Power Measurement and Data Logger with High-Resolution for Industrial DC-Grid Application

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Abstract – power and energy measurement and monitoring is a key leading factor for many industries in terms of energy and cost efficiency evaluation. Due to trends of Smart Grid concept application in industrial environment, including decentralized DC-Grid implementation, for precise evaluation – faster and lower cost measurement equipment is needed. Manufacturing industry use lot of industrial robots that have dynamic load characteristics, and to know their consumption faster measurement equipment is needed.

This paper gives brief description of developed power measurement equipment, its structure and interconnection to industrial PROFInet network. Further as a testing method steady state and dynamic loads are selected and analyzed. For testing, specially created industrial DC-Grid testing environment and equipment has been used. Testing results shows that selected method and idea is working, and it is able to measure dynamic loads with high resolution. For other industrial load types, discussion rises, about how detailed resolution is needed in industrial SmartGrids, as energy forecast is a new trend in robotic industry, and manufacturing planning.

Keywords – Smart Grids, industrial power systems, power measurement

I. INTRODUCTION

Emerging trends towards intensive enhancement of electrical power supply systems for integration of new types of electrical power generation solutions, extensive power and related operating information flow management and intelligent utilization of electrical infrastructure can be summarized as Smart grid. Existing power distribution system is AC based, but with Smart Grid concept, and DC source integration to the AC grid raises question for AC-Grid implementation feasibility, where some preliminary researches shows advantages of DC-Grid implementation [1]. Some studies show that powering equipment from AC or DC based equivalent power source in home or office application [2]-[4], the DC-Grid is more efficient, due to fact that less conversion stages are used, and has improved network quality.

In Smart Grid context electric car or even only a smart battery [5] - energy storage system can be both - consumer or prosumer [6]-[9], by means that regenerative braking energy can be stored and re-used on demand. Integration of such new power sources in Smart Grid also creates not only problem of safety issues – fast DC circuit breakers [10], over current protection [11], but also a need for fast and cheap energy flow control instruments for distributed power metering and monitoring applications [12],[13]. The ability to obtain data about instantaneous power consumption or generation is crucial for operation of any higher level system management effort. Since many power consumer devices today can be referred as smart or advanced electromechanical devices, regardless of their task or operation principles, it could be said that they are based on one or several electro-technological molecules as represented in Fig. 1.

II. TARGET SYSTEM STRUCTURE

The same is true also for electric smart grids, regardless of their size where actuators can be seen as power generating units and sensors provide information about power flow. Various enabling technologies are already available on the market, considering methods of data transmission within power system, including embedded power line communication systems, various telecommunication standards and industrial communication protocols. By increasing share of power measurement equipment units within power systems, in respect to existing setups of nowadays, such parameters as reliability, self-consumption and investment costs have significant role for decision making of major installation of such devices. New developments, along with existing AC distribution system approach, considering DC power supply in various applications, present demand for adaption of existing power measurement equipment. The practical application of power meter unit has been done considering industrial DC microgrid as case study scenario of intelligent power supply system.

![Fig. 1. Visual example of electro-technical molecule structure.](image-url)
The concept of such innovative electrical infrastructure has been developed within AREUS project [14] considering 600V DC voltage based energy distribution, recuperation, storage and exchange operation within manufacturing application. The principal structure of such system has been presented in Fig. 2.

A lot of electrical energy consumers or sources operate on DC-Grid. AC/DC or DC/AC converters make possible to use them also in AC environment. Energy storage devices like super capacitors, batteries, hydrogen cells etc. allow to store and re-use energy and are designed for DC applications. Such devices are connected to the DC or AC grid via unidirectional or bidirectional energy flow converters. In order to control energy flow of this equipment directly points out necessity to know energy and power values - instant or over milliseconds long periods of time, for correct and effective converter and stable power-grid operation. Moreover simultaneous energy flow monitoring near DC microgrid consumers and energy sources as well as AC grid allow to determine system efficiency and evaluate for weak points of system from energy flow point of view. Mentioned above allow to make changes in to device workflow in order to increase efficiency, if possible or necessary. Potential application for intelligent system power flow balancing for manufacturing process has been presented in [15].

III. MEASUREMENT SYSTEM DEVELOPMENT

Energy measurement device can be seen as system combined of set of several subsystems designed for specific tasks. The workflow of energy measurement device can be divided into sequence of electrical quantity acquisition, evaluation and information flow within communication infrastructure. In particular case communication within industrial protocol Profinet was advantageous since application is within automated manufacturing industry case.

A. Suggestions on Electrical Energy Measurement

Typically energy consumption calculations are based on instant power values, especially if consumer generates non-sinusoidal current form. Instant current and voltage value readings (samples) are made and following multiplication are used to calculate instant power, average power or consumed energy [16], [17]. Sampling rate must be at least 4.2 kHz or 42 samples per 1/2T according to standard EN 61000-3-2 [21] and Nyquist frequency.

Active and reactive power measurements and calculations is a continuous dispute between scientists for non linear (or non sinusoidal) waveforms. In general, for power analysis, two main approaches exist, where one is Budeanu’s definition based on current and voltage value harmonic parameters (1), or Fryze’s definition (2) basing on voltage and current RMS (Root Mean Square) values, calculating power by active and reactive component values.

\[
P = U_0 I_0 \sum_{n=1}^{\infty} U_n I_n \cos \varphi_n; \quad Q = \sum_{n=1}^{\infty} U_n I_n \sin \varphi_n \tag{1}
\]

\[
\lambda = \frac{P}{S} = \frac{1}{T} \int_{0}^{T} u dt i dt \quad \frac{1}{T} \int_{0}^{T} u^2 dt \frac{1}{T} \int_{0}^{T} i^2 dt \tag{2}
\]

Other method is voltage and current values averaging via multi-order delta-sigma modulation and the following multiplication [18]. Thus electrical energy measuring, monitoring device installation near every consumer or generator is very expensive. Several methods are proposed to lower costs, for example [19], [20], in order to achieve widespread electrical energy measuring/monitoring devices installations. The main disadvantage is necessity of separate power source for measuring IC’s power feed and resulting increase in to measuring device self-consumption. Moreover, high speed analog-digital converters read grid noise (and generate sampling noise by themselves) and high order filtering must be applied for correct results.

Thus there is a difference between AC and DC energy measurements due to AC and DC environment difference (power factor existing in to AC grid and not existing in to DC grid, for example), especially if bi-directional energy flow take place.

Non-even sampling energy consumption measuring method was proposed to overcome mentioned above disadvantages. Method allow to measure bi-directional AC or DC energy flow, design low self power consumption devices and perform measurements down to every 10 ms for DC grids or 20 ms for AC grids or several grids for simultaneous readings.

B. Non-even sampling method

According to non-even sampling method [16], amount of consumed or generated electrical energy during the predefined period of time, is directly proportional to the sum of current samples over this time, multiplied by voltage-
frequency transfer coefficient, if current sampling rate are modulated by applied voltage value. Fig. 3.

Converter does not utilize any transformers or voltage dividers and are electrically isolated from micro-controller circuit.

C. Industrial protocol selection and integration

There are various industrial communication protocols and their evaluation [22],[23], but Profinet IO is leading standard for industrial communications, as it is simple in use and installation, and implementation of PROFlenergy [24] gives benefit in terms of energy monitoring and evaluation. It can be configured to deliver data in 1 ms or faster (Isochronous Real Time Profinet IO) from one device to another. [25] PM is connected to Profinet IO via Anybus CompactCom (AnybusCC) module from HMS. This module enables developer of embedded system to connect to Profinet IO without advanced knowledge of functionality of Profinet IO.

Data cables in Profinet system are normally made of copper wires. And 100m cable can be crossed by 1 bit in 0.5 μs. Bridge delay (delay present in switch) depends on conformance type of Profinet IO and its maximum value can be from 3 μs (IRT) to 10 μs (RT). Time of package transmission from device depends on length of telegram. If telegram which consists of 84 bytes is stent (shortest possible Ethernet telegram), than it is 6.72 μs are needed and if telegram is 1538 bytes long, than transmission time is 123.04 μs. [26] For example, if data has to cross 4 switch devices, connections are 100m long and shortest Ethernet packet is used as presented in Fig. 4, then data transmission time can be calculated as shown in (3):

$$4 \cdot (10 \mu s + 5.0 \mu s) + 72.6 \mu s = 48.72 \mu s$$ (3)

In case of RT Profinet IO configuration, time that is needed for data to arrive from AnybusCC to PLC in case of 1 switch and 100m long connecting wire and telegram size of 1538 bytes should not exceed $0.5 + 10 + 123.04 = 133.54 \mu s$. Another part of circuit that introduces delay is PM data sending to AnybusCC. The fastest (but most complex) is parallel connection to AnybusCC. That would result in approximately 30 ns longer delay time [27]. By summing all possible delay times, is required shorter time period, than shortest possible bus-cycle time – 250 μs (IRT Profinet IO).

By choosing previously described configurations, in one minute data from one PM can be sent to PLC 1s/250 μs = 4000 times.

IV. EXPERIMENTAL SETUP AND MEASUREMENT METHODS

Verification of developed active power measurement system has been realized within industrial DC microgrid operation with nominal voltage of 600V (see Fig. 5).

Central element of DC microgrid supply is common AC/DC interface converter (1) of nominal power 55kW for bidirectional power flow operation with common current sensing technology available at industry, but keeping in mind that it is also possible to use sensorless topologies as described in [28]. The converter perform task of stable 600V voltage supply on DC microgrid side. The AC side power flow is controlled for power factor correction and current harmonic reduction by means of applied passive filter unit.
The power flow within DC microgrid is enabled by means of drive stand units for power flow emulation (2 and 3). The power range of each of power emulator units is within 22kW for both consuming and regenerating energy into common DC microgrid. Such equipment has been designed in order to replicate various power consumption profiles that appear in industrial manufacturing operations taking also possible potential of recuperated energy to be reused within common DC power grid. The operating power profiles applied for dynamic verification of power meter equipment has been obtained from industrial robotic manufacturing application.

As shown in Fig. 5., for future testing is planned also using other load types, such as solar panel DC/DC converters (9), Lithium-ion battery energy storage system (4), supercapacitor energy storage system (5), and also a 600V DC powered industrial robot prototype (6), controlled by robot controller (7) and industrial cell Master PLC controller (8), also wind generator (PMSG) (10) driven by AC motor can be used as testing object.

For laboratory measurements three tests have been created and measured under steady state load, dynamic load (real robot consumption profile), and comparison with data obtained through Profinet network.

Developed power measurement hardware testing prototype is shown in Fig. 7, where it has measurement module [12],[13] with two communication outputs, where AnyBus module is devoted for Profinet communication with Programmable Logic Controller, and additional optical circuit is for
communication and data transfer to personal computer. Device is powered from 24VDC voltage, voltage measurements can be done in a range of 200-700VDC and nominal is 600VDC, current measurements in a range +/-70A, max measurement resolution is 1ms, but nominal resolution is 20ms.

![Diagram](image)

**Fig. 7. Developed power measurement hardware testing prototype.**

Novel power measurement equipment has been compared to existing laboratory grade Newtons N4L power analyzer with power measurement functionality. In order to verify any existing deviation of obtained data extracted by means of power measurement prototype with respect to existing and calibrated equipment by manufacturer N4L, model PPA3340 data has been collected at steady state operation within power range of 18kW recuperating to 20kW consumption, by means of parallel measurements.

In order to evaluate dynamic response of power meter prototype the electrical quantities of voltage and current has been obtained by means of oscilloscope along with direct power measurement of measurand. In this case a motor drive based system (see Fig. 6.) is used to test the AREUS DC power meter. The system can dynamically control the DC power flow in both consumption and generation modes within its respected power boundaries of -22kW to +22kW.

The power flow control is realized by dynamically changing the torque of an asynchronous machine, whilst keeping its rotational speed constant (4).

\[ P_{DC} = TW \cdot \omega \]  

where 
- \( P_{DC} \) – power measured at the DC bus of the frequency converter driving the asynchronous machine,
- \( T \) – mechanical torque,
- \( \omega \) – rotor angular velocity.

\[ T_{set} = \left( \frac{P_{err} \cdot W_{PI} + P_{DCs}}{\omega} \right) \]  

where
- \( T_{set} \) – the set torque value,
- \( P_{err} \) – the difference between the set and the measured DC power,
- \( W_{PI} \) – the transfer function of a parallel PI regulator,
- \( P_{DCs} \) – the set power value.

AREUS DC power meter is implemented in the feedback loop of the system’s power flow controller (Fig. 8), which enables the inclusion of various regulation methods, thus optimizing the system’s performance. The control method used in equation (5) enables 100% precise recreation of a real industrial robot electrical load (consumption profile), thus giving real-life dynamic testing environment for power measurement device.

PROFINET Data acquisition network structure and functionality of CMs (communications module) has been tested in line structure of Profinet IO network (Fig. 9).

**Fig. 9. Line structure of Profinet IO network.**

Structure is possible because the Profinet IO 2-Port Plug-In Module (AnybusCC) has built in switch. For tests, CM in conjunction with PM, has been used, which is dedicated to measure power at nodes of DC busses of industrial robots. As a PLC has been used CPU 1212C from Siemens, IR Profinet IO standard and for visualization of system functionality has been used Siemens TIA portal integrated plotting tool and afterwards data has been extracted and formatted with MS Excel (Fig. 12).

**V. EXPERIMENTAL RESULTS AND ANALYSIS**

The novel DC power meter is connected in series between the AFE 600 VDC output and the motor drive system’s DC input and measures the momentary DC power values. Two types of verification experiments are performed. In one case the dynamic power flow of an industrial robot is emulated with the motor drive system. The DC power meter’s averaging time is set to 15 ms. As a comparison, the DC power is measured with Rigol DS1104Z oscilloscope, using PROSyS CP 35 current probe and Tektronix P5200 differential voltage probe. The logged data from both measuring devices are summarized in Fig. 10.

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The second case verification tests were performed by applying constant power values throughout the motor drive system's power range (Fig. 11). In this case, the novel DC power meter's measurements are compared with data from N4L PPA5530 power analyzer (voltage measurement – internal, current measurement with HF100 current shunt). The PPA5530 was set to DC coupling, 5 Hz filtering. Acquisition window was set to 15 ms.

VI. CONCLUSIONS

In both steady and dynamic testing cases developed power measurement equipment shows very fast, precise and stable measurement that are even faster than N4L PPA5530 power analyzer. The measurement deviation in work range is within acceptable range.

Implementation of optical communication interface allowed stable real-time measurement data transmission to the personal (PC) computer database, thus eliminating connection problems and PC due to various electromagnetic interference (EMI) radiations, caused by typical industrial equipment.

CM working speed is fast enough to replicate power curves of industrial robots, although PM is not connected directly to AnybusCC by parallel connection, but through one intermediate node and serial connections.

Next measurements should be done in other non-linear load situations, and compared against measurements done with more faster and precise calibrated equipment. In case of Profinet usage and PLCs, discussion starts on the time resolution for dynamic loads and PLC ability to send the necessary data. At these testing loads, the 20 ms resolution is enough for energy calculation, but more load types should be tested to validate this approach energy forecast.

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