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Motor Command and Supervision Using the Magnetic Components of the Insulation Fault Protection System for Power Line Communication

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ABSTRACT

This work proposes an additional function for a VSD (Variable Speed Drive) which sends and receives information over the power lines and simultaneously, implements the protection against insulation faults to earth. Using the magnetic components of the insulation fault protection system of the motor, the prototype injects and detects the communication signals over the power line. The system works on both communication schemes, with and without the PWM (Pulse Width Modulation) perturbation in the power lines, which are the two possible real applications. In order to set a proper communication between the motor and the drive, the communication channel was modeled and the noise was characterized. An FSK modulation and demodulation scheme was developed and tested. A 10 kbps communication over a 125m length of cable and over a 1km pi-section model of the same cable was successfully achieved with the laboratory prototype.

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1. INTRODUCTION

Induction motors are widely used at industry for motion control system due to their low cost and the relative low frequency of maintenance [1]. Anyway, a severe failure in such systems can cause significant economic losses due to the stop of production for long time spans. Because of that, many research works are focused on developing reliable ways for motor control diagnosing their conditions and performance (sensing motor parameters), and protecting them (keeping the mechanical and thermal conditions within acceptable limits) [2]-[4]. Statistics show that annual down times of 0.5% to 4% may be expected [5]. When it is necessary to regulate the motor speed, VSDs are used, which command the motor with adjustable frequencies and voltages using different Pulse Width Modulation (PWM) techniques [6]-[7].

VSDs sometimes require received control and diagnosis information both from the monitoring station and the motor [8]-[11]. This communication is commonly done using industrial communication protocols which need additional wires that can increase the system cost, and many times may be difficult or even impossible to install due to the inaccessibility to the place where the motors are mounted [12]. In some cases long cables need to be used, with lengths from a few hundred meters to a kilometer, between the motor and its driver [12]-[13]. Examples of these are underground pump driving motors, heaters used in industry and mines, and wind generators [8].

Also, these motor drives, integrate protection functions against overload, short circuit between phases and insulation faults, among others. The main causes of motor failure are the variation of the feeding phase voltages, mechanical overloads, and problems produced by inadequate or faulted electrical installations [3],[4],[14]. Other causes may include the aging of the motor or eventual adverse environmental conditions. Most of these events lead to an increase of the current and to a subsequent rise of motor temperature. An unacceptable overheating of the motor could damage the insulation of the windings taking the motor out of service [4],[14],[15]. The high dv/dt, characteristic of PWM VSDs, is a source of further stress and deterioration of the insulation.

There are many works, such as [8]-[11],[13], in which the power lines feeding the motor are used as communication channel to transmit commands and diagnose information. In this work, in addition of profiting of the power lines as a communication channel, the magnetic components of the insulation fault protection system (commonly used in VSDs) are used as communication coupling devices. This approach implies the difficulty of transmitting and detecting signals with the common mode noise injected by the high voltage PWM signals. The inductive coupling proof to be the more reliable in PWM networks [8], but the communication signals are injected in common mode to be able of insulation fault detections.

Due to the fact that the signal injection is in common mode, the communication channel and the noise are studied for this particular scheme using the ABCD transmission matrix of the system components as in [13]. Based on the communication channel model obtained, an FSK system was designed, implemented and tested. A 10 kbps communication over a length of 125 m of 4 x 6 mm^2 ETIX cable was successfully achieved. Also, the system was tested successfully with 8 sections of PI circuit (representing 125 m each section) emulating the behavior of 1 km of the same cable.

2. PROTECTION AND COMMNAD SYSTEM

2.1. Basic Protection Scheme

Basic protection functions are commonly integrated in VSDs, such as insulation fault detection. These systems are generally implemented as differential relays [16],[17], which are conceptually based on a property of single-phase and three-phase systems, which states that in absence of insulation faults the sum of the line currents must be null. This scheme switches-off the motor whenever a zero sequence current in the feed lines appears.

As stated in [18] if the differential protection scheme is built using small-cores transformers, two transformers are required. One injects a high frequency zero sequence current to be detected by the second one only if an insulation fault occur. This scheme is shown in Figure 1.

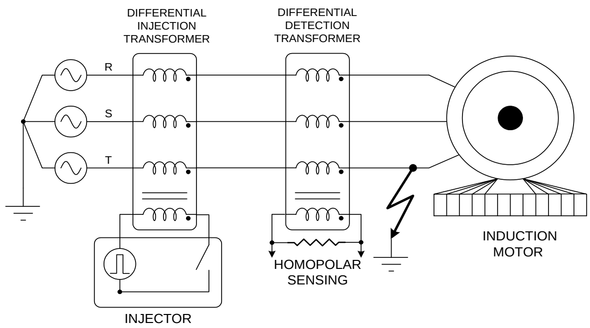


Figure 1. Injection and detection signal scheme for insulation fault detection

The signal injection circuit will not produce a high-frequency circulating current as long as the motor does not have a neutral connection, which is the usual case. In this situation, the secondary of the differential current detection transformer presents no induced voltage. The signal will be effectively injected and detected when a ground or neutral fault occurs because that only the homopolar current could produce a net flux in the transformer core to induce a detectable secondary voltage. If the neutral terminal is accessible to the operator, both line-to-ground and line-to-neutral faults can be discriminated between each other by using two detection circuits and passing the neutral wire through one of the detection transformer cores.

2.2. Communication Signal Coupling using the Magnetic Components of Insulation Fault Protection System

The previous section introduced the use of current transformers for motor protection against insulation faults. The following describes the use of the magnetic components as coupling devices interfacing with the power lines to inject and recover commands, without losing the capacity of insulation fault detection. Depending on the specific application, there are two possible communication system schemes.

One corresponds to the case where the data flow is between the supervision system and the variable speed drive (Figure 2). Under these conditions, if the inverter has a filter at the input (which usually has), the flowing currents do not have a high harmonic distortion, which is the most favorable case for setting the communication. On the other hand, a more adverse scenario is present when the communication is stablished between the motor and the inverter (Figure 3), due to the high voltage PWM signal presence on the power lines, which pollute the communication media and degrade the signal to noise ratio. In this scheme the motor could be sending diagnosis information to the supervision system, such as motor winding temperature, vibration, etc.

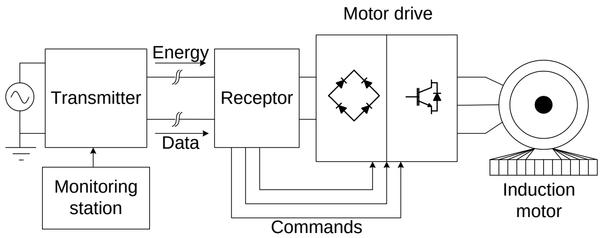


Figure 2. Inverter-Motor remote command

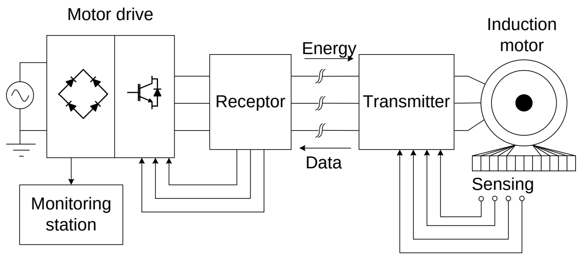


Figure 3. Motor parameters remote sensing

In order to allow the communication to the monitor system, an FSK modulation and demodulation scheme was implemented using an FPGA and ASIC (Application Specific Circuit) which implements the demodulator by Switched Capacitor technique [19]. Both the injection and detection signal circuit use the magnetic components of the insulation fault protection system, as coupling interfaces to the power lines. As concluded in [8] the inductive coupling interface is the more reliable.

Figure 4 shows the system when used to send and receive diagnosis information from the motor to the inverter. This scheme is the most interesting because their requirements, given that the communication must be set in the presence of the PWM signal. The dv/dt filter at the inverter output is optional and it is not needed to set the communication, but to protect the induction motor against surge waves because of long cables.

2.3. Communication Channel Modelling

In all data transmission system, it is customary to analyze the media which transport the communication signals and the existing noise to properly design the communication system.

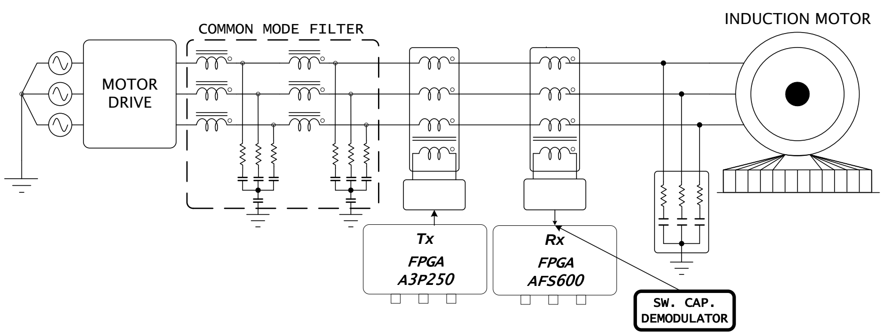


Figure 4. Injection and recovering data scheme in PWM network. The power cable is connected between the injection and detection current transformers

The communication scheme of Figure 4 can be represented by the general communication model shown in Figure 5. The model consists of the impulsive response of the channel communication media, and the additive noise at the receiver end. According to this simple model, the signal at the receiver end can be written as:

$$r(t) = s(t) * h(t) + n(t) \tag{1}$$

where *s(t)* is the injected signal by the transmitter, *h(t)* is the impulsive response of the media and *n(t)* is the noise at the receiver end.

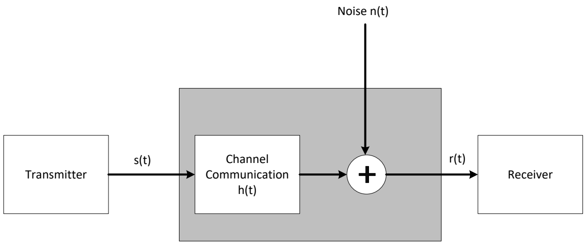


Figure 5. General channel model

In general PLC systems are difficult to model due to the multiple paths that the signal can take. In the case of the communication between the motor and the inverter the scheme is simpler because the components of the system are well defined. As the injected signal is homopolar, the common mode impedance of each component must be modeled. In this section, the channel communication is studied, obtaining the frequency response between the sender and the receiver, by the ABCD transmission matrix method as in [13].

All the components that integrate the whole system are described by their own transmission matrix, and then, the chain rule is applied in order to obtain the complete transfer characteristic. As shown in Figure 4, the signal is injected by the transmitter through the inductive coupling at the motor side. Then, the data travel through the power lines to the receiver end, where the inductive coupling of the receptor demodulates the information. Additionally, in parallel with the motor and the inverter (if no dv/dt filter is connected) there are common mode impedances (series RC) that allow the homopolar current to flow.

Figure 6 shows the coupling interface at the transmitter and receiver ends. The injection current transformer is commanded by a push-pull circuit. Notice that the receiver current transformer is connected to the Switched Capacitor demodulator. All the impedance models of each component of the communication system were modelled by the transmission matrixes that respond to the next equations, depending whether the impedance be connected in series or parallel with the signal path:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & Z_s \\ 0 & 1 \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{1}{Z_p} & 1 \end{pmatrix} \tag{3}$$

Then applying the chain rule, the total transmission matrix is obtained between the transmitter and receiver. The individual transmission matrix connection is shown in Figure 7. The total quadripole transmission matrix connection is also shown in the same figure. Each transmission matrix of the Figure 7a corresponds to:

Tpi: Injector's parallel impedance transmission matrix.
Tsi: Injector's series impedance transmission matrix
Tm: Motor's and parallel leakage's impedance transmission matrix.
Tc: Cable's transmission matrix.
Tfi: Inverter's and parallel leakage's impedance transmission matrix.
Tsd: Detector's series impedance transmission matrix.
Tsp: Detector's parallel impedance transmission matrix.

Finally, in Figure 8, the frequency response of channel communication between the motor and the inverter modelled and measured is plotted taking into account that:

$$H = \frac{U_0}{U_g} = \frac{Z_L}{AZ_L + B + CZ_LZ_g + DZ_g} \tag{4}$$

The measurement setup includes a function generator with 50 ohms output impedance and a regular oscilloscope. The sinusoidal frequency of the signal at the function generator was varied between 10 kHz-1 MHz and the injected and detected signal was measured. The discrepancy in the model and measurement around the frequency corners is due to the sensibility of the oscilloscope (mV signal was measured for that frequencies).

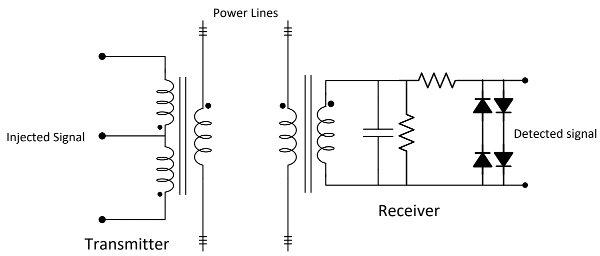


Figure 6. Transmitter and Receiver coupling interface

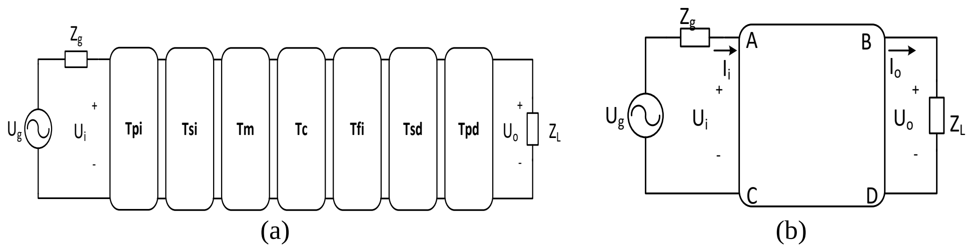


Figure 7. (a) Chain transmission matrix Communication channel model between the motor and the inverter. (b) Quadripole model through the ABCD transmission matrix excited by a generator with impedance Z_g and connected to a load Z_L

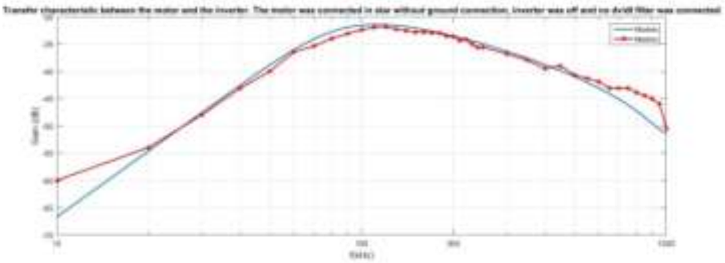
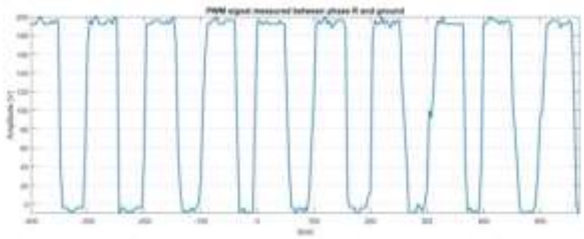


Figure 8. Communication channel frequency response between the motor and the inverter to the frequency band of 10kHz-1MHz

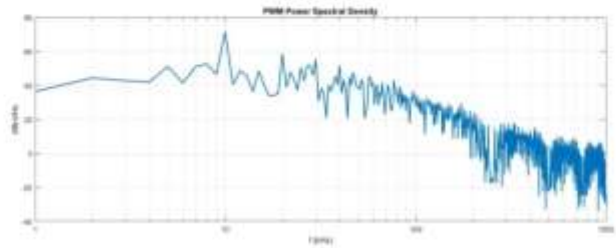
2.4. Noise Characterization

As important as model the communication channel is to characterize the source of noise in the media. In [20] the authors say that the power lines do not conform an AWGN channel. Also, in [21] it is argued that the noise sources are as diverse as colored noise, narrow band noise and periodic and aperiodic impulsive noise. In inverter fed power lines the main cause of noise is the high voltage PWM signal.

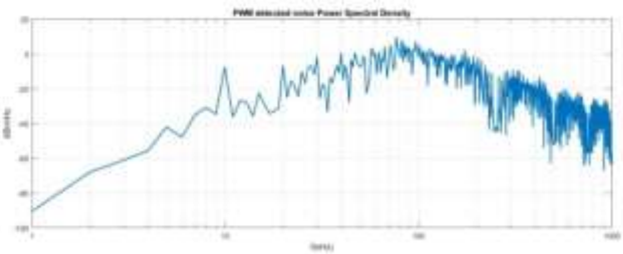
The inverter output IGBTs has high dv/dt variations. The usual switching frequency varies between 2-20 kHz. The level of detected noise at the receiver end will depend on the connection or not of the dv/dt filter at the output of the inverter. The Figure 9 shows the PWM signal measured between a phase and ground and it's PSD. Also the PSD of the detected noise is plotted for no filter at the inverter output connected. The switching frequency is 10 kHz. Figure 9.c shows how the noise detected because of the PWM signal is severely diminished by the communication channel.



(a)



(b)



(c)

Figure 9. (a) PWM signal measured at the inverter output (b) PSD of PWM signal and (c) PSD of the PWM noise detected at the receiver end

3. EXPERIMENTAL RESULTS

The laboratory experimental setup is represented in Figure 10. A 0.4kW Hitachi VFD was connected to a 0.18kW Siemens induction motor, through a 125 m 4x6 mm^2 ETIX power cable. The FSK modulator and demodulator implemented were coupled through the coupling interface shown in Figure 6. Also the RC network at the motor and inverter ends was connected in order to provide a path to the communication signals. As shown in Figure 10 there is no need to connect a dv/dt filter at the inverter output to establish a proper communication.

In Figure 11 the insulation fault protection measurement are presented. Abrupt leakage impedance was connected and the detected rectified and the alarm signals were measured. The delay of the insulation fault detection can be seen in Figure 11, and it is of the order of 5 µs, which not only allow human [22] and motor protection but also protection of the IGBT modules as well.

Then the communication system tests were performed to show the no influence of the PWM signal to recover the injected commands in the power lines. Three motor commands were implemented in the prototype which are forward, reverse and stop commands. Figure 12 show the detected signal and demodulated bit for a 0-1-0 bit sequence. Figure 13 show the transmitted and demodulated bit for the three commands implemented with the inverter on.

As can be seen in Figures 12 and 13 the bit rate obtained is 10 kbps. The same bit rate was achieved in the laboratory setup with the PI sections circuits that emulates a 1 km of 4 x 6 mm^2 ETIX power cable. The cable electrical parameters were obtained by finite element method (FEM) simulation of the geometry of the cable provided by the manufacturer.

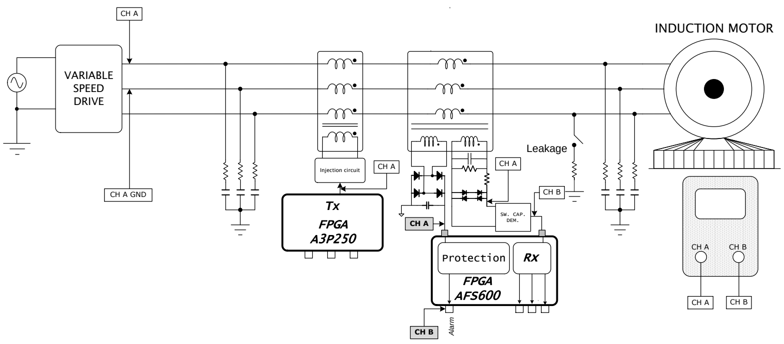


Figure 10. Laboratory experimental setup for protection and power line communication test

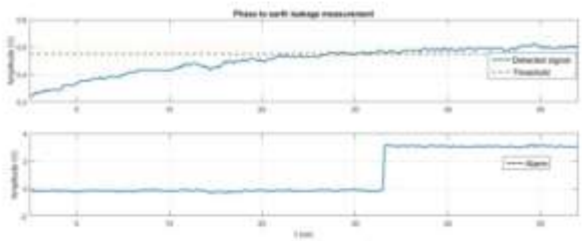


Figure 11. Insulation fault protection measurement

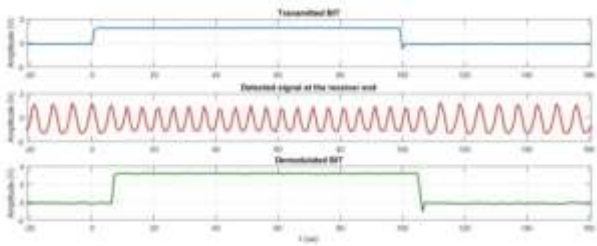
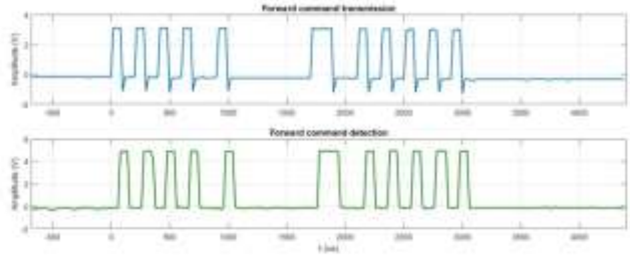
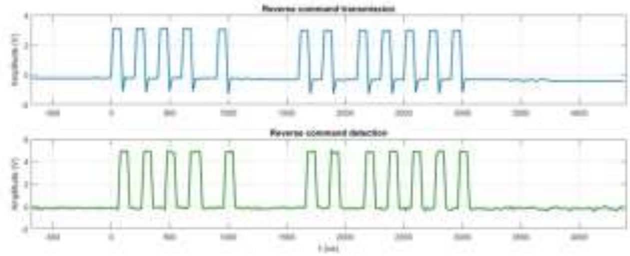


Figure 12. Communication system measurements



(a)



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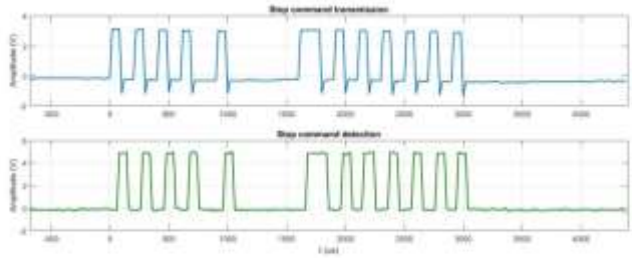

(c)

Figure 13. Received commands in the PWM network (a) Forward (b) Reverse (c) Stop

4. CONCLUSION

In this work, magnetic components of the insulation fault protection system, commonly used in VSDs, were used as coupling interfaces to the power lines in order to achieve a communication through them. A 10 kbps communication over a 125 m length of cable and over a 1 km pi-section circuit that emulate the behavior of the same cable was successfully achieved with the laboratory prototype. Also, both protection and communication functions can simultaneously work. A channel communication and noise model for the common mode injection scheme over the 10 kHz – 1 MHz band was obtained.

The insulation fault detection delay is of the order of few µs, which not only allow human and motor protection but of the IGBT modules of the inverter as well. The apparently weakest point of the system is maybe it's bigger advantage with respect of the other works, and it is the injection and detection common mode signal. If one or even two wires of the power line fails (cutoff) the system can warn the monitoring system by establishing communication through the remaining wire.

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Hernan E. Tacca was born in Argentina on December 15, 1954. He received the B.E. degree in electrical engineering from the University of Buenos Aires (Argentina), in 1981 and the M.S. and Ph.D. degrees from the University of Sciences and Technologies of Lille (France) in 1988 and 1993, respectively. In 1998 he received the Doctorate degree from the University of Buenos Aires. Since 1984, he has been with the Faculty of Engineering of the University of Buenos Aires, where he is currently full Professor and engaged in teaching and research in the areas of industrial electronics. His research interest are in the field of SMPS, UPS, battery chargers, soft-switching techniques and microcontroller control of power converters.