Synchronization of current and voltage measurements in a modular motor diagnostic system

Marcin Bajer
ABB

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ABB Corporate Research, Starowiślna 13a, 31-038 Kraków, Poland

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M.Sc. Marcin Bajer

Graduated from University of Science and Technology in Kraków, Poland, in field of Computer Control Systems. Since 2008 he has been working at ABB Corporate Research in Kraków, where he is responsible for programming and testing embedded devices. His research interests also cover industrial communication protocols, Linux kernel and mobile technology.

e-mail: marcin.bajer@pl.abb.com

Synchronizacja czasowa pomiarów prądu i napięcia w modułowym systemie diagnostyki silnika elektrycznego

Streszczenie

W artykule opisano zagadnienie precyzyjnej synchronizacji czasowej elementów rozproszonego systemu automatyki przemysłowej. W pierwszej części zostały zaprezentowane dostępne rozwiązania umożliwiające monitorowania zależności czasowych pomiędzy zdarzeniami w rozległej sieci komunikacyjnej. Jako przykład opisano działanie *Network Time Protocol* (NTP) służącego do synchronizacji czasowej urządzeń w sieci Internet.

W dalszej części publikacji główny nacisk został położony na opisanie systemów w których komunikacja odbywa się przy użyciu magistrali szeregowej opartej o interfejs RS-485. Problem przedstawiono na podstawie synchronizacji czasowej pomiarów napięcia i prądu dla celów wyznaczenia mocy czynnej w modułowym systemie sterownika silników elektrycznych. Wynalezione rozwiązanie tego zagadnienia zostało zgłoszone jako patent i może być rozszerzona na większość systemów rozporoszonych w których wymiana danych odbywa się przez interfejs szeregowy.

W kolejnej części przedstawiono rozwiązanie pozwalające na walidację dokładności algorytmu dla różnych przebiegów prądu oraz napięcia. Aby nie wpływać na poszczególne elementy systemu testy oparto na obserwacji danych wymienianych pomiędzy elementami systemu.

Słowa kluczowe: rozproszony system diagnostyki, RS-485, komunikacja szeregowa, synchronizacja, moc czynna, współczynnik mocy.

Abstract

The purpose of this paper is to describe problem of precise time synchronization between elements in distributed automation system.

At the beginning, to present current state of art, Network Time Protocol was described. Further, the main focus is placed on describing this problem in context of systems in which interconnection is done with RS-485 serial communication. The issue is presented based on solution used for active power calculation in modular motor control system. In this case, to determine power factor, precise calculation of delay between voltage and current zero crossings measured by discrete modules is required. Invented solution of this problem can be extended to most of distributed systems interconnected with serial interface.

Further in the article the method to validate algorithm accuracy for different voltage and current plots was presented.

Keywords: distributed diagnostic, RS-485, serial communication, time synchronization, active power, power factor

1. Time synchronization in wide spread communication networks

Increasing modularity is a global trend among manufacturers of industrial automation. The use of distributed architectures in industrial applications results with greater flexibility and allows integrators to tailor the system to exact customer's needs. In many cases this involves using communication networks to spread sensors, actuators and control logic over a large area.

Synchronization in distributed systems is much more difficult in comparison to uniprocessor or multiprocessor devices. Network synchronization deals with the problem of distributing time and frequency among widespread remote locations, often interconnected by non-deterministic, bandwidth limited bus. In such systems each module has his own internal clock. Even if all clock will be once synced, eventually, after time they will lost synchronization due to clock drift. Depending on the bus and application several time synchronization algorithms have been designed.

Before going into details, it is recommended to first clarify meaning of two synchronization quality indicators: accuracy and precision. Precise algorithm will generate all results close to each other, but constant error may be introduced. In case of accurate algorithm there is no constant error but results are less repeatable.

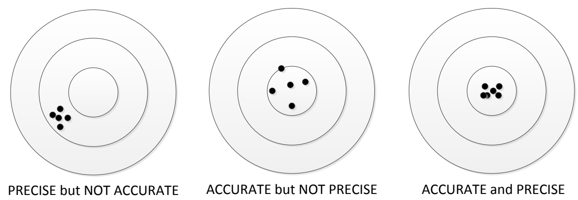

Fig. 1 Time synchronization quality indicators [1]
Rys. 1 Wyznaczniki jakości synchronizacji czasowej [1]

For further discussions about time synchronization it is worth also to divide industrial automation buses into two main types base on media access algorithm.

The traditional fieldbus are based on Master-Slave/Token passing technology which do not involve any packet switching. Nodes are interconnected point-to-point or with serial connection (Profibus, Modbus RTU). RS-485 is commonly used as physical layer. In this case time to transport data between nodes is deterministic.

Recently, due to popularity of Ethernet, fieldbuses which uses multiple medium access and packet switching technology are growing in popularity (i.e. Profinet, EthernetIP, EtherCAT). In those networks data to be transferred is grouped into packets. Switching networks can share common paths for transferring data between network segments. Moreover, sometimes multiple paths can be used for communication between two network nodes.

Although, Ethernet based industrial communication protocols were modified to increase its real-time characteristics, data transfer delays in those networks may vary. Time synchronization in such networks is more difficult.

2. Network Time Protocol

Network Time Protocol is the most popular protocol for time synchronization in packet-switched, variable latency networks. Although the details of the algorithm are complicated, its general idea is pretty simple. Client requests the current time from a server, and uses the response to set its own clock.

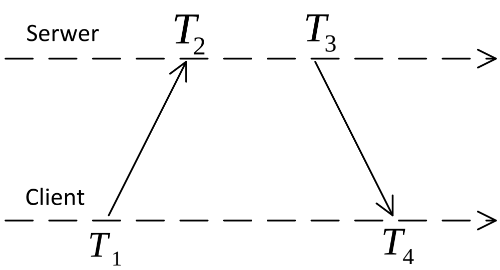

Fig. 2 Working principle of *Network Time Protocol*
Rys. 2 Zasada działania *Network Time Protocol*

Base on time stamps of sending and receiving messages in Slave and Master it is possible to calculate the transmission delay (1) and offset between client and server clocks (2) [2].

(1) $$\mathrm{delay} = (T_4 - T_1) - (T_3 - T_2)$$

(2) $$\mathrm{offset} = \frac{(T_2 - T_1) + (T_3 - T_4)}{2}$$

Multiple levels were introduced in global structure of NTP servers. Atomic clock sources are on the top, providing most accurate clock source. Higher level servers are time servers for lower level computers, but it is not necessary true that the stratums are indicators of quality or reliability [3]. The main purpose of leveling is to prevent cyclic dependency.

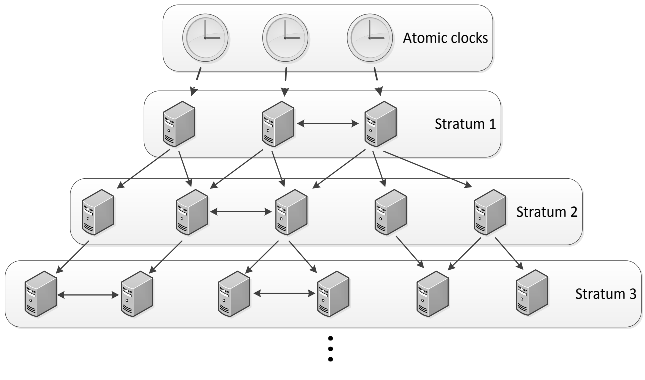

Fig. 3 Topology of NTP servers
Rys. 3 Topologia serwerów NTP

3. The purpose for distributed motor diagnostics

Industry consumes 42% of all electricity produced worldwide. Two third of this is used by electric motors which gives 28% global energy consumption [4]. Large industrial facilities often contains thousands of electrical motors. Ensuring their correct work is crucial since breakdown can generate significant financial losses or even impact of safety of people on the site. Providing flexible, cost efficient solution for motor control and diagnostic is a demanding task.

In many simple systems to provide required diagnostics functionalities it is sufficient to monitor feed motor currents. Base on this, problems such as phase lost, wrong phase sequence, overcurrent, undercurrent, earth fault and many others can be detected. With thermal model of the motor embedded into controller it is also possible to protect motor from overheating.

The main problem with such approach is that motor start is needed to notice the problem. In many cases it is required to forbid motor start to protect whole installation against impact of faulty power supply. In order to achieve this, voltage monitoring is necessary.

4. Background of the current and voltage measurements synchronization problem

There is many reasons why it is expected to provide a system in which separate modules for voltage and current measurement are being used. The main is cost efficiency – customers can decide for which elements of the system supplementary protection is needed. In addition bus interconnection between elements of the control system enables more flexibility of placing modules in the production cell.

Those factors lead to decision that motor control system described in this article is modular. The main unit measures 3 phase current and provides interface to access data by the field devices (PLCs, HMI). System can be extended with Voltage Measurement Unit and Digital IO Unit.

In most cases measurements are independent – to provide required information about voltage quality (under/overvoltage, voltage sag and dip, high level of THD) voltage measurement unit does not require any information about current. The same statement applies to current monitoring.

The typical situation where it is necessary to combine voltage and current measurements is active power calculation.

(3) $$P = U_{RMS} I_{RMS} \cos(\varphi)$$

To compute power factor exact time stamps of current and voltage zero crossings are needed.

5. Required accuracy of synchronization

To validate the feasibility of the idea of calculating active power by separate devices it is needed to estimate needed precision of time synchronization.

Error of the active power measurement may be represented by the absolute error – the actual amount of error described in measured value units or by relative error - ratio comparing the error to the size of measurements.

$$E_{absolute} = \left| x_{measured} - x_{real} \right| \tag{4}$$

$$E_{relative} = \frac{E_{absolute}}{\left| x_{real} \right|} \qquad x_{real} \neq 0 \tag{5}$$

The highest absolute error of power factor measurements occurs for $\varphi = \frac{\Pi}{2}$ since at this point $\frac{\partial \cos(\varphi)}{\partial \varphi} = \max$. To calculate needed absolute accuracy of time synchronization following equation applies:

$$\Delta t_{phi} = \frac{1}{2\Pi f} \arcsin(\Delta_{\cos(phi)}) \tag{6}$$

Assuming we would like to achieve accuracy of $\cos(\varphi) \pm 0.01$ synchronization error must by below Δt_{phi}=31,8 us for network frequency 50Hz.

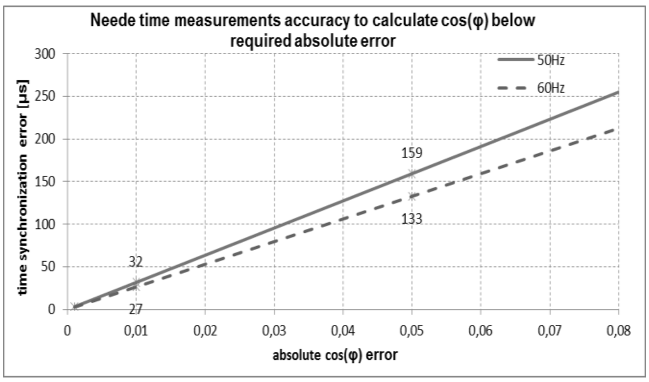

Fig. 4 Relation between allowed absolute error of power factor and accuracy of time synchronization needed

Rys 4 Zależności między dozwolonym błędem bezwzględnym współczynnika mocy a wymaganą dokładnością synchronizacji czasowej

The relative error approaches infinity for $\cos(\varphi) = 0$. To achieve meaningful results we can assume that in most cases motor works with power factor between 0.4 and 0.8.

Base on plots above shows that to achieve absolute error of power factor below ±0.1 and percent in standard operating range below 5% it is needed to calculate time difference between voltage and current zero crossings with accuracy less than 32µs. Assuming standard serial bus baudrate of 115200, this means synchronization needs to be done with accuracy of ~3,5 bit.

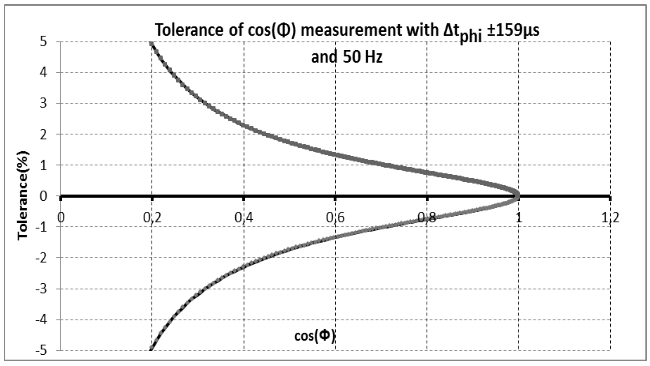

Fig. 5 Plot of relative error of power factor calculation for constant error in φ calculation

Rys 5 Zależność względnego błędu współczynnika mocy dla stałego błędu wyliczenia φ

6. Synchronization algorithm

The system architecture was presented in *Fig.* 6. Current measurement unit is a Master, there can be many extension modules which are Slaves on bus.

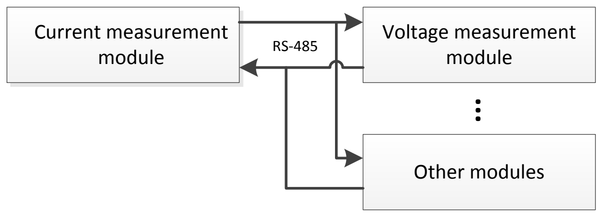

Fig. 6 Architecture of developed motor diagnostic system

Rys 6 Architektura rozwijanego systemu diagnostyki systemu

Since both device use standard inexpensive quartz crystal to keep common time base it is needed to perform synchronization often to avoid clock drift.

Another limitation was the assumption that regular RS-485 interface should be used. This imposes the limitation of both physical interface as well as its hardware implementations in microprocessor (IRQ handling).

Of course, using Ethernet would solve the problem since accuracy of NTP is far better than required in this case. Although, Ethernet has many additional advantages, it is complex protocol and its implementation is much more expensive – additional cost cannot be justified in this case.

All of those requirements lead to the solution described further in this article.

The current state of art is that in most cases to calculate time difference between events captured by distributed measurement units time stamp to each of events is added. The alternative solution would be to add separate bus wire, to be used only for synchronization purpose.

Since both devices operate asynchronously to each other, with different clock signal frequency, a special telegram sequence was designed for data exchange and synchronization. The complete message exchange sequence was described in *Fig. 8*.

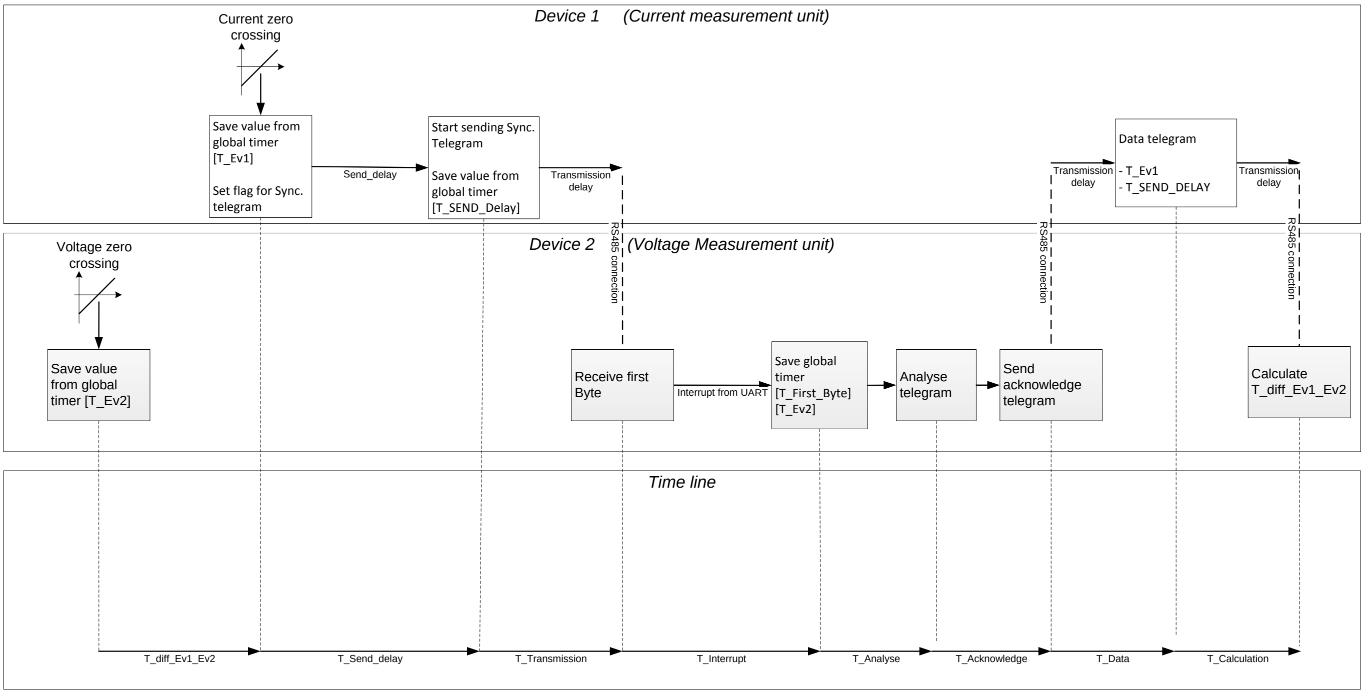

Fig. 7 Details of the synchronization algorithm
Rys. 7 Szczegółowy opis algorytmu synchronizacji

$$T_{Diff\_Ev1\_Ev2} = [T_{First\_Byte} - ((T_{Send\_Delay} - T_{Ev1}) + T_{Transmission} + T_{Interrupt})] - T_{Ev2} \tag{7}$$

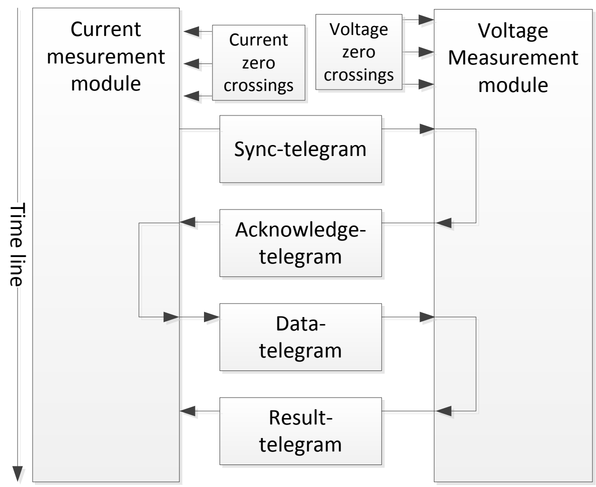

Fig. 8 Overview of power factor calculation algorithm
Rys. 8 Schemat algorytmu obliczania współczynnika mocy

The details of the synchronization algorithm are shown in *Fig.* 7. Each telegram contains CRC. To reduce needed computation power and speedup frame composition “Sync-Telegram” and “Acknowledge Telegrams” have fixed content. Their only purpose is to indicate a common reference event in time base on which synchronization is done.

Both devices are saving the time stamp of the event base on their internal clock (*T_Send_Delay*, *T_First_Byte*). As it was described before in this article, the transport delay in case of RS485 is deterministic. It consists time of sending one byte over the bus (*T_Transmission*) and the time to handle serial port interrupt in the receiver (*T_Interrupt*). With acceptable error it can assumed that sum of those is constant. It can be calculated using the serial port baud rate or determined by measurement and is therefore known in advance. In this way required corrections can be introduced to *T_First_Byte* on the second device.

The "Data Telegram" contains the event time (*T_Ev1*) and time of sending synchronization telegram (*T_Send_Delay*). Base on those information the second device is able to calculated time difference (*T_diff_Ev1_Ev2*) between events 1 (*T_Ev1*) and 2 (*T_Ev2*) (7).

The serial data transmission is independent from asynchronous Events 1 and 2. The time between synchronization telegram and data telegram can be extended to fit application needs (CPU/communication bus load). Also, the time between first event and synchronization telegram can be longer, but it needs to be remembered that clock drift will impact the results. In both cases the limitation is the size of the register which is used for saving time stamps.

With the presented approach the frequency of system timers running on Device 1 and 2 can be different. Recalculation to common time base can be done during calculation of difference between events (*T_diff_Ev1_Ev2*).

Another advantage of such approach is the fact that the synchronization is taking place after each event [*T_Ev1*] detection. The algorithm is resistant to clock drift since only time between first event and synchronization event is important for a calculations.

7. Tests of the solution

To ensure the correct behavior of the algorithm two kind of tests were performed. First, to ensure the solution is working, system described in *Fig.* 9 was prepared. The idea was to test only the feasibility of the proposed solution. To avoid hardware differences (A/D converters, UART) the same hardware was used.

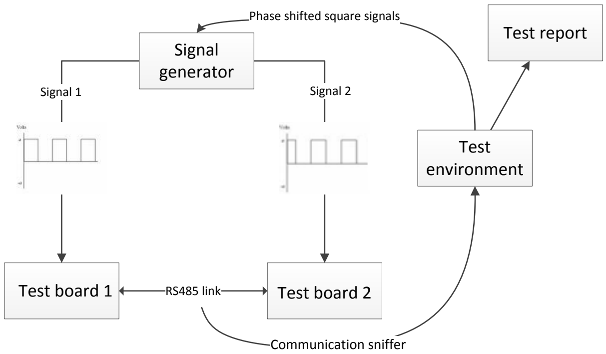

Fig. 9 Idea of algorithm feasibility tests
Rys. 9 Idea testów weryfikacyjnych poprawności działania algorytmu

All tests were performed with help of dedicated test environment which can control signal generator to generate square wave signals with different phase shift. On test board mock software was implement. In addition test environment was sniffing RS-485 to capture calculated value of phase shift between signals. As the result of the test report was generated.

The second test was performed on the end product before its release. Instead of square wave, current and voltage plots were generated. Different level of THD were introduced in addition, to test its impact on power calculation accuracy. Tests shown there were no additional corrections needed to the algorithm.

8. Summary

In this paper solution for synchronizing asynchronous events detected by distributed modules was presented. The test has shown that this solution is working and provide significant amount of flexibility in implementation. Synchronization error is negligible in comparison to other delays (A/D conversion delay and filter, measurement offset..etc).

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