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Customized Narrowband PLC System for Medium-Voltage Distribution Lines

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Abstract- This paper presents the development of a narrow-band power line communication (PLC) system for the automation of typical Brazilian medium-voltage distribution feeders. The first phase of the development is completed, and resulted in a stable PLC system operating a serial link between the substation control room and equipment installed along 13.8 kV feeders. The second phase intends to provide an Ethernet link over the PLC system for feeders operating at 13.8 kV and 34.5 kV. The results achieved are presented, with emphasis on the coupling technique employed to transfer the PLC signal to / from the line and on the configuration of the transceivers.

Keywords- *Cupler, Ethernet, Power Line Communication*

I. INTRODUCTION

Power transmission lines are used to transport communication signals since long time ago [1]. Recently, this technique has received attention from power utilities interested in the network automation and management, in the context of smart grid applications [2]-[5].

Although power line communication (PLC) is well consolidated on power transmission lines, its application on medium-voltage (MV) distribution lines faces several technical obstacles. For instance, the distribution lines present several branches and ends-of-line that generate wave reflections. The reflected waves interact with the original wave, creating standing waves that presents points of null, i.e., where the signal intensity is negligible. Moreover, the line losses are frequency-dependent and produce signal attenuation and distortion [6]. Distribution lines also present relatively high levels of noise, due to its proximity with the load, which reduces the signal to noise ratio at the entrance of the transceivers. Therefore, a PLC system for the medium voltage lines faces several challenges to its deployment.

Besides the technical challenges, there are also economic constraints that have to be fulfilled in order to let the PLC system to be competitive. In Brazil, the main competing technologies for medium-voltage distribution line automation are GPRS General Packet Radio Service (GPRS) and Point-to-Multipoint (P2MP) radio.

The propagation of PLC signals on MV lines depends on the specific characteristics of the lines [6]-[9]. To date, the data related to the PLC performance on typical Brazilian MV distribution lines is very scarce. The specific characteristics of these lines include a wide range of rated voltages (11.9 kV to 34.5 kV), several types of aerial structures and feeder topologies. Therefore, Equatorial Energia and Fundação CPqD joined efforts in order to study this issue and to develop a customized PLC system for the automation of its MV power distribution lines.

The main objective of this development is to have a transparent communication link that allows the automation of the line equipment, such as circuit breakers, automatic reclosers, voltage regulators, etc. This equipment is installed in distribution feeders that usually have radial configurations and several branches. In order to better address the technical challenges involved in this work, it was decided to split its development in two phases (A and B).

Phase A addressed the power line interfaces, such as the signal coupling / decoupling, the powering of the transceivers, and the field installation. The PLC transceiver used a single-frequency carrier and its application was limited to feeders with 13.8 kV rated voltage. The prototypes from Phase A were deployed in the network and provided reliable operation.

Phase B focused on improving the communication interfaces and deploying internet protocol (IP) over the PLC link. The PLC transceiver used several carriers and the application was expanded to feeders with rated voltages from 13.8 kV to 34.5 kV. The prototypes from Phase B were deployed on the network and provided stable and reliable operation to communicate with SCADA supervisory.

This paper presents the main aspects of this development and it is organized as follows. Section II presents the PLC coupler circuit and its theoretical model. Section III describes Phase A, including the main results from the field trial. Section IV addresses Phase B, with emphasis on its innovative configuration. Finally, Section V presents some discussions and Section VI draws the main conclusions of the paper.

II. POWER LINE COUPLER

A. *Coupler Circuit*

The signal coupling to and from the line is carried out by a coupler that uses a high-voltage capacitor and a signal-conditioning circuit. Fig. 1 shows a simplified diagram of the coupler, where can be identified its main features. The high-voltage capacitor C_1 limits the power frequency current (60 Hz), which is drained to earth by L_1. The PLC signal flow is depicted by the arrows shown in Fig. 1.a, where it goes through the capacitors C_1, C_2, C_3 and the transformer T_2. The signal is then available at the secondary of T_2, which is connected to the transceiver signal circuitry (terminals *a* and *b*). It is worth to mention that the leakage inductance of T_2 is complemented by an inductor placed at the printed circuit board (PCB) in order to compensate the capacitive impedance provided by C_1.

The energy flow is shown by the arrows in Fig. 1.b, where the power frequency voltage developed across the capacitor C_2 is provided at the secondary of the transformer T_1 (terminals *b* and *c*). The energy delivered by the transformer T_1 is used to power the transceiver.

The terminals *a*, *b*, and *c* are connected to the transceiver, where the conductor *b* is earthed. Fig. 2 shows the power line coupler rated at 34.5 kV. The main structure with bushings is high-voltage capacitor C_1 and the small box attached to the capacitor body houses the filtering circuit depicted in Fig. 1. A switch inside the box selects the operating voltage (13.8 kV or 34.5 kV) for the powering circuit by varying the value of C_2.

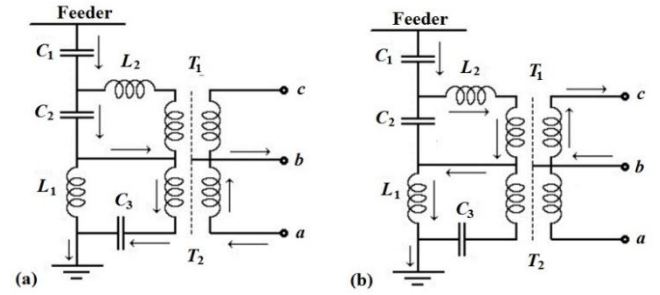


Figure 1. Simplified coupler diagram. (a) Signal flow; (b) Energy flow.

Figure 2. Views of the PLC coupler (rated for 34.5 kV).

B. *Coupler Model*

Considering an ideal coupler, the signal circuit can be represented by the one shown in Fig. 3. In this figure, *V* is the transceiver open-circuit voltage, *R* is its internal impedance, *Z* is the impedance presented by the feeder, and *n* is T_2 turn ratio. It is straightforward to show that the maximum power delivered to the feeder is obtained when the transceiver impedance matches the feeder impedance, which gives the optimum turn-ratio:

$$n = \sqrt{Z/R} \tag{1}$$

Although the PLC transceiver has an impedance adapting algorithm that tracks the changes of *Z*, a careful selection of *n* optimizes the transceiver performance. A dynamic adjustment of *n*, as proposed in [10], would be good option. However, instability may arise from the simultaneous operation of the impedance adapting process for both the PLC transceiver and the coupler. Therefore, *n* was selected based on a probabilistic approach described in the following.

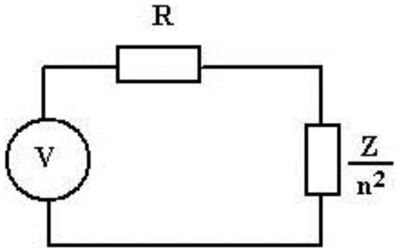


Figure 3. Coupler equivalent circuit.

Let us denote by Z_0 the line characteristic impedance and that the transceiver is connected to the extremity of a long line. Depending on the number of line branches and on the load characteristics, one may expect that the impedance "seen" by the transceiver is in the range $0 \le Z \le Z_0$. For the type of structures commonly used in MV lines in Brazil, $Z_0 \approx 460\ \Omega$.

From Fig. 3, the power transferred from the transceiver to the line is:

$$P = \frac{V^2 n^2 Z}{\left(n^2 R + Z\right)^2} \tag{2}$$

Assuming that the probability density function of *Z* is uniformly distributed in the interval $0 \le Z \le Z_0$, one can express this function as:

- $f_Z(z) = 1/Z_0$ *if* $0 \le z \le Z_0$ *and*
- $f_Z(z) = 0$ *otherwise*.

Therefore, according to [11], the expected value of $P(Z)$ is

$$E\left[P\right] = \int_{-\infty}^{+\infty} P(z)\, f_Z(z)\, dz = \frac{V^2 n^2}{Z_0} \int_0^{Z_0} \frac{z}{\left(n^2 R + z\right)^2}\, dz \tag{3}$$

which leads to

$$E[P] = \frac{V^2 n^2}{Z_0}\left[\ln\left(\frac{n^2 R + Z_0}{n^2 R}\right) - \frac{Z_0}{\left(n^2 R + Z_0\right)}\right] \tag{4}$$

The maximum value of E[P] is obtained by deriving (4) with respect to *n* and making this derivative equal to zero. This gives the optimum value of *n*:

$$n = \sqrt{\frac{Z_0\, k}{2R}} \tag{5}$$

where $k = 0{,}92481$ is a numerical constant. For instance, for $Z_0 = 460\ \Omega$ e $R = 6\ \Omega$, (5) gives $n = 6.0$. It is worth to highlight that this result is based on the assumption that the probability density function of Z is uniformly distributed and the transceiver is connected to the line extremity. If the transceiver is connected to a point of the line with m long branches (or feeders), the line characteristic impedance Z_0 is divided by m and the optimum transformer turn ratio is

$$n = \sqrt{\frac{Z_0\, k}{2Rm}} \tag{6}$$

In this example, if the transceiver is connected to a substation bus containing 4 feeders, then the optimum turn-ratio is 3.0. Under these assumptions, the expected value of Z can be easily computed by the same rationale and gives

$$Z = \frac{Z_0}{2m} \tag{7}$$

III. PHASE A

In the first phase of the project (Phase A), the substation control room equipment was connected to the PLC transceiver through a fiber optics link operating with serial (RS-232) interfaces. The transceiver modulates the serial signal over a PLC carrier that transports it through the medium-voltage line up to another coupler / transceiver pair that provides the signal to the line equipment serial port. Fig. 4 shows an overview of the PLC system developed in this phase.

The PLC transceiver used a single carrier (82.05 kHz) modulated by half-duplex frequency shift keying (FSK). The transceiver was implemented with the chipset ST7540$^{\text{TM}}$ [12], which has maximum bit rate of 4800 bps. The communication interfaces at both substation and line equipment were serial (RS-232), operating with the Distributed Network Protocol (DNP3). The signal coupling was capacitive and the coupler had also the function of powering the transceiver (see Fig. 1.b). A backup battery was connected to the DC bus of the transceiver, in order to power the PLC communication link in case of power outage.

At the power substation, the transceiver and the coupler were installed at the first structure of the aerial feeder. The data connection between the Control Room and the transceiver was made by a fiber optics cable and a pair of serial optical modems (see Fig. 4). The fiber cable was laid in the trenches of the substation yard. The coupler connection to the power line was made through a mechanical switch equipped with a line fuse. Fig. 5 shows examples of the coupler installation on structures of the 13.8 kV power distribution line.

At the distribution network, the transceiver was installed inside the equipment remote control unit. A mechanical switch with a fuse was also used to connect the coupler to the power line. Fig. 6 shows the coupler installation close to an automatic switch. The field trial installation for Phase A was restricted to only two feeders, with relatively short distances between the transceivers: 1.2 and 2.0 km.

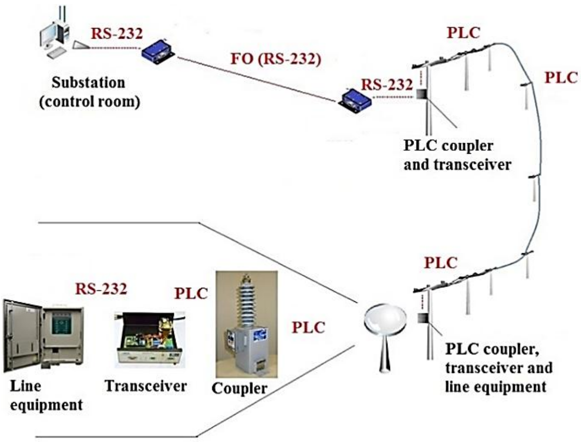


Figure 4. Diagram of Phase A system witth RS232 comunnication with equipment.

Figure 5. Details of coupler installation on the power line structure.

Figure 6. Example of coupler installation at an automatic switch.

During the installation process, a test device was inserted in the PLC communication path in order to assess the line impedance. At the substation side, the value obtained for the impedance "seen" by the transceiver (after the coupler) was 29 Ω. Considering that there were 8 feeders connected to the same bus ($m = 8$), the most probable value according to (7) is 28,8 Ω, which matches almost exactly the measured one.

A similar measurement was carried out at one transceiver installation. In this case, there were two lines (upstream and downstream the feeder) at the installation point ($m = 2$). The measured impedance value was 120 Ω, which is also close to the theoretical one from (7) (115 Ω). These results seem to support the assumption that the probability density function of Z is uniformly distributed, as considered in the former section. It is worth to mention that this value is close to the average value reported in [13], although their measurements were made at much higher frequencies.

The communication link was subjected to tests in the downstream (substation to equipment) and upstream (equipment to substation) directions. The PLC packets were always received without errors in the downstream direction, whereas some random errors were observed in the upstream direction. The reason for this asymmetry was not clear, and it is likely due to different signal to noise ratios at both sites. In any case, the inherent redundancy of the communication protocol made these errors irrelevant to the system operation. The PLC link was considered sufficiently stable to enter into operation, and it remained on duty for more than a year.

IV. PHASE B

The second phase of the project (Phase B) was dedicated to improve the communication interfaces, update the modulation technique and cover higher rated voltages. The communication interfaces at both substation and line equipment were defined as Ethernet (ETH) operating over the PLC communication link, as proposed in [14]. A short-range radio link was implemented in order to facilitate the installation of the transceivers at the substation. Fig. 7 shows a diagram of the PLC system, where can be seen that ETH communication is fully deployed through the network.

Fig. 8 shows the transceiver printed circuit board, where its main components can be seen. The connector at the lower end receives three conductors from the coupler (see Fig. 1), carrying the PLC signal and electric power to the circuitry. The RJ45 connector at the left-hand side is intended to be connected to the client equipment through an UTP (unshielded twisted pair) cable. This connection also provides 12 V_{DC} for powering the client equipment through PoE (Power over Ethernet). This is intended to power a short range radio unit used to connect the transceiver with the equipment installed at the substation control room (see Fig. 7).

The adoption of ETH required the disassembly, processing and assembly of the ETH frames within the transceiver, so that a transparent ETH link could be established for the client equipment. This real time data manipulation required the use of a powerful processing module (Toradex Colibri^{TM}), which contrasted with the relatively simple microprocessor used in Phase A transceiver.

The ST7540^{TM} chipset was replaced by the ST7590^{TM}, which modulates 96 carriers in the frequency band from 42 kHz to 89 kHz [15]. The modulation technique is orthogonal frequency-division multiplex (OFDM) using variants of differential phase shift keying (DPSK), which can reach a maximum bit rate of 128 kbps. This is also a significant improvement with respect to the former system, as OFDM is much more resistant to noise and standing wave phenomena than the single FSK carrier used in Phase A. Moreover, the multi-carrier modulation allows a significant higher throughput of the data link (up to 128 kbps) when compared with the one of Phase A (up to 4.8 kbps). Finally, it is worth to mention that the ST7590^{TM} provides an output power at its analog front end (AFE) which is about 3.5 times higher than the one from ST7540^{TM}.

The bench tests carried out with the prototypes showed a stable operation during several days. These tests were performed by sending messages in both directions, and checking the received messages for errors. The incoming data from the ETH interface is stored in a buffer and is transmitted through the PLC interface. The round trip latency for short messages is around 700ms and it is due mostly to the PLC link.

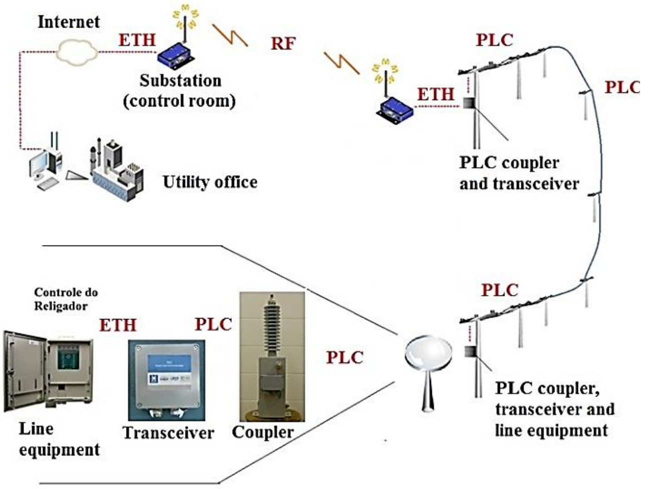


Figure 7. Diagram of Phase B system with ethernet interface with equipament.

The signal coupling in Phase B is also capacitive and the coupler has the function of powering the transceiver at 200 V_{AC}. The application was expanded to feeders with rated voltages from 13.8 kV to 34.5 kV, using the same coupler. The selection of the rated voltage is made by a switch installed inside the coupler tuning box. The decision of using the same high-voltage capacitor for both voltages is because the utilities involved in the project (Cemar and Celpa) use 34.5 kV bushings for 13.8 kV lines at coastal areas, due to pollution concerns. Therefore, a single high-voltage capacitor rated for 34.5 kV (see Fig. 2) was the best choice at this stage.

Figure 8. Transceiver printed circuit board.

Fig. 9 shows the PLC transceiver in its enclosure, which is prepared for external use. The enclosure is made of aluminum and is protected against the ingression of dust and water jets, being classified as IP65 according to IEC 60529 [16]. The connectors are also prepared for external use and have metallic clamps to be held on the enclosure. The status of the transceiver (idle, receiving data, and transmitting data) can be assessed from the outside by a single LED installed at the enclosure lateral wall.

Figure 9. PLC transceiver in its enclosure.

The prototypes for Phase B field trial are currently being tested. The field trial installation for Phase B was restricted to only two feeders, with distances between the transceivers of 1.2 and 5.4 km. The distribution feeders selected for the field trial operate in 13.8 kV and they are located at the cities of Campinas-SP e Belém –PA

Thus, the complete PLC system was installed on distribution network to validate its operation under real operating conditions. This system consists of: SEL relay control, two PLC modems, two PLC couplers, radios and computer to simulate the supervisory.

The Fig 10 shows a satellite image of the PLC system installed at the 1.2km feeder located at CPqD in Campinas - SP. The coupler was connected to the medium voltage network through a fuse switch whose function is to protect the network in case of PLC system failures.

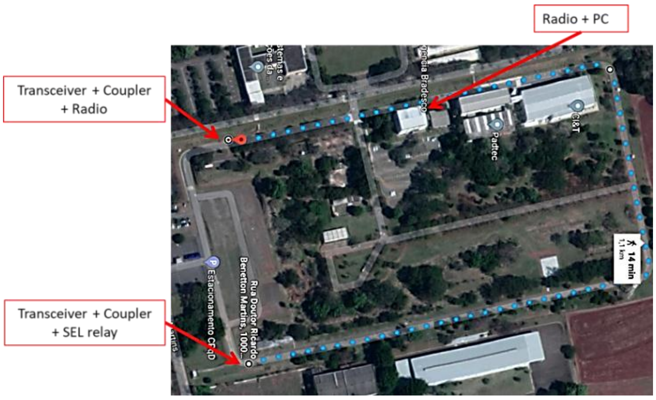


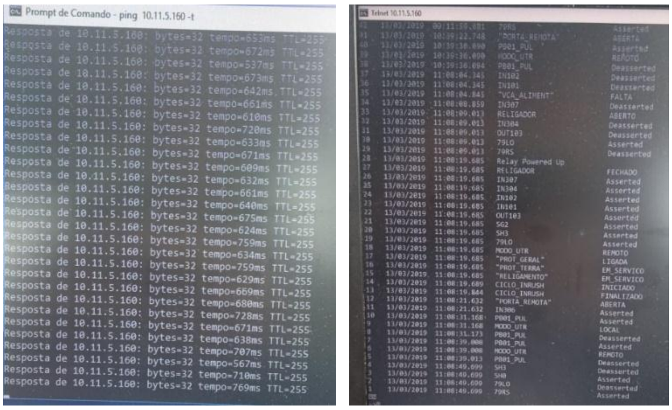
Figure 10. Satellite view of PLC system installed on CPqD

The Fig 11 and Fig 12 show the installation steps of the PLC system on the equipment and substation side, respectively.

Figure 11. Installation of PLC system (coupler/ transceiver/SEL relay) on equipment side.

Figure 12. Installation of PLC system (coupler/ transceiver/radio) on substation side.

The tests performed were successful and demonstrated that the PLC system is stable and suitable for use with distribution network equipment using ethernet interface. The validation of the field system was performed by the PING and TELNET command on the SEL-Schweitzer Engineering Laboratories relay (the last 100 events were requested) as shown in Figure 13. In addition, communication tests with the SEL relay were performed using the software that simulates SCADA.



Prompt de Comando - ping 10.11.5.160 -t

```
Resposta de 10.11.5.160: bytes=32 tempo=653ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=672ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=537ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=673ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=642ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=661ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=610ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=720ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=633ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=671ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=609ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=632ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=661ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=640ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=675ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=624ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=759ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=634ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=759ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=629ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=669ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=680ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=728ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=671ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=638ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=707ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=567ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=710ms TTL=255
Resposta de 10.11.5.160: bytes=32 tempo=769ms TTL=255
```

(a)

Telnet 10.11.5.160

```
42  13/03/2019  09:11:58.681  79RS                Asserted
41  13/03/2019  10:39:22.748  "PORTA_REMOTA"      ABERTA
40  13/03/2019  10:39:30.090  P801_PUL            Asserted
39  13/03/2019  10:39:36.090  MODO_UTR            REMOTO
38  13/03/2019  10:39:36.094  P801_PUL            Deasserted
37  13/03/2019  11:08:04.345  IN102               Deasserted
36  13/03/2019  11:08:04.345  IN101               Deasserted
35  13/03/2019  11:08:04.845  "VCA_ALIMENT"       FALTA
34  13/03/2019  11:08:08.859  IN307               Deasserted
33  13/03/2019  11:08:09.013  RELIGADOR           ABERTO
32  13/03/2019  11:08:09.013  IN304               Deasserted
31  13/03/2019  11:08:09.013  OUT103              Deasserted
30  13/03/2019  11:08:09.013  79LO                Asserted
29  13/03/2019  11:08:09.013  79RS                Deasserted
28  13/03/2019  11:08:19.685  Relay Powered Up
27  13/03/2019  11:08:19.685  RELIGADOR           FECHADO
26  13/03/2019  11:08:19.685  IN307               Asserted
25  13/03/2019  11:08:19.685  IN304               Asserted
24  13/03/2019  11:08:19.685  IN102               Asserted
23  13/03/2019  11:08:19.685  IN101               Asserted
22  13/03/2019  11:08:19.685  OUT103              Asserted
21  13/03/2019  11:08:19.685  SG2                 Asserted
20  13/03/2019  11:08:19.685  SH3                 Asserted
19  13/03/2019  11:08:19.685  79LO                Asserted
18  13/03/2019  11:08:19.685  MODO_UTR            REMOTO
17  13/03/2019  11:08:19.685  "PROT_GERAL"        LIGADA
16  13/03/2019  11:08:19.685  "PROT_TERRA"        EM_SERVICO
15  13/03/2019  11:08:19.685  "RELIGAMENTO"       EM_SERVICO
14  13/03/2019  11:08:19.689  CICLO_INRUSH        INICIADO
13  13/03/2019  11:08:19.844  CICLO_INRUSH        FINALIZADO
12  13/03/2019  11:08:21.632  "PORTA_REMOTA"      ABERTA
11  13/03/2019  11:08:21.632  IN306               Asserted
10  13/03/2019  11:08:31.168  P801_PUL            Asserted
 9  13/03/2019  11:08:31.168  MODO_UTR            LOCAL
 8  13/03/2019  11:08:31.173  P801_PUL            Deasserted
 7  13/03/2019  11:08:39.008  P801_PUL            Asserted
 6  13/03/2019  11:08:39.008  MODO_UTR            REMOTO
 5  13/03/2019  11:08:39.013  P801_PUL            Deasserted
 4  13/03/2019  11:08:49.699  SH3                 Deasserted
 3  13/03/2019  11:08:49.699  SH0                 Asserted
 2  13/03/2019  11:08:49.699  79LO                Deasserted
 1  13/03/2019  11:08:49.699  79RS                Asserted
```

(b)

Figure 13. (a) Tests performed with ping command (b) Request of the last 100 relay events via TELNET

V. DISCUSSION

A recurrent question regarding the use of narrow-band PLC for equipment automation is the line length that the PLC signal can reach without a repeater. Of course, this question has not a single answer, as it depends on a number of factors, such as the line topology (number of branches, type of conductors, spacing between conductors, etc), the effect of transformers and their loads, the effect of line equipment (e.g., voltage regulators), and the presence of noise.

In order to shed some light on this subject, some tests were carried out using PLC transceivers based on the ST7590™ chipsets running on serial ports and artificial line segments to represent the electric power network. The description of PLC artificial lines design and operation can be found in [17]. The tests were conducted using typical configurations of urban distribution feeders, and noise effects were neglected. These tests showed that stable operation could be obtained for distance between transceivers up to 10 km. Reducing the number of feeder branches improves significantly the signal integrity, so that much larger distances could be reached in rural feeders.

The relatively large distances for the PLC link require the use of low-frequency carriers, which are characteristic of narrow-band PLC. This necessarily restricts the throughput of the communication link and limits its applications to equipment automation. The requirement of running ETH interfaces over the PLC link poses another restriction on the system throughput, due to the overhead required by the internet protocol (IP). On the other hand, this restriction is partially compensated by the higher bit rate achieved by ST7590™ chipset. Through of field tests, the system proved to be sufficient to communicate with the equipment of the distribution network and presented a throughput of 5000 bps.

The PLC system has bandwidth limitations, throughput of 5000 bps and a latency of approximately 700ms for each packet trafficked. In addition, the PLC chipset can only travel 300 bytes per message, so any TCP / IP message larger than 300 bytes will be fragmented. Therefore, the SCADA must be adjusted to meet these requirements and enable its operation in conjunction with the PLC system. To do this, you must adjust the link timeout, the application timeout and request only the information necessary for the operation, avoiding data overload in the PLC network.

All field tests so far have been performed on 13.8kV distribution feeders and should also be performed on 34.5kV. However, the use of PLC in the 34.5kV distribution feeders should only impact the transceiver power circuit.

The coupler theoretical model presented in Section II.B allows an interesting interpretation of the results. Assuming that the probability density function of Z is uniformly distributed in the interval $0 \leq Z \leq Z_0/m$, the expected value of Z as given by (7) is not surprising. Indeed, under this assumption the expected value should be the average value. However, in order to maximize the expected power transmitted to the line, the transceiver should not be matched to expected value of Z, but to an impedance value slightly smaller given by

$$Z = \frac{Z_0\,k}{2\,m} \tag{7}$$

VI. CONCLUSION

This paper presented the development of a custom narrowband PLC system for the automation of typical Brazilian medium voltage distribution lines. The project showed that the PLC system can provide a reliable and stable ethernet communication link between the substation control room and equipment installed along with a distribution network feeder.

The solution is transparent and allows bidirectional traffic of various protocols. In addition, this system can be applied in 13.8kV and 34.5kV distribution network.

The first phase of the project showed that the PLC system can provide reliable and stable serial communication (with a maximum bit rate of 4800 bps) between the substation control room and equipment installed along a 13.8 distribution feeder. kV. The second phase of the project improved the PLC system to incorporate Ethernet interfaces, higher data throughput and higher feeder voltage (up to 34.5 kV). The field test of the PLC system was performed on 13.8kV feeders and was stable and had a communication rate of approximately 5kbps with latency of approximately 700ms.

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