Rising energy costs, a green image and fulfilling of political demands are some reasons, why companies try to reduce their energy consumption. Biggest challenge is to identify potentials, derive measures and realize them. Although, measuring instruments are available in a great variety there exists no cheap and flexible system, which uses the measured line for supply and data transmission. This innovation, introduced in this paper, delivers a new possibility for post-crosslinking and smart energy monitoring. Based on current powerline-communication (PLC) technologies and modulation methods, a hardware was developed. A program handles the PLC and manages the measuring. The system has sensors for alternating voltage and current and calculates frequency, power factor, active, reactive and apparent power. For visualization and further analysis, a software was established. The complete system was evaluated in a production facility. The accuracy shows a difference of 1.5 % to a reference.

Keywords: powerline communication, energy measurement, production efficiency, plant crosslinking, smart manufacturing, Industrial IoT

1 INTRODUCTION

Whether large-scale enterprises or SME (small and medium-sized enterprises) – energy costs are a steadily increasing factor in almost every company balance [1]. In the manufacturing sector, these expenditures already account for an average of 3 to 12 % of the total costs, while the proportion can even rise up to 50 % in energy-intensive industries. In addition, there will be the ongoing world energy demand and the scarcity of natural energy sources – energy prices will continue to grow strongly in the future [2]. The challenge here is primarily to identify optimization opportunities in existing production facilities, to derive economically justifiable measures and to implement them. However, companies usually miss suitable methods for a complete identification of potentials for energy savings. Due to the large analysis effort, companies can only implement a small part of the measures [3]. Especially before this background, but also due to rising energy costs, energy management is getting more and more into the focus of public and politics [4]. At the same time, the public interest in the impact of companies on the environment is growing and new government guidelines for the sustainable use of the resources are being adopted [4]. Energy management systems (EMS) can systematically help enterprises and organizations to exploit unused energy efficiency potentials, decrease costs, and reduce emissions, thereby increasing their competitiveness in the long term [5].

Based on a PDCA-cycle (plan-do-check-act), a continual improvement process is integrated directly into the daily business of the organization [6]. Figure 1 shows the schematic structure of the PDCA-cycle in the context of an EMS. On basis of a defined energy policy, a regular planning and implementation of measures follows. With the help of measurements, audits or reviews, the implementation is checked. If necessary corrections are made. This process results in continual improvements [3].

The EmoPro label stands for the energy analysis system, discussed in this thesis, which is intended to enable simple data acquisition in production systems. The focus of this work therefore lies on the system element measurement and monitoring, whereby the process of “measurement” is the main part.

2 SYSTEM DESCRIPTION

2.1 Objective

Energy measuring systems to fulfill the requirements according to DIN EN ISO 50.001 or for other measuring tasks are available in a great variety and different price classes. However, there is no flexible energy measuring system available, which simultaneously uses the measured line for its own power supply and for data transmission. In conventional measuring instruments, signal acquisition and data transmission are independent parts and both physically and logically separated from each other. The use of powerline-communication (PLC) technology now allows these separate functions to be combined on a common basis – the powerline.
This base also supplies the system with electrical energy and thus enables the fulfillment of three requirements:

- Interface for signal acquisition.
- Communication channel for data transmission.
- Supply of electrical energy.

The combination of these three points represents a unique feature compared to conventional measuring systems. In addition to these main aspects, the PLC also offers the following advantages in combination with a measuring system:

- Low system complexity.
- High fail safety.
- Low installation effort.
- Low costs.
- Little space requirement and lightweight.

2.2 Hardware description

The system consists of three modules. The socket adapter is a simple connector between the main module and a standard power socket. The measuring adapter is a connector between the main module and the measured machine. It also includes the measuring hardware for current and voltage acquisition. For the current measurement, LEM’s LTS 25-NP for PCB mounting is used. It’s a closed loop multirange current transducer using the Hall Effect. The measuring module is designed for $I_{max} = 20$ A each phase. Figure 3 shows a 3D-CAD of the module.

Figure 3. 3D-CAD of measuring adapter.

The main module is the core of the system. It’s responsible for following tasks:

- Energy supply for the system (sensors, peripherals).
- Analog to digital conversion of acquired signals.
- Calculation of energy data.
- Modulation onto the powerline (transmission mode).
- Demodulation from the powerline (reception mode).
- Interface to the environment (USB, Ethernet).

Figure 4 shows the collaboration between the measuring module and the main module. In addition, the schematic diagram of the main module is illustrated. A power supply unit (PSU) delivers 5 V for the sensors, 12 V for the PLC-amplification and 3.3 V for the microcontroller and its peripherals. The controller manages the machine signal acquisition via an analog to digital converter (ADC), the communication to the PLC-Modem and the connection to a higher instance via Ethernet or USB.

Figure 4. Topology of the main module.

There are six ADC-channels reserved for voltage and current measurement of each phase of the powerline. The data acquisition channels have the following characteristics:

- Resolution: 10 bit each channel.
- Sample rate: 83.3 kS/s each channel.
- Primary voltage: 230 V (AC).
- Primary current: 0 – 20 A (AC).

2.3 Measuring principle

Focus of the system lies in the generation of energy data of the considered production machine. Therefore, the measuring module is connected in series to the loads.
power supply. The hardware is designed to acquire electrical voltage \( u(t) \) and current \( i(t) \) of the mains in a 400 V three-phase-system. Based on these values, the instantaneous active power of the load can be determined as followed [15]:

\[
p_x(t) = u_x(t) \cdot i_x(t)
\]

(1)

With \( x = 1, 2 \) and \( 3 \) for each phase conductor. Building the average of \( p(t) \) leads to the active power [15]:

\[
P_x = \frac{1}{T} \int_0^T p_x(t) \, dt
\]

(2)

To gain a high accuracy, the active power \( P \) is calculated over two sine periods \( T \), each lasting 20 ms. Finally, the total active power is gained:

\[
P_{\text{total}} = P_1 + P_2 + P_3
\]

(3)

Based on the instantaneous signals, the rms-values (root mean square) are set up and the apparent power is calculated [15]:

\[
S_{\text{total}} = U_{\text{total}} \cdot I_{\text{total}} = S_1 + S_2 + S_3
\]

(4)

The quotient of active and apparent power delivers the power factor (PF) [15]:

\[
\text{PF} = \cos(\varphi) = \frac{P_{\text{total}}}{S_{\text{total}}}
\]

(5)

After connecting to the measuring board, the system immediately starts the computing and modulates the data protocol onto the powerline.

2.4 Modulation principle

The modulation methods DBPSK, DQPSK and D8PSK (differential binary, quaternary or eight phase shift keying) in conjunction with the OFDM (Orthogonal Frequency-Division Multiplexing) are used in the case of powerline communication technology. These are variants of differential phase-shift keying, in which the information is transmitted by varying the phase position of the carrier frequency. For example, a binary "1" is transmitted at the DBPSK by 180°, while a digital "0" is displaced by the dominant phase by 0° [16]. The DQPSK uses so-called dibits and thus two bits to modulate the signal. If the value "00" is sent, the phase position remains unchanged. For dibit "01" the phase is shifted by +90°, with "10" by -90° and in the case of "11" by +180° [17]. The DBPSK is ultimately based on tribits. In this method, three information bits are thus contained in the phase difference of two successive symbols [18].

2.5 Information System Architecture and Database connection

EmoPro devices located on the production line are connected with a database server using specific architectures such as Profibus, LAN, WLAN or Bluetooth. These devices measure the manufacturing data, which is acquired and stored to a database by an acquisition application running on a database server. Through a webserver the acquired data is made accessible for monitoring and controlling operations. An application running on the webserver accesses the acquired data and offers it in a structured way in a REST/HTTP service that can be accessed by both intranet and internet. In order to accomplish this information exchange, the data previously stored in a database is requested and converted to text more precisely to JSON (Java Script Object Notation). On the device end, which could be web browser, a smartphone or a smartwatch application this JSON string is converted back to data. Therefore, the REST/HTTP service becomes the data source, that can access for different types of applications simultaneously. Note that current smartwatch technique doesn’t allow to communicate directly with external services. A smartphone is currently still required that manages service communication.

2.6 User Interfaces

Using industrial M2M (machine-to-machine) communication protocols and interfaces, recorded process and machine data is accessible worldwide. Mobile devices enact these standardized and web-based interfaces for accessing recorded data. Based on that wearables provide a multiplicity of monitoring functions to users: (i) visualization and confirmation of alarm and error messages; (ii) observation of current status information and process parameters of different production modules; (iii) graphical visualization of recorded process data and based on that statistic process control mechanisms (e.g., Nelson Rules) and (iv) communication between different operating users. Thus, responsible operating and maintenance staff is pointed to current alarm messages or instructions of machinery in real time on smartphones or smartwatches on their wrist. Here, messages and instructions are transmitted to responsible users through visual, acoustic and, in case of noisy environments through haptic signals like vibration alarms. By means of configurable user roles or user priority groups, production or shift supervisors, equipment operators or maintenance staff are able to react to disturbances and changes situations immediately.

2.7 Evaluation of the System

For the determination of the measuring accuracy, the system was compared with a commercially available, calibrated measuring device. For this purpose, a three-phase industrial vacuum cleaner RUWAC DS 1220 with a rated active power of 2.2 kW was operated under three operating states and the energy profiles were measured. The reference measurement was performed with a Chauvin Arnoux C.A 8335 power analyzer. The values of the EmoPro-Sensor showed average deviation of 1.5 % compared to the reference in all three operating states of the vacuum cleaner. The different operating states were performed by defined variations of the suction opening. The data transmission rate via the powerline was tested in the switching cabinets of a lathe DMU 50 eVolution (machine 2), both from DMG Mori AG. The different modulation methods DBPSK, DQPSK and D8PSK with various lengths of the connection line were considered. For the test, a measuring adapter was installed in the machines switching cabinet and a main module (send) was connected to it. Outside of the cabinet a second main module (receive) was connected with a socket adapter and plugged to the mains. The results, shown in Table 1 were acquired with a testing software from Atmel called PLC PHY Tester Tool.
(FFT) or discrete wavelet transform (DWT) is performed. Additionally, some preprocessing like fast Fourier transform generates an adjusted internal transmission protocol. In systems with more computational performance, the network connection. The training is applied on an external party. This leads to the current approach to use embedded systems for a preprocessing of the data, which can reduce the data size and therefore lowers the costs for server and cloud capacity. Nevertheless, the cloud is not a perfect solution. Based on a network connection, the cloud comes with variable and high latency and a limited upload bandwidth. Furthermore, the external processing includes additional costs and can make the data accessible to third parties. This leads to the current approach to use embedded systems for a preprocessing of the data, which can reduce the data size and therefore lowers the costs for server and cloud capacity.

In a so-called Big-Little neural network architecture is presented. The little neural network only classifies a subset of the output classes and can be executed locally with limited processing performance on an embedded system. When the little network can’t classify the input signal, a big neural network in the cloud can be called up. Thereby the cloud computing decreases, but is still necessary.

Our future goal is to completely reduce the cloud usage. During some further tests, problems concerning the transmission security occurred. In certain machine types, it was impossible to send data from the inside of the switching cabinet to the outside. In these systems, filters located directly after the main switch could be found. These can have a low impedance with respect to the selected transmission channel and can derive the signal against a compensation potential. The transmission is attenuated or completely prevented. The assumption suggests that in this case the sending main module was installed in the immediate vicinity of those filters so the signal could not be propagated in the network. However, for this case more detailed investigations are required.

2.8 Encountered Difficulties

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3 OUTLOOK

In order to create intelligent applications for industrial systems, massive quantities of data coming from several sensors must be processed and analyzed to gain contextual and useful information. At the moment, cloud computing seems to be the most comfortable way to perform this data processing, benefiting from the enormous computing power and scalability of its infrastructure. Nevertheless, the cloud is not a perfect solution. Based on a network connection, the cloud comes with variable and high latency and a limited upload bandwidth.

For both machine types, the highest data rates (27.4 kbit/s) without any transmission errors (100 % received frames) are obtained with the D8PSK.

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Table 1. Results of the transmission test.

<table>
<thead>
<tr>
<th>modulation scheme</th>
<th>machine type</th>
<th>connection cable [m]</th>
<th>received frames [%]</th>
<th>data rate [kbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBPSK</td>
<td>1</td>
<td>25</td>
<td>62</td>
<td>15.3</td>
</tr>
<tr>
<td>DQPSK</td>
<td>1</td>
<td>25</td>
<td>98</td>
<td>23.3</td>
</tr>
<tr>
<td>DBPSK</td>
<td>1</td>
<td>25</td>
<td>100</td>
<td>27.4</td>
</tr>
<tr>
<td>DBPSK</td>
<td>2</td>
<td>18</td>
<td>63</td>
<td>15.1</td>
</tr>
<tr>
<td>DQPSK</td>
<td>2</td>
<td>18</td>
<td>100</td>
<td>23.2</td>
</tr>
<tr>
<td>D8PSK</td>
<td>2</td>
<td>18</td>
<td>100</td>
<td>27.4</td>
</tr>
</tbody>
</table>

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4 SUMMARY

In this paper a PLC-based measuring system for machine crosslinking and monitoring, called EmoPro is introduced. It uses the powerline as transmission channel, power supply and measuring line. The system has sensors for alternating voltage and current and calculates frequency, power factor, active, reactive and apparent power. It can be installed in a machine in less than three minutes. The complete system was tested in a milling machine and a lathe. Hereby, a data rate of about 27.4 kbit/s has been achieved and the accuracy of the sensor shows a difference of 1.5 % to a calibrated reference.

5 REFERENCES


![Figure 5. Lean Data Module for a decentralized smart data analysis.](image-url)


