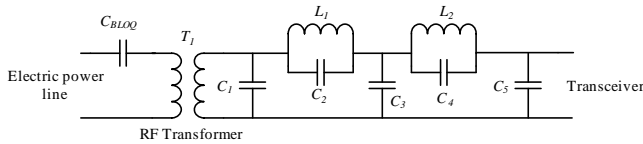

Fig. 4: Circuit of a capacitive PLC coupler.

F. Electric protection

All telecommunication technologies are bound to comply with electromagnetic compatibility (EMC) standards, whose requirements depend on the environment [78], [79]. The PLC coupling circuit, which is physically connected to power cables, is occasionally subjected to significant high voltage and current transients and, as a consequence, damages to the circuits of the PLC transceiver may happen [80], [81]. For instance, in HV and MV, a strong current pulse of short rise time is created when a distribution transformer fails due to a short circuit or when power cables fall to the ground (high impedance faults) or touch each other. Similarly, a lightning strike near the power cable yields a traveling wave that may destroy the PLC transceiver.

With this in mind, surge protective devices (SPD) attempt to limit the voltage supplied to an electric device by either blocking or shorting to ground any unwanted voltages above a safe threshold. An SPD must simultaneously provide low insertion loss in all operating frequency and adequate surge protection in all ports of the PLC coupler. The SPD must not interfere with the frequency spectrum of the transmitted signal.

Typical SPD used in PLC couplers are metal oxide varistor (MOV), Zener diodes, high-speed switching diodes and gas discharge tubes (GDT).

In [82] was proposed a surge protection circuit for HV based PLC systems aiming to achieve protection against an induced surge in one conductor of the transmission line, to offer protection against a common mode surge induced in both conductors of the transmission line, and yield protection against the potential rise of the earth conductor during an occurrence of high surge current through the earth conductor.

In [83] the authors analyzed the influence of capacitance of an MOV on the insertion loss of a PLC coupler. Although, the capacitance characteristics of an MOV and diodes, such as Zener and high-speed switching diodes [52], may cause distortion in the frequency response (S_{12} or S_{21} scattering parameter) of PLC couplers, their usage is widely adopted because the cost-benefit is the best available. In order to avoid the disturbing effect of MOVs, GDTs can replace them in PLC couplers designed to operate at frequencies above 35 MHz. Regarding, the frequency band between 1.7 and 100 MHz, Fig. 5 shows the effect of an MOV and Zener diode working together in concatenated way on the frequency response magnitude of a PLC coupler in comparison with a GDT. It is important to mention that the majority of studies and simulations of SPD effect covers the frequency up to 30 MHz [2]. However, nothing has being discussed in the literature about its protection efficiency capabilities and its impact on the signal distortion at the frequencies higher than 30 MHz. Furthermore, the use of transient voltage surge protection (TVSP) [84] can also be investigated to replace Zener diodes or high-speed switching diodes for frequencies above 35 MHz in PLC coupler.
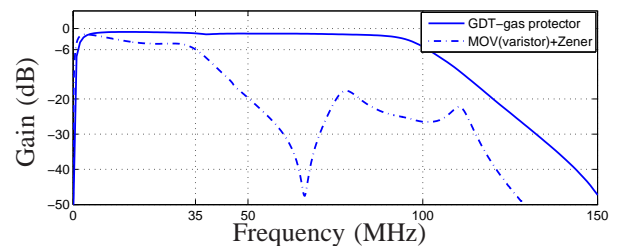

Fig. 5: Distortion of frequency response magnitude of a capacitive and low voltage PLC coupler in the frequency band 1.7 - 100 MHz due the use of different types of protective circuit.

Fig. 6 shows a typical protection for inductive and capacitive PLC coupler circuits. The capacitive coupler requires the use of MOV, fuse and Zener diodes to protect the transceiver circuit. The inductive coupler does the same by exploiting the limitations of the maximum magnetic flux density of the ferrite core to avoid spikes of current in the secondary windings and by concatenating high-speed switching diodes at the secondary windings of the ferrite core to limit the voltage. The use of MOV [85] and diodes for protection purposes needs to be analyzed based on the operating frequency of the PLC system and the voltage level of the mains signal in the electric power system.
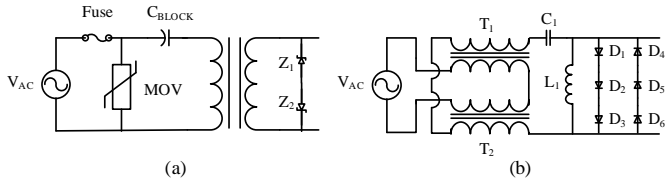
Fig. 6: Typical protection circuit for PLC coupler. (a) Capacitive coupler and (b) Inductive Coupler.

G. Components

Due to the cost and size, the components used in a PLC coupler circuit are passive (resistors, capacitors, transformers, and inductors). Therefore, particular attention on the self-resonant frequency of inductors and capacitors and on the frequency response of the transformer must be carefully considered. Additionally, the behavior of other components due to the chosen operating frequency of the PLC system needs to be carefully taken into account, especially in high frequencies [86]. In high frequencies, the skin effect is the phenomenon in which the apparent resistance of a wire increases as the frequency increases. If a voltage is maintained at a constant DC level, current flow will be uniform throughout the area of the wire. However, as the frequency increases, the magnetic field near the center of the wire increases the local reactance. The charge carriers then move towards the edge of the wire, decreasing the effective area and increasing the apparent resistance of the inductor winding [87], [88], capacitor [89], and resistor.

In fact, at high frequencies, the physical length, width, and height of components, the properties of the conductors and dielectrics, plus the types of electrodes for attachment to external circuits all have to influence the performance of a PLC coupler circuit. Fig. 7 shows a high-frequency lumped circuit models for a resistor, a capacitor and an inductor. Note that the additional capacitance due to the attached electrodes is usually included in the nominal value of the capacitance. Despite the parasitic resistances and reactances, the mounting of devices on a PCB can introduce significant additional capacitance to the body of the component [42]. This capacitance and the added inductance of the pads and traces, which are used to attach a component and are typically considered part of the circuit, affect the frequency response and impedance matching of a PLC coupler. In the design of PLC coupler for broadband data communication, it is important to take it into account.
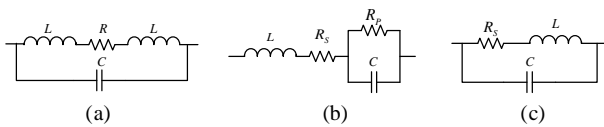

Fig. 7: Equivalent circuit for RF model. (a) Resistor, (b) Capacitor and (c) Inductor.

H. Cost and complexity

The main advantages of the PLC technology are the use of electric power system infrastructures for costs and expenditures reduction and the easy deployment of new telecommunication networks over such infrastructure [90]. Regarding HV and MV PLC couplers, some care must be taken into account due to the complexity of the coupler construction, which may increase costs due to the isolation need at these voltages levels. Moreover, PLC coupler designers must pay particular attention to the external environment which is subjected to rain, snow, and lightning on the power cable [91]. Due to these constraints and environment issues, the cost of the capacitive coupler is very high and high at HV and MV, respectively. Due to saturation of magnetic flux inside the core and the cost to handle it, inductive coupling is only used at MV and LV. Moreover, in LV, the PLC couplers are constructed at a relatively low cost. Usually, a PLC capacitive coupler requires low complexity and cost since the components are available commercially. In [66], a PLC coupler without transformer was proposed for eliminating this costly component, while maintaining impedance matching with the electric power grids. Overall, complexity and cost of PLC coupler increase when voltage levels and bandwidth increase. Also, they increase when perfect impedance matching is mandatory.

III. CLASSIFICATION OF PLC COUPLERS

In general, PLC couplers can be grouped according to different criteria and this work outlines a classification based on the type of physical couplings, voltage levels, frequency bandwidths, propagation modes, and numbers of connections.

A. Based on the type of physical connection

Based on the type of physical connection, the coupling can be capacitive, inductive, resistive, and by the antenna. Note that antenna could be seen as a kind of inductive coupling, but we prefer to keep it separate because its mechanical construction is totally different.

1) Capacitive: Capacitive coupling is the serial insertion of one or more capacitors in direct contact with the power cable. It offers low impedance path the high-frequency components of the power line signal and, at the same time, it blocks the mains signal by presenting a high impedance to it. Among the four types of PLC couplers, it has the lowest insertion loss, thus ensuring the highest power transfer [92]. As shown in Fig. 8, there are two types of capacitive coupler: (a) with a transformer to provide galvanic isolation (T_1) and to limit transients based on the core saturation; and (b) without transformer, which is a low-cost option with the disadvantage of not providing galvanic isolation. While the use of capacitive coupling with transformer is strongly recommended in AC electric circuits, mainly when the voltage amplitude of the mains signal increases, the use of capacitive coupler may also be useful for DC buses [93], [94] in which the voltage level is low, such as in vehicle [95], ships, and spacecraft environments. In [96], the author proposed a capacitive coupler to operate in low-voltage DC electric power grids when the frequency bandwidth is between 1 MHz and 30 MHz and the voltage level of mains signal is up to 750 V_{DC}.
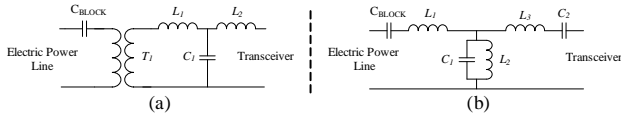
Fig. 8: Equivalent circuit for capacitive PLC coupler. (a) Coupling with galvanic isolation and (b) Transformerless coupling.

2) Inductive: The inductive PLC coupler can be realized with (series inductive coupling) or without (shunt inductive coupling) galvanic isolation to the power cable [97]. In the inductive PLC coupler, electric current flows through the winding coil and yields an electromagnetic field which inductively loads the signal into the conductor, as showed in Fig. 9, where T_1 and T_2 are inductive couplers. Structurally, it consists of a magnetic core with gaps and the output coil is connected to the transceiver, both of which are wound around the core. Its installation does not require lockout of the electric power grids because there is no electric connection between the power cables and the PLC coupler.
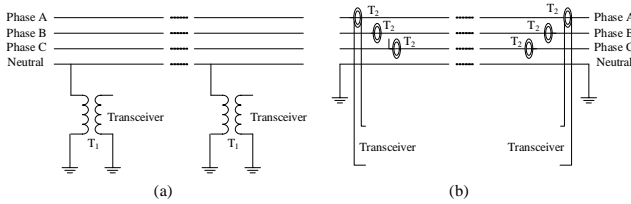

Fig. 9: (a) serial inductive coupler and (b) shunt inductive coupler.

In inductive PLC couplers, the mains current can flow, unlimited, through the magnetic core clamped over the wires as shown in [98]. Toroidal transformers typically have copper wire wrapped around a toroidal core so that the magnetic flux, which occurs inside the coil, does not leak out. The properties of the toroidal core current transformers, such as maximum transmissible primary current, amplitude, and phase error as well as linearity, are basically determined by the material used in the core [99]. High magnetic coupling coefficient values are desirable in inductive couplers for offering low insertion loss and return loss, as well as for covering wide frequency bandwidth. In [100], insertion losses of inductive couplers based on Rogowski coil and a conventional (ferrite based) inductive coupler were compared. The authors measured the variation of insertion loss response of an inductive coupler in high current test in the frequency range of 1.7 MHz and 40 MHz. The performance of couplers based on Rogowski coil is stable because the relative permeability of an implemented coupler is very low and it is not saturated according to an increase of current.

Inductive coupling offers many degrees of freedom for system design by varying geometric parameters to tune parasitic elements, such as the crossover capacitance between the spirals, the magnetic coupling coefficient, inductance ratio and impedance terminations. The geometry and electromagnetic properties of coiled wire over the ferrite core result in a high impedance for high-frequency signals. In [101] was shown that

the inductance of a choke depends not only on the geometry of the windings and the core but also on the permeability of the core material. The distributed capacitance between the winding turns acts as a shunt capacitor on the inductor resulting in the occurrence of resonance at a given frequency. Furthermore, the inductive PLC coupler shows good performance in low impedance power cable and yields low energy radiation [102]. The coupling efficiency varies according to distinct factors such as the shape and magnetic characteristics of the magnetic core, the length of the gaps, and the characteristic impedance of power cable [102].

It is important to emphasize that the nonlinearity of the magnetic material together with the magneto-motive force rising from zero to a maximum, twice each cycle of the mains signal, causes distortions, such as amplitude modulation of the transmitted and received signals.

3) Resistive: The resistive coupler is constituted by a voltage divider, a bandpass filter, and an amplifier. The voltage divider drops the voltage signal from the power cable and, in the following, the bandpass filter attenuates the out of band signals. Finally, the amplifier boosts the voltage signal amplitude for a further analog-to-digital conversion. Theoretically, injection and extraction of signals into/from the power cable are possible; however, only the extraction of the signal seems to be practicable. For instance, [21] proposed a circuit for a resistive coupler, see Fig. 10. As we can see, it is constituted by a voltage divider, a buffer, a band-pass filter, and an amplifier. Due to its nature, the resistive PLC coupler may be suitable for coupling narrowband PLC system in low-voltage electric power grids.
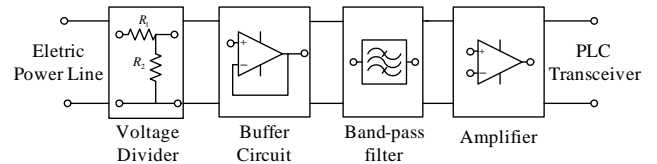
Fig. 10: The block diagram of the resistive PLC coupler.

4) Antenna: The first form of coupling PLC transceivers to power cables was based on an antenna due to its simplicity, low cost, and easy installation and operation [18]. Fig. 11 shows a typical antenna coupling. These antennas were mounted below the power lines on the tower structure and the high-frequency carrier signal was induced in parallel with the power cable. The size of antennas exceeded 300 feet in length and was designed to the carrier frequency employed for voice communication [103]. However, coupling antennas are quite inefficient because there is a lot of power lost in the coupling with the electric power grid.

In 1921, AT&T began to develop the first PLC transceiver with an antenna coupling (analog modulation, simplex transmission, and transmission power of 50 W) for voice signals communication, control, operation, and maintenance of the distribution electric power system. However, problems such as impedance mismatching between the antenna and the power cable and the length of the antenna for working with the

low frequencies motivated the development of capacitive and inductive couplers.

Currently, the use of antenna coupling is under investigation for broadband PLC to offer mobility to PLC users, introducing both PLC and wireless transceivers called hybrid PLC-wireless [19], [20], [104]. Furthermore, the power cable can be seen as an antenna for the propagation of RF signals, such as WiFi, [105]–[107] which can reduce the investment with cabling and repeaters. In [108], the authors characterized the LV power cable to use as an antenna to propagate RF signal in ultra-high-frequency (UHF). The range of tested frequencies in power cable extends to 550 MHz beyond the current IEEE 802.11g standard which has a center frequency of 2.45 GHz and an 80 MHz frequency bandwidth. It experimentally demonstrated that LV electric power grids can be used as an antenna in the UHF in the frequency range from 1 GHz to 3 GHz.
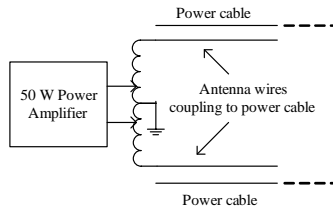

Fig. 11: Equivalent circuit of antenna wires.

B. Based on voltage level

Regardless of the electric power grids to be AC or DC, the coupling can be classified according to their voltage level as follows [109]:

1) High voltage: The coupling capacitor is the most widely used component that enables signal coupling to and from the HV power cable [110]. Standards have been established for ratings and tests power capacitor (i.e., isolation) which must be met by coupling capacitors in HV. The requirements and essential characteristics of capacitive coupling for HV have been standardized in ANSI C93.1 [111].

In [112], the author describes capacitive and SISO couplers for HV transmission lines designed for narrowband and broadband PLC transceivers between the phase conductor and the earth. Basically, there are two types of phase to ground narrowband resonant schemes for coupling. Fig. 12 shows the single-frequency and the two-frequency resonant circuits that implement such scheme.

The modeling approach and analysis of component influence on the performance of PLC transceiver show the behavior of complex coupling with many co-existing carrier frequencies are discussed in [113]. Also, it addressed the development and application of a PLC modem components, including single and double-frequency line traps, line tuning units, coupling capacitor voltage transformers (CCVTs), transmitters, receivers, balanced and skewed hybrids, and signal level probes in an 115 kV transmission line.

The inductive coupling for HV transmission lines is more sensitive to HV fluctuations, impulsive noise, corona effects, and voltage arcing between phases than capacitive coupling
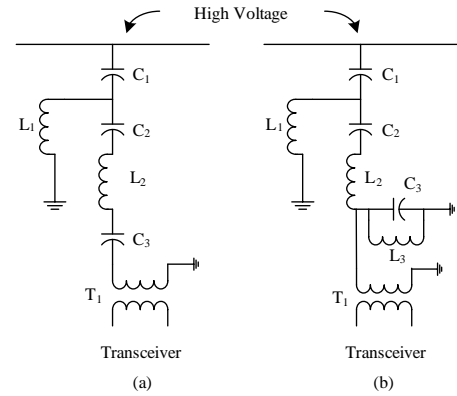

Fig. 12: Typical coupling schemes for HV transmission lines. (a) Phase-to-ground coupled single frequency narrowband and (b) Phase-to-ground coupled two frequency narrowband.

because it results in the saturation of the core [114]. Also, it shows more insertion loss than capacitive coupling. On the other hand, the greatest advantages of the inductive couplers, when compared to capacitive couplers are: during installation, there is no interruption in the electricity supply, low cost of production and installation, and the galvanic isolation among the HV transmission lines and the transceiver circuit [115]. The inductive coupling in HV transmission lines acts as an electrical protection. For instance, if there is an increase in electrical current in the HV transmission lines due to short-circuit or short discharges, the voltage is limited by the saturation of the magnetic flux inside the core of the inductive coupler, due to the saturation of the RF transformer core.

2) Medium voltage: In recent years, the idea of using the existing MV electric distribution grids as a medium for data communications became a reality. In fact, such infrastructure can be used to constitute data communication backbone to meet protection, metering, distribution, automation, and control, by connecting several substations [116].

The MV couplers must withstand high differential voltages among phases and earth. As a consequence, it requires special components, which make these devices more expensive and more complex to implement than LV couplers but much less expensive than HV couplers. The requirements for the installation of capacitors in MV must also follow the ANSI C93.1 [111].

Similar to HV PLC couplers, the MV PLC coupler must be in compliance with the requirement of the utility and applicable regulation (e.g. insulation level of feeding cable, grounding, mechanical strength, lifetime, and climatic category). In the case of switching the MV switchboard, or in the case of short circuit, the MV PLC coupler must be able to support transient currents higher than 20 kA with no mechanical damage or change of frequency response not exceeding 1.5 dB [117].

In [118], [119], a capacitive SISO PLC coupler for broadband PLC was proposed. Fig. 13 shows the MV PLC coupler device which can work with voltage levels as high as 11 kV. In this proposal, the PLC coupler is connected to phases and line trap circuit. The low impedance of the electric power

lines causes a mismatch between the PLC coupler and electric power line. The line trap circuit is a parallel resonant circuit, mounted in-line on AC transmission power lines to prevent the transmission of high-frequency carrier signals of AC power line communication to unwanted destinations. It is used to trap the low-frequency signal of AC power line and offer a high impedance to the high-frequency signal of a PLC transceiver. Two RF transformers are used to achieve the desired isolation. The series combination of L_S and C_S forms a band-pass filter to block the AC power line and a low impedance for the signal of PLC transceivers. The resonant frequencies of the three circuits (L_S, C_S, L and C) are designed as the midband frequency of the PLC coupler. The MOV together with D_{Z1} and D_{Z2} (Zener diodes) are responsible for the electric protection.
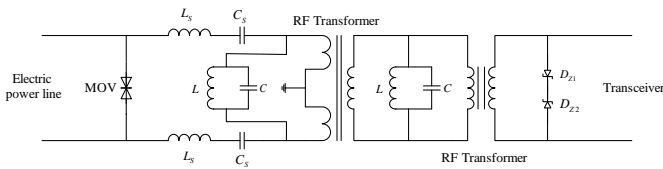

Fig. 13: Typical capacitive coupling circuit for MV.

When inductive PLC coupler comes to matter, there are two options available for installation: the inductive PLC coupler is clamped around an MV power cable, or the inductive PLC coupler is serially connected between the neutral line of the MV circuit and the ground wire if it is available [115]. The former has the advantage of offering galvanic isolation from the power cable and its installation is done without powering off. On the other hand, its disadvantage is that high current on the MV power cable causes the magnetic saturation of the RF transformer and, as a consequence, the insertion of relevant loss. The latter has the advantage of facing low saturation magnetic flux density because of the low-level current flowing between neutral and ground lines resulting in low insertion loss. Moreover, it offers an interesting cost effective solution because the PLC coupler has a small size in comparison to capacitive MV PLC coupler [97]. In addition, due to its characteristics, the distance for signal transmission can be long [120]–[122].

3) Low voltage: Typical LV power cables consist of three conductors, a phase, a neutral, and ground. Two of these three conductors can be used to create a communication channel. The scenario for the LV electric power grids is different compared with HV and MV ones, as discussed in [123] because the LV power cable is derived from secondary windings of the MV/LV power transformer and the energy is delivered to a large number small consumers. The dynamic of the loads in the LV electric power grids yields emissions and interference associated with appliances, motors, and other loads, which make them the most hostile environment for data communication purposes [124], [125], difficulty impedance matching among PLC transceivers and power lines. Due to the low cost of LV PLC couplers, some features can be improved, such as impedance matching with electric power grids by using, for instance, the RF transformer ratio transformation or

the design of adaptive matching impedance and selective filters that is capable of attenuating unwanted frequencies which may cause interference with the PLC system.

In [70] it was shown that the analog filter is the key issue of LV PLC capacitive coupler. The authors showed how to build the filter circuit model for LV, and the Butterworth band-pass filter which frequency band is from 1 MHz up to 30 MHz was designed. The main issues for designing a capacitive SISO PLC coupler was discussed in Section II.

The inductive coupling has been studied in motor cable communication [126] for a voltage of 400 V_{DC}. The inductive PLC coupler for motor cable communication is tuned for the low voltage direct current (LVDC) [127]. The inductive couplers are not commonly used in consumer applications, in which the connection with the power cable is made through an electrical wall outlet. The typical circuit of LVDC and the basic structure of the proposed PLC-base communication architecture can be accessed in [128]. Also, we point that an LVDC is very common in vehicles.

C. Based on type of voltage

The use of PLC in AC electric power grids is widespread, but the voltage of electric circuits can be classified into two categories: AC and DC. However, despite the popularity of PLC system over AC electrical circuits, there are a lot of research focus on facilitating communication over DC electric circuits. In [93], the DC PLC coupler is developed on the basis of AC PLC coupler. Essentially, the fundamental structure of a DC PLC coupler is very similar to the AC PLC coupler. In [129] were investigated the possibility of using the PLC technology to transmit data along differential DC power buses employed in spacecraft.

The inductive and capacitive PLC coupler can be designed to work in different levels of voltage in AC or DC electrical circuits. DC PLC coupler uses a series capacitor connected with the power cable such as AC PLC coupler does. The capacitor blocks the AC or DC mains signal and passes high frequencies for a wide range of frequencies. In inductive coupling without galvanic contact with the DC bus voltage, the inductive PLC coupler, installed in parallel with DC bus, injects the PLC signal following the principle of magnetic induction, which is exploited in inductive coupling, see Section III-A-2.

The applicability of narrowband and broadband PLC for the LVDC electrical circuits communication is shown in [130]. In [131] narrowband capacitive couplers that are differentially connected between the neutral and DC conductors in bipolar ± 750 V_{DC} is proposed. An inductive coupler is used in [132] for analysis of noise in broadband PLC in DC power cables.

D. Based on frequency band

The PLC system has a range of frequency bands allocated to narrowband and broadband PLC data communications. Therefore, the PLC couplers can be classified as narrowband (frequency range between 0 kHz and 500 kHz) [38], [52] and broadband (frequency range from 1.7 MHz to 500 MHz) [102], [118]. The frequency bandwidth is determined by low and high

cut-off frequencies at 3 dB attenuation and can be modified in function of filter design. The parameters of the RF transformer, analog filter, and electric protection must be designed in accord with the chosen frequency band desired [37], [43].

E. Based on propagation mode

Power cable wiring installations in a residence make use of three wires, namely phase, neutral, and protective ground, which can be modeled as parallel conductors sheathed in a dielectric material [133]. The PLC couplers can inject a signal in the power cable along the wire in two ways: DM and CM [134].

The DM is the normal current conduction mode by a two-wire circuit. The current flows in a wire in phase opposition of the other wire, the electromagnetic fields generated by the currents actually cancel out each other. On the other hand, in the CM, the current goes through all the wires in the same direction causing the addition of electromagnetic fields, yielding significant levels of electromagnetic interference (EMI) [135].

Fig. 14 shows a high-frequency equivalent circuit of a PLC channel illustrating the creation of CM signals due to current I_{cm} and voltage V_{cm} with respect to the ground, originated unintentionally in an unbalanced electric power cable. It creates a parasitic capacitance with respect to ground and causes a CM current to return to the source through the parasitic capacitance (C_{para}). In this model, we have a three-wire power line cable in which the Ground wire is the reference conductor. The I_{dm} current flows in the Phase wire from/to PLC Couplers and returns via the Neutral wire. The I_{cm} currents flow from/to PLC Couplers in the Live and Neutral wires and return to PLC Couplers via the Ground wire. I_{cm} flows back to the location where it was converted via unwanted parasitic components C_{para}, ground and any other asymmetry.
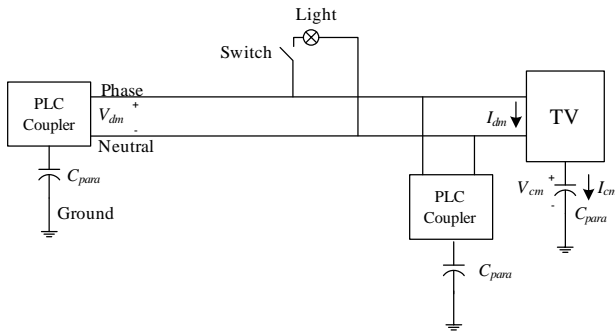

Fig. 14: High frequency equivalent circuit of a DM.

F. Based on number of connections

The wires in HV, MV, and LV electric power grids can be used to provide more than one path for data communication. Hence, the coupling circuits can be classified according to the number of connections. The power cable in HV and MV consists of three phase wires where the same signal can be sent by three different paths. The power cable in LV is composed of three phase conductors and one neutral

TABLE I: Types of connections.

Mode	Transformer (Tx)	Transformer (Rx)
1X1 (SISO)	P-N	P
1X2 (SIMO)	P-N	P, CM
1X3 (SIMO)	P-N	P, N, PE
1X4 (SIMO)	P-N	P, N, PE, CM
2X2 (MIMO)	P-N, P-PE	P, PE
2X3 (MIMO)	P-N, P-PE	P, N,PE
2X4 (MIMO)	P-N, P-PE	P, N, PE, CM

conductor and, therefore, there are four paths available for data communication [136], [137]. In this context, the connection between two PLC transceivers can be classified in terms of SISO, single input multiple outputs (SIMO), multiple inputs multiple outputs (MISO), and multiple inputs multiple outputs (MIMO).

The SISO coupling is the simplest form of coupling with power cable. In LV, the connection of PLC couplers can be performed by the phase and neutral wires or phase to phase wires. Such connection in HV and MV occurs among phases. The advantage of the SISO PLC coupler is its simplicity and low cost. The majority of PLC systems are SISO.

To have the SIMO and MISO PLC couplers, connecting at HV and MV, all three phases wires must be available. The SIMO PLC coupler is connected in two phases to transmit the signal from the transceiver circuit and it receives the signal in three phases. In that case, the signal is induced in the third phase.

In MIMO coupling at HV and MV, all three phase wires can be used, simultaneously. The MIMO PLC coupler is connected in three phases to transmit the signal and it receives the signal in two phases. For LV electric power grids the electrical protective wire and protective earth (PE), allows the creation of another path between two PLC couplers [138]. Table I and Fig. 15 show the configuration mode of SISO, SIMO and MIMO. In [138], the authors show the results of channel measurements motivated to implement a MIMO PLC equivalent circuit explaining the creation and reception of CM signals. Two RF transformers are connected in triangle and star configuration providing several paths for data communication.
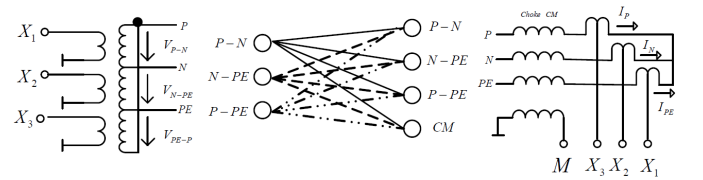
Fig. 15: MIMO PLC Coupler.

IV. FUTURE WORKS

Although, there is a scarce effort toward PLC coupling research. The coupling unit is perhaps one of the most important components in a PLC transceiver. Therefore, the design of a PLC coupler capable of handling the complexity, dynamic and diversity of electric power system is a challenging issue for the PLC research community. With this regards, in the following, we enumerate some important question deserving

more attention in order to come up with improved coupling solution:

- The measurement of access impedances is of particular importance since it is necessary for designing efficient and effective couplers, for improving the performance of PLC coupling [129]. It is important to know time and frequency behaviors of resistive and reactive components of such impedance. Lack of this very important information has led to the design of poor quality and low efficient coupling devices in the past.

- Research and development of new components and material for electrical protection of the transceiver circuits for broadband PLC. Very limited research efforts have been expended in the area of special materials for couples, especially when compared to the work on materials for the design of advanced transformers. For instance, the use of nanocrystalline magnetic materials to substitute the ferrite and nanomaterials for capacitive devices. This kind of material will considerably reduce the cost of current coupling devices used in medium and high voltage electric power systems.

- The design of low-cost surge protective components when the frequency is over 35 MHz. Our review showed that GDT and TVSP are the most recommended if the mains voltage is high; however, their cost may limit the use of them in commercial coupling devices.

- The development of simple and effective coupling circuits that is capable of performing impedance matching to maximize power transfer. The introduction of such kind of coupler will result in a remarkable improvement of PLC technology.

V. CONCLUSION

A review on the use of couplers to enable data communications over AC and DC electric power grid has been presented. The PLC couplers enable data communications over power lines by injecting/extracting data signals into or from these power lines either by differential mode or by common mode. The review showed that the introduction of couplers to connect the PLC transceivers to electric power circuits could be used to minimize both signal distortion and insertion loss and improvement is needed to enhance PLC systems performed.

In this regard, we isolated the key points related to the design of a PLC coupler, such as the PCB, insertion and return loss, galvanic isolation, impedance matching, filtering, and protection. Additionally, We provided a classification of PLC couplers based on the type of physical coupling, voltage levels, frequency bandwidth, propagation mode and a number of connections. These fundamental concepts are provided to suffice basic understanding about some relevant issues related to the design of PLC couplers.

Finally, we pointed out some important research questions whose investigations can result in the design of a new generations of efficient and effective PLC couplers.

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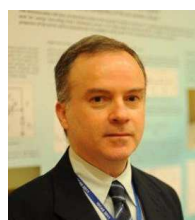
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