Variables in the maintenance of electric motors, by power line communication and multi-criteria analysis

Murilo Oliveira Leme
Flavio Trojan
Antonio Augusto de Paula Xavier
Federal University of Technology, Parana, Brazil
Corresponding author: muriloleme@utfpr.edu.br

Abstract
This paper explores the measuring of variables such as electric current, voltage, temperature, and vibrations in the maintenance of electric motors, by power line communications, at industrial production in order to identify the better moment to realize the maintenance by multi-criteria analysis. An application and its results are also presented.

Keywords: multi-criteria, maintenance, electric motor

Introduction

The correct monitoring of the operating status of electric motors in industrial processes, with evaluations of the important variables for that operation, can support decision making regarding the best maintenance time. Consequently, it can contribute to a better performance in the production process.

As electric motors represent a significant part of the investment account in the industry, a common practice is having spare motors for critical processes that often sit unused for significant periods of time, but the appropriate care of the motors that are not in operation is crucial for their successful commissioning also requires outlays (McElveen, *et al.*, 2013).

Electric motors contribute significantly to the operating cost, not only with repair of motors, but also regarding reliability as well as energy cost, efficiency and inadequate repairs. Therefore, repairing quickly at a reasonable cost and getting the machine back in service has been the primary concern (Whelan, *et al.* 2006).

The maintenance management has an important role in the success of programs to combat waste and the effectiveness of control techniques and systems management. The activities cannot cease without causing unacceptable losses to the productive process. Thus, the maintenance sometimes has the same importance degree of the production. (Trojan and Morais, 2012). The use of predictive maintenance is still expensive and new techniques need to be developed, in order to have a tool with great efficiency and low cost at the same time.

This paper presents a multi-criteria analysis for decision making of maintenance management in production and operations management, through data acquisition by sensors connected to electric motors, which monitor the important variables for predictive maintenance such as voltage, current, vibration, temperature. This data is transmitted by the electrical communication network (I2PLC technology), leading to an array of multi-criteria evaluation to decide on the best time to stop for maintenance. This kind of data transmission does not require specific cables for communication, because it is done through the main conductors.

Thus, this work combines the monitoring technique in power line communication with a multi-criteria analysis tool, for operations and maintenance management with low cost and high efficiency.

Power Line Communications (PLC)

The PLC technology, acronym of the English Power Line Communication is a proposal of the use of electricity distribution networks as a carrier for data communication by superimposing an information signal to the AC (Alternate Current) signal.

This technique using the power grid for data transmission is not new and has been a focus of research for internet transmission. This technology is an alternative to provide broadband services to neighborhoods and regions where other services such as ADSL (Assymmetric Digital Subscribe Line), cable or wireless cater not based on cost / benefit (Zattar and Carrijo, 2012).

In 2005, 20 companies agreed to form the IEEE 1901 a working group sponsored by the IEEE Communications Society, which resulted in standards for Broadband, i.e., access to Internet applications, voice over IP, and utility applications such as controlling energy use by suppliers of electricity (Goldfisher and Tanabe, 2010).

PLC services became very competitive with other services such as ADSL, so they can take advantage of existing infrastructure and vast extended power electric network, but, the power system originally was not designed for communication, and several phenomena occur inside it; the strong attenuation and disturbances prevent the transmission of signals at high frequency, and hence a limited top speed is achieved (Melit *et al.*, 2012).

This technology is envisioned as a platform for various smart grid applications, including real-time monitoring and load balancing, improving grid robustness to disturbances, integrating alternate energy sources into the grid, with smart metering in frequent meter reading, making it possible to provide the end user with information about the load usage, which can be used to optimize power generation and perform load management with finer time granularity to save on energy costs (Nassar *et al.*, 2012).

PLC systems may be placed in three bandwidth categories (Nassar *et al.*, 2012): Ultra narrowband (UNB) systems operating in the 0,3 – 3,0 kHz band to provide about 100b/s over ranges up to 150Km; Narrowband (NB) or low-frequency (LF) systems which operate in 3-500 kHz band to deliver a few kilobits per second in the single carrier case and up to 800kb/s in the multicarrier case; Broadband (BB) or high-frequency (HF) systems that operate in the 1,8-250 MHz band to provide up to 200Mb/s for home area networks. The IEEE P1901 standard and the approved ITU G.996x recommendations (G.hh) are the most recent standards.

The use of PLC in industrial environment for data acquisition in the frequencies between 8kHz and 64kHz was tested with various types of noise inserted in the electrical network and all data was acquired successfully, proving the feasibility of the technique in an industrial environment (Leme *et al.*, 2013).

Thus, in this study we used the PLC technique to send information collected from sensors connected in electric motors to a Personal Computer, thus avoiding the need for passing new cables for communication.

Monitoring and diagnosis of electric motors with predictive maintenance through PLC

Electric motors present different repair services, and a few or no decision which anticipates the repair before of the damage, and therefore the adequate management of this repair service is an opportunity to improve operating efficiency by increasing quality and lowering overall cost (Whelan *et al.*, 2006). The goal of a predictive maintenance program is to identify an unsatisfactory condition before it results in motor failure or damage. Unplanned motor failures result in costly downtime and are generally rather more expensive and difficult to repair, and replacement motors are not always readily available from manufactures, and storage of spare motors as replacements is costly and always impractical (Soergel and Rastgoufard, 1996).

One strategy using improved maintenance operations conditions is a technique based on detecting initial failures. This methodology allows trend monitoring and prediction of failure function, and expert systems can be adapted for machine condition based on monitoring data interpretation, due its ability to identify systematic reasoning processes (Rad *et al.*, 2011). Energy monitoring and fault diagnostics are critical for industrial motor systems to maintain safety, efficiency and operational availability. Early detection of motor system failures through fault diagnosis and prognostics allows appropriate maintenance to be scheduled proactively to prevent motor failures. Traditionally, energy monitoring and fault detection systems in industrial plants are realized in wired systems formed by communication cables and various types of sensors. The installation and maintenance of these cables and sensors are usually much more expensive than the cost of the sensors themselves (Lu and Gungor, 2009).

Industrial networks are concerned with the implementation of protocols between field devices, digital controllers, and software packages and also external systems. The development of industrial communication protocols began due to both end-user requirements as well as the appearance of new technologies, which were adapted to industrial settings. These communications by protocols are common. More recently, digital control systems started to incorporate networking at all levels of the industrial control, as well as the inter-networking of business and industrial equipment using Ethernet standards and resulted in a networking environment that appears similar to conventional networks at the physical level, but which has significantly different requirements referred to as fieldbus protocols (Galloway and Hancke, 2013).

In Figure 1, the diagram of how the sensor readings are performed in engines and the transmission of this information by the power line is shown.

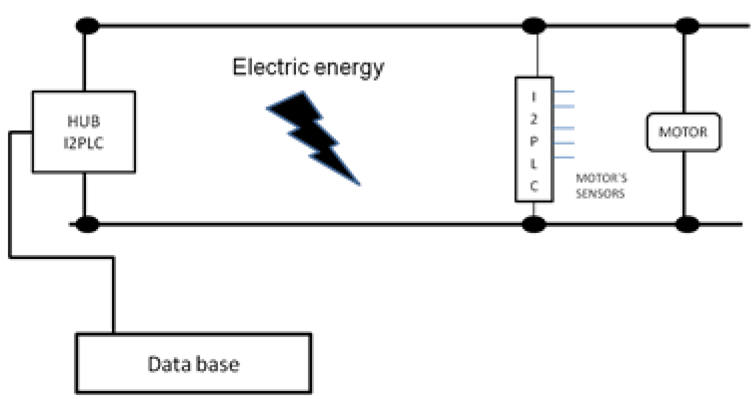


Figure 1 – Diagram of Power line Communications

The modules that read the information from the sensors in the engines are called remote modules I2PLC (Industrial Interface by Power Line Communications), while the I2PLC concentrator module receives the information of all modules for the analysis on a personal computer.

Sensors of remote module I2PLC

For the evaluation of the data read regarding electric motors conditions for maintenance management through multi-criteria analysis, the following variables were defined: voltage, current, vibration, engine temperature, ambient temperature and humidity.

In this study, four single-phase motors were installed for the collection of information and analysis. Figure 2 shows how the I2PLC system was implemented to read each variable related with the electric motor systems.

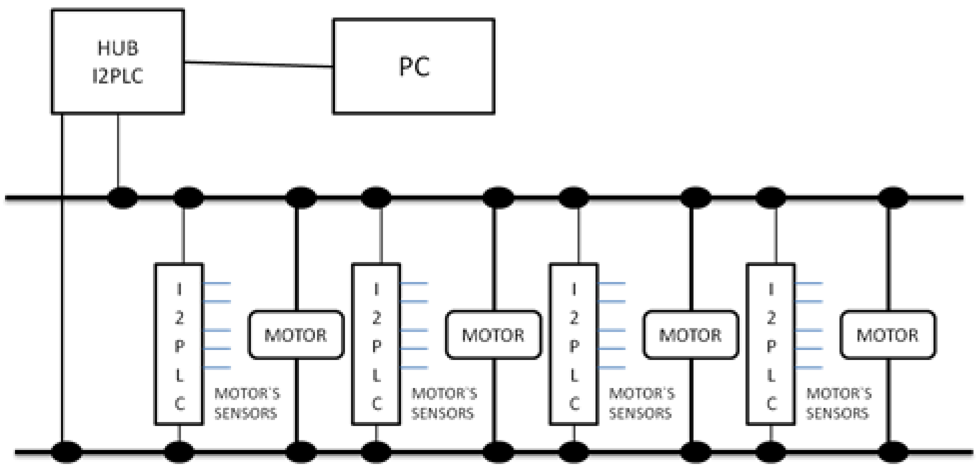


Figure 2 – Architecture of sensor installation

Each variable was measured every one minute and sent to the HUB I2PLC, which in turn forwarded the information to the computer, thereby forming a data base with information field of each of the motors for operating conditions analysis.

Multi-criteria decision analysis in maintenance management

The multi-criteria analysis has been an important tool to support decisions. It presents several kinds of methods and techniques regarding problems in production and management. In this work, multi-criteria analysis was approached regarding maintenance management in operation of electric motors related with production and operations management.

Various factors have influenced the choice of multi-criteria method, among which stand out: the problematic which is being approached, the decision-maker’s preference structure and the context of the problem. The context of this problem directs to a non-compensatory approach, due to the impossibility of having unlimited compensations in these criteria classes, therefore, without the establishment of trade-offs. The methods that fit these circumstances are called outranking methods (Roy, 1985).

The outranking methods allow the fact that small differences between the evaluations of the alternatives are not always significant (Vincke, 1992). Among the methods based on outranking relations, the PROMETHEE I method was selected for this work, which focuses on the ordination of electric motors that have continuous deviations in the monitored variables in its operation. In the general form, the PROMETHEE methods aim to help the decision maker in the evaluation of a set of alternatives (*A*), generally finite. It considers the criteria of evaluation g_j where: $j = 1,2, \ldots, n$.

For the establishment of an outranking relation, considering all the criteria for each pair of actions, the definition of a global preference index of action over another is expressed by the equation (1):

$$\prod(a,b) = \sum_{j=1}^{k} P_j(a,b)w_j \tag{1}$$

Where;

w_j ⇨ relative importance of criteria (weights);

$P_j(a,b)$ ⇨ preference functions, intra-criterion information.

Another important concept is related to outranking flows (Brans and Mareschal, 2005). The output outranking flow, expressed in equation (2), indicates the trend of one alternative to over-classify heavily the other alternatives, and

$$\phi^+(a) = \frac{1}{n-1}\sum_{x \in A} \pi(a,x) \tag{2}$$

The input outranking flow, expressed in equation (3).

$$\phi^-(a) = \frac{1}{n-1}\sum_{x \in A} \pi(x,a) \tag{3}$$

In this method, in particular, the partial ordination uses the intersection of the two outranking flows, inflow and outflow, as expressed in (4) (Brans and Mareschal, 2005):

$$\begin{aligned}
&aPb \Leftrightarrow \begin{cases} \phi^+(a) > \phi^+(b) \text{ and } \phi^-(a) < \phi^-(b), \text{ or} \\ \phi^+(a) = \phi^+(b) \text{ and } \phi^-(a) < \phi^-(b), \text{ or} \\ \phi^+(a) > \phi^+(b) \text{ and } \phi^-(a) = \phi^-(b). \end{cases} \\
&aIb \Leftrightarrow \phi^+(a) = \phi^+(b) \text{ and } \phi^-(a) = \phi^-(b) \\
&aRb \Leftrightarrow \text{ in other cases}
\end{aligned} \tag{4}$$

In the PROMETHEE I, certain alternatives remain incomparable. Only the preferences established and confirmed by both outranking flows are presented to the decision maker. Where (*P*, *I*, *R*) correspond to Preference, Indifference and Incomparability of PROMETHEE I. These are the possible results of the comparison between two alternatives.

The application of multi-criteria analysis using I2PLC for predictive maintenance

In this application, data was collected in a sampling of four electric motors in operation, considering a sampling time of one minute, with data about voltage, current, humidity, ambient temperature, engine temperature and vibration.

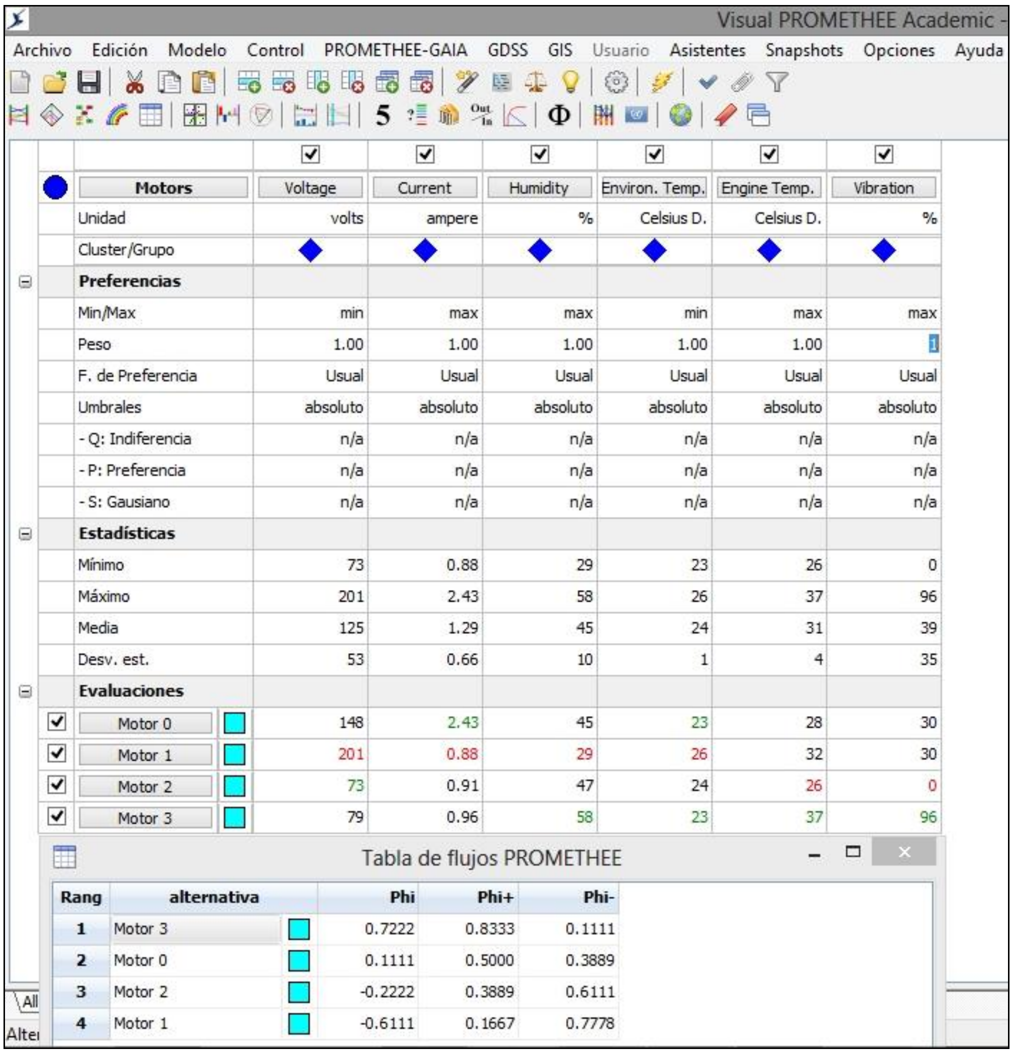
Table 1 presents one fragment of the data in order to show the format in which the data was collected. Thirty two times of variable data was measured by the I2PLC technology and in sequence it was analyzed by a multi-criteria method in order to improve decisions in predictive maintenance. In Table 1, it is possible to notice some of the variable behavior, but it is necessary to consider all variables at the same time. It generates a dynamic behavior revealing which equipment was presenting damage over that time. In the sequence, the data was organized in order to use the multi-criteria method to ordinate the electric motors, according to the variations and considering the variables as criteria and the electric motors as alternatives.

Table 1 – Data sampling of four electric motors

Time	**Motor**	**Voltage** (V)	**Current** (A)	**Humidity** (%)	**Ambient Temp.**	**Engine Temp.**	**Vibration** (%)	**Time** hh:mm	**Month**	**Day**
T_0	M_0	110	0.94	47	22	24	21	16:50	Dec	17
	M_1	220	22.00	32	24	24	2			
	M_2	110	0.87	50	25	25	3			
	M_3	220	0.96	59	23	23	13			
T_1	M_0	110	0.93	45	22	24	29	16:51	Dec	17
	M_1	200	0.88	28	25	25	2			
	M_2	110	0.84	48	26	26	9			
	M_3	200	0.94	59	24	24	98			
T_2	M_0	220	21.38	45	22	30	58	16:52	Dec	17
	M_1	220	21.34	28	25	34	64			
	M_2	142	6.06	48	26	26	39			
	M_3	92	5.55	59	24	24	29			
T_3	M_0	220	19.53	45	22	28	56	16:53	Dec	17
	M_1	220	19.25	28	25	29	53			
	M_2	121	4.44	48	26	24	67			
	M_3	154	3.65	59	24	25	62			
T_4	M_0	110	30.00	45	22	30	13	16:54	Dec	17
	M_1	108	30.00	28	25	34	10			
	M_2	110	30.00	48	26	26	13			
	M_3	108	30.00	59	24	24	10			
T_5	M_0	220	19.53	45	22	28	2	16:55	Dec	17
	M_1	220	19.25	28	25	29	3			
	M_2	121	4.44	48	26	24	2			
	M_3	154	3.65	59	24	25	3			
T_6	M_0	110	30.00	45	22	30	13	16:56	Dec	17
...	M_1	108	30.00	28	25	34	10			
	M_2	110	30.00	48	26	26	13			
T_{31}	M_3	108	30.00	59	24	24	10			

The PROMETHEE I method was used in this application because it presents a non-compensatory approach. In this work we only needed to compare the alternatives (electric motors) in order to notice which piece of equipment was in maintenance status and how many times it happened. Thus, it will be possible to program the maintenance using predictive concepts.

An academic edition of Visual PROMETHEE software was used in this phase to support the analysis, version 1.4.0.0 developed by Bertrand Mareschal (2011-2013). Figure 3 shows as an example of the application in PROMETHEE software in one part of the analysis only.



Motors	Voltage	Current	Humidity	Environ. Temp.	Engine Temp.	Vibration
Unidad	volts	ampere	%	Celsius D.	Celsius D.	%
Cluster/Grupo						
Preferencias						
Min/Max	min	max	max	min	max	max
Peso	1.00	1.00	1.00	1.00	1.00	1
F. de Preferencia	Usual	Usual	Usual	Usual	Usual	Usual
Umbrales	absoluto	absoluto	absoluto	absoluto	absoluto	absoluto
- Q: Indiferencia	n/a	n/a	n/a	n/a	n/a	n/a
- P: Preferencia	n/a	n/a	n/a	n/a	n/a	n/a
- S: Gausiano	n/a	n/a	n/a	n/a	n/a	n/a
Estadísticas						
Mínimo	73	0.88	29	23	26	0
Máximo	201	2.43	58	26	37	96
Media	125	1.29	45	24	31	39
Desv. est.	53	0.66	10	1	4	35
Evaluaciones						
Motor 0	148	2.43	45	23	28	30
Motor 1	201	0.88	29	26	32	30
Motor 2	73	0.91	47	24	26	0
Motor 3	79	0.96	58	23	37	96

Rang	alternativa	Phi	Phi+	Phi-
1	Motor 3	0.7222	0.8333	0.1111
2	Motor 0	0.1111	0.5000	0.3889
3	Motor 2	-0.2222	0.3889	0.6111
4	Motor 1	-0.6111	0.1667	0.7778

Figure 3 – PROMETHEE-I method application

In Table 2, the results of each application of times with PROMETHEE I method are presented. Each ordination means the electric motor state in relation to its operation at that minute.

Each last position (fourth position in this case) means that electric motor needed maintenance. In the right table, the last position received number “1”, and the times in which the electric motor needed the maintenance intervention were computed, i.e., that electric motor was presenting many variations in all criteria at the minute of measurement.

Table 2 – Ordination of motors by multi-criteria analysis

Resultant ordination						Times to maintenance				
Time	**$Motor_0$**	**$Motor_1$**	**$Motor_2$**	**$Motor_3$**		**Time**	**$Motor_0$**	**$Motor_1$**	**$Motor_2$**	**$Motor_3$**
T_0	4 th	1 st	2 nd	3 rd		T_0	1	-	-	-
T_1	3 rd	2 nd	1 st	4 th		T_1	-	-	-	1
T_2	4 th	3 rd	1 st	2 nd		T_2	1	-	-	-
T_3	4 th	1 st	2 nd	3 rd		T_3	1	-	-	-
T_4	4 th	2 nd	1 st	3 rd		T_4	1	-	-	-
T_5	3 rd	3 rd	2 nd	4 th		T_5	-	-	-	1
T_6	4 th	2 nd	1 st	3 rd		T_6	1	-	-	-
T_7	3 rd	2 nd	1 st	4 th		T_7	-	-	-	1
T_8	3 rd	2 nd	1 st	4 th		T_8	-	-	-	1
T_9	3 rd	2 nd	1 st	4 th		T_9	-	-	-	1
T_{10}	3 rd	2 nd	1 st	4 th		T_{10}	-	-	-	1
T_{11}	2 nd	3 rd	1 st	4 th		T_{11}	-	-	-	1
T_{12}	3 rd	2 nd	1 st	4 th		T_{12}	-	-	-	1
T_{13}	3 rd	4 th	1 st	2 nd		T_{13}	-	1	-	-
T_{14}	3 rd	2 nd	1 st	4 th		T_{14}	-	-	-	1
T_{15}	3 rd	4 th	1 st	2 nd		T_{15}	-	1	-	-
T_{16}	3 rd	4 th	1 st	2 nd		T_{16}	-	1	-	-
T_{17}	2 nd	3 rd	1 st	4 th		T_{17}	-	-	-	1
T_{18}	3 rd	4 th	1 st	2 nd		T_{18}	-	1	-	-
T_{19}	3 rd	2 nd	1 st	4 th		T_{19}	-	-	-	1
T_{20}	3 rd	2 nd	1 st	4 th		T_{20}	-	-	-	1
T_{21}	3 rd	2 nd	1 st	4 th		T_{21}	-	-	-	1
T_{22}	3 rd	2 nd	1 st	4 th		T_{22}	-	-	-	1
T_{23}	3 rd	1 st	2 nd	4 th		T_{23}	-	-	-	1
T_{24}	3 rd	1 st	2 nd	4 th		T_{24}	-	-	-	1
T_{25}	2 nd	1 st	3 rd	4 th		T_{25}	-	-	-	1
T_{26}	3 rd	2 nd	1 st	4 th		T_{26}	-	-	-	1
T_{27}	3 rd	1 st	2 nd	4 th		T_{27}	-	-	-	1
T_{28}	3 rd	2 nd	1 st	4 th		T_{28}	-	-	-	1
T_{29}	3 rd	2 nd	1 st	4 th		T_{29}	-	-	-	1
T_{30}	3 rd	1 st	2 nd	4 th		T_{30}	-	-	-	1
T_{31}	3 rd	1 st	2 nd	4 th		T_{31}	-	-	-	1
Sum	98	68	42	114		Times	5	4	0	23

The results of this application indicate that the electric motor three (M_3) had 23 occurrences of maintenance requirement. The multi-criteria application also revealed that this motor was having elevations in all of the variables concomitantly, whenever compared with other electric motors.

Final remarks

In the maintenance management one important way to guarantee efficiency and availability in productive process and operations is failure prediction before it happens. In order to reach this prediction, the major part of the variables related with the process or equipment in focus must be considered. Thus, the utilization of the multi-criteria techniques, allied with the monitoring of these variables in real time by the technology I2PLC, suggested in this work, represents a new development in the predictive maintenance concepts.

The use of I2PLC as a tool for data acquisition was also feasible for sending information by the main conductors, sensors connected to the electric motors. This technique can facilitate the collection of information on the performance and proper operation of electric motors for decision making, without the need for cable routing for this purpose, taking advantage of the existing electrical network for information traffic, making this process easier and lowering costs.

Actually, predictive maintenance still needs to prioritize settings, because it is a system which operates in parallel with the production line, it is very expensive and needs many hours of planning.

This work proposes a joint operation between production and monitoring for predictive maintenance, using sensors in all important variables of the process. After this, the proposal permits a multi-criteria analysis, using the PROMETHEE outranking method, for doing an ordination and verifying the need for maintenance in the equipment in a predictive way.

Still, some developments need to be improved. It is necessary to determine a reference line for maintenance status. Thus, the electric motors will be compared with this reference and in order to not present false states. Another improvement is a software or supervisory system for a graphical and statistical management of the process.

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