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ENERGY MEASUREMENT FOR CONSUMER LOADS IN BUILDINGS USING FIELD BUS SYSTEM FOR HOME AUTOMATION

Dipl.-Ing. T. Kurczveil, Dipl.-Ing. P. Diekhake, M.Sc. J. Liu, Prof. Dr.-Ing. Dr. h.c. mult. E. Schnieder

Institute for Traffic Safety and Automation Engineering, Technische Universität Braunschweig, Germany,
{kurczveil, diekhake, liu, schnieder}@iva.ing.tu-bs.de

Abstract: Energy is one of the most important fundamentals of modern societies. Due to limited resources, the responsible use is becoming increasingly urgent. Particularly in buildings the energy consumption can be reduced significantly by applying intelligent solutions. One basis for these solutions, such as load management for optimized energy distribution, is the energy metering of components in electric systems. In this abstract, a field bus system is presented that, due to its local distribution, is suitable for energy consumption measurement of its individual components. After presenting the bus system, its concept, and a summary of the mathematic algorithm, an example application will be shown to exemplify the functionality.

Keywords: home automation, energy meter, decentralized system, low cost field bus system

1. INTRODUCTION

The basis of an intelligent load management system is to provide information about the power consumption of individual consumers. Especially for locally distributed building automation systems, this represents a particular challenge: the acquisition of consumption data usually comes with high costs or inadequate measurement uncertainties. This abstract presents a way of measuring the energy consumption of individual appliances within a building using a single calibrated power meter. This will allow the determination of the current energy state of an electric system (e.g. building), representing a necessary condition for a local load management. The prerequisite for the presented algorithms is the use of the SmallCAN automation system, whose architecture is designed to take into account the operating state of its participants.

2. FIELD BUS SYSTEM SMALLCAN

SmallCAN is a field bus system that was developed at the Institute for Traffic Safety and Automation Engineering and optimized for the application as a building automation system. The optimization includes the administration of up to 1000 participants (connected by means of a universal bus coupler) and an extent of the bus line up to 1000 m. One major goal of SmallCAN is a complete decentralization and thus to minimize wiring and eliminate costs for the design of a central unit. The pursuit of this decentralization means that each participating actor and sensor is equipped with its own (integrated) transceiver. For this purpose a low-cost, energy-saving, and universally applicable SmallCAN bus coupler has been developed. With this approach, isolated solutions can be avoided and each device can be adjusted and optimized for the prevailing situation. In addition to the universal expandability and clear arrangement, the decentralized structure has the advantage of detecting the operating state of individual devices, e.g. consumers. Thus, SmallCAN represents a comprehensive system of intelligent sensors that allows the energy metering of individual electric appliances that are connected to the system. The decentralized distribution and possibility for a high number of bus nodes calls for the use of an inexpensive, energy-saving, and universally applicable bus coupler. For the application on the hardware side, application modules are used. In combination with the bus coupler, any electric component can become a compatible participant on the SmallCAN bus. The power consumption of application modules, including the bus coupler, is strategically limited to 80mW. This way, participating modules can be supplied with energy over the bus cable. Even with a high number of bus nodes, one power supply is sufficient for most systems.

The investment costs for an application module are kept at a minimum in the system design. The components consist of standard, cost-effective components and cases and do not require additional customizations. The resulting bus nodes can be connected flexibly with in simple bus topology. The bus medium is a regular telephone cable.

The software of each bus coupler consists of the following modular components:

1. operating system

2. special function

3. freely located special function

The operating system (OS) of the bus coupler contains all the necessary routines for bus communication. Special functions (SF) control and monitor the hardware that is located on the application adapter. SFs represent the actual function of the bus node and/or application module. Freely

located special functions (FSF) are independent from the presiding hardware and perform further processing of data that is sent onto the bus. As hardware independent functions, FSFs can be outsourced locally onto any bus coupler with sufficient capacity for the required calculations.
Any SmallCAN-system can be connected to a PC server via conventional LAN and controlled by SmallCAN Tool. Its main tasks are the configuration, parameterization, visualization, programming, network management, and application management. The configuration is performed by writing the sender and receiver addresses of bus messages into in the EEPROM memory of the respective bus couplers.

3. CONCEPT FOR ENERGY METERING

The concept of energy consumption measurement of individual components is shown in Figure 1. First, the current total power output of all elements is determined by a single energy meter. The current power consumption of all devices and the total energy consumption of the system can be calculated by a SF and sent from there as telegrams onto the bus.

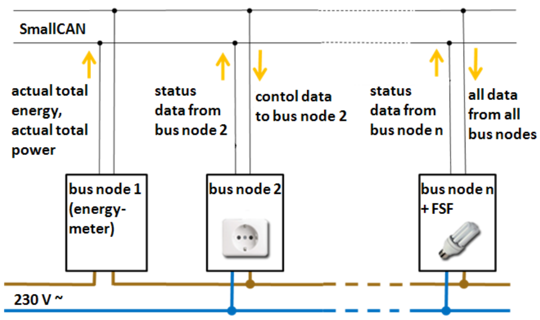

Figure 1: Concept for energy consumption measurement with SmallCAN.

SmallCAN allows the control of its locally distributed components (consumers). Additionally, the current operating states (on or off) and hardware failures can be detected. Functions for controlling the components and for state detections are performed by SFs that receive the data messages for its control algorithms from the bus and send state-relevant information to the bus.

An FSF is used to further evaluate the received data from the bus. This software module can be flashed on any coupler with enough free memory. In the example of figure 1 the bus coupler of bus node *n* is used. The FSF determines the performance of each individual consumer and transmits the information back to the bus.

All relevant message IDs are entered in the receive list of the bus coupler that includes the FSF. The sending telegram IDs from FSFs are in a corresponding sending list.

4. SMALLCAN APPLICATION MODULES

The implementation of the described basic concept requires on one hand an application adapter for additional evaluations of an energy meter and on the other the extension of application modules with specific hardware.

For the AC energy meter evaluation, an application module has been developed that reads the input of current pulses supplied via an S0 interface. Pulses within a respective period of time are counted by the SF that runs on the bus coupler. With the specific meter constant (e.g. 2000 pulses per kWh), the current power consumption of the whole SmallCAN system including connected consumers can be determined subsequently.

New circuitry is required (located at the corresponding device) for the control of individual consumers and the detection of their operating. The following functions can therefore be executed at each consumer by SFs:

1. The load is switched via opto-electric relays.

2. The monitoring of the supply voltage of 230V AC is performed by optocouplers. The output voltage of the opto-electric relays is monitored, to allow the detection of relay defects.

3. It must be ensured further that no consumer defects exist. Therefore, the output of the switching relays is checked for short circuits and current. The detection of a short circuit performed by means of checking the voltage over a series resistance. An error message is sent onto the bus if a critical threshold voltage is exceeded. Similarly, the current detection is performed by checking the voltage over a sensing resistor.

4. Each application module also includes the necessary hardware to evaluate the time for a half-wave over time in an SF. This allows for validating the determined consumption data.

5. MATHEMATICAL BASIS FOR CALCULATING THE POWER CONSUMPTIONS OF CONSUMERS

If a SmallCAN system equipped with necessary components for power measurement, the calculations can be initiated by a change of operating state (one or more consumer is turned on or off) and are executed in two steps.

The state vector $\underline{Z}[k]$ describes the prevailing system state at the discrete time k, whose elements $Z_{i=1\ldots n}[k]$ can accept only binary values to describe the states of all consumers (on or off) at time k. The number of elements n is thus equal to the number of electrical consumers connected.

For n consumers, the possible combinations for the state vector ${}^{j=1\ldots 2^n}\underline{Z}$ are 2^n. With the aim to determine the average power consumption of individual consumers, the state vectors must be amended with the necessary data on energy consumption per time unit. To allow for a full acquisition, the system matrix $\underline{S}$ is defined in a first step that reflects the required memory used on the microcontroller and assigns each possible system state, a summed dwell time ${}^{j}T$ and the sum of energy ${}^{j}E$ consumed in the respective state. The system matrix $\underline{S}$, with which this information can be detected for all the system state possibilities is shown in equation (1). The agglomerated state matrix $\underline{Z}_A$ here represents all possible state combinations. The time spent in the respective states ${}^{j}\underline{Z}$ is mapped to the vector $\underline{T}$ and the consumed energy in $\underline{E}$.

$$S = \left[\underline{Z}_{\mathrm{A}} \middle| \ \underline{T} \ \ \underline{E}\right] = \begin{bmatrix} {}^{j=1}\underline{Z} & {}^{j=1}T & {}^{j=1}E \\ {}^{2}\underline{Z} & {}^{2}T & {}^{2}E \\ {}^{3}\underline{Z} & {}^{3}T & {}^{3}E \\ \vdots & \vdots & \vdots \\ {}^{2^n}\underline{Z} & {}^{2^n}T & {}^{2^n}E \end{bmatrix} = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 & {}^{j=1}T & {}^{j=1}E \\ 0 & 0 & \cdots & 0 & 1 & {}^{2}T & {}^{2}E \\ 0 & 0 & \cdots & 1 & 0 & {}^{3}T & {}^{3}E \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 1 & 1 & \cdots & 1 & 1 & {}^{2^n}T & {}^{2^n}E \end{bmatrix} \quad (1)$$

Equation system (2) can thus be set up to calculate the power consumption $\underline{P}$ for all consumers.

$$\underline{Z}_{\mathrm{A}} \cdot \underline{P} = \begin{pmatrix} {}^{j=1}\underline{\underline{Z}} \\ {}^{2}\underline{\underline{Z}} \\ {}^{3}\underline{\underline{Z}} \\ \vdots \\ {}^{2^n}\underline{\underline{Z}} \end{pmatrix} \cdot \underline{P} = \begin{pmatrix} 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 1 \\ 0 & 0 & \cdots & 1 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 1 & 1 & \cdots & 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} P_{i=1} \\ \vdots \\ P_n \end{pmatrix} = \begin{pmatrix} {}^{j=1}E / {}^{j=1}T \\ {}^{2}E / {}^{2}T \\ {}^{3}E / {}^{3}T \\ \vdots \\ {}^{2^n}E / {}^{2^n}T \end{pmatrix} \quad (2)$$

Assuming that every consumer has a power consumption $P_i > 0\mathrm{W}$, the non-negative coefficient matrix that is described by the agglomerated state matrix $\underline{Z}_A$, results in an inhomogeneous system of equations $\underline{A}\underline{x} = \underline{b}$ for the non-trivial solution $\underline{x} \neq \underline{0}$. This information can be extracted from the system matrix, by taking all rows of the system matrix $\underline{S}$ into consideration, to which entries for the time ${}^{j}T \neq 0$ apply. This results in the reduced system matrix $\underline{S}_{\mathrm{red}}$ with which the consumption data can be calculated for all consumers by means of the Gauss-Jordan algorithm.

$$\mathrm{rank}\begin{pmatrix} \vdots \\ {}^{j}\underline{Z}\left({}^{j}T \neq 0\right) \\ \vdots \end{pmatrix} = \mathrm{rank}\left(\underline{Z}_{\mathrm{A,red}}\right) = n. \quad (3)$$

This form of data acquisition allows for the determination of the power consumption of individual components; however, considering the overdetermined system of equations (2) (and hence the exponential correlation) the calculations are performed at the expense of redundantly used memory. With the assumption that 4 bytes are claimed per variable ${}^{j}T$ and ${}^{j}E$, and neglecting the reduced state matrix $\underline{Z}_{\mathrm{A,red}}$, the required memory for the calculation is

$$M(n) = 2^n \cdot 2 \cdot 4\ \mathrm{Byte}. \quad (4)$$

However, since many home automation systems are characterized by a high number of consumers, this section will present a method, to calculate the power consumption of individual consumers that shows a linear correlation between the number of consumers and needed memory. The approach is to avoid linear combinations in the reduced system matrix $\underline{S}_{\mathrm{red}}$ or reduced state matrix $\underline{Z}_{\mathrm{A,red}}$. The rank of the reduced state matrix will remain unchanged $\underline{Z}_{\mathrm{A,red}} \leq n$, while the number of rows in the system matrix $\underline{S}_{\mathrm{red}}$ is reduced to maximum n.

The initial memory assignment will take place depending on of the system image, and allocates memory for a reduced system matrix $\underline{S}_{\mathrm{red}}$, which has the same number of rows n, as consumers in the system. The reserved memory is filled continuously filled with data during runtime during runtime from which the power consumption can be calculated for each consumer. The vectors $\underline{T}$ and $\underline{E}$ are initiated as zero vectors and the reduced state matrix with the rank of zero.

Step 1:

Each change of state $\underline{Z}[k] \neq \underline{Z}[k-1]$ (by switching on or off one or more consumers) at the time k, initiates an increment of the auxiliary variables for the consumed energy ${}^{\mathrm{temp}}\underline{E}$ and duration ${}^{\mathrm{temp}}\underline{T}$ (starting from value 0). The binary auxiliary vector ${}^{\mathrm{temp}}\underline{Z} = \underline{Z}[k]$ is used to help identify the operating state at the current time k. After the next state change, these variables are only added to the reduced system matrix $\underline{S}_{\mathrm{red}}$, if a rank increase can be achieved.

$$\mathrm{rank}\begin{bmatrix} \underline{Z}_{\mathrm{A,red}} \\ {}^{\mathrm{temp}}\underline{Z} \end{bmatrix} > \mathrm{rank}\left(\underline{Z}_{\mathrm{A,red}}\right) \rightarrow \underline{S}_{\mathrm{red,neu}} = \begin{bmatrix} \underline{S}_{\mathrm{red}} \\ \hline {}^{\mathrm{temp}}\underline{Z} \middle| \ {}^{\mathrm{temp}}T \ \ {}^{\mathrm{temp}}E \end{bmatrix} \quad (5)$$

This ensures that only new information about the power consumption is accumulated in the reduced system matrix $\underline{S}_{\mathrm{red}}$. This accumulation continues until the highest possible rank n is achieved. If the auxiliary variables cannot be used for a rank increase, the redundantly available consumption data can be used to validate the available data by means of suitable filtering. These considerations represent a basis for future research.

Step 2:

In a second step, the data on power consumption are calculated using the Gauss-Jordan algorithm. In case the reduced system matrix $\underline{S}_{\mathrm{red}}$ is already filled to the rank n, data of the total power consumption for each of the n consumers can be determined. If the full rank n is not achieved, there are two possible reasons:

1. At least one consumer has been not turned on or off since the beginning of operation.

2. At least two consumers have been switched on or off since the beginning of operation, at the same time.

Both cases are characterized by the fact that the resulting system of equations is underdetermined and

$$\mathrm{rank}(\underline{Z}_{\mathrm{A,red}}) = m < n \qquad (6)$$

applies. Thus, data on only m consumers (combinations) can be determined. In the first case, the reduced state matrix possesses all the state vectors ${}^{j=1\ldots m}\underline{Z}_{\mathrm{GJ}}$ after the Gauss-Jordan algorithm have exactly one element with the value 1, but there are also zero columns. The system of equations is underdetermined. In the second case, at least one state vector ${}^{j}\underline{Z}_{\mathrm{GJ}}$ after the Gauss-Jordan algorithm has more than one element with the value 1. The system of equations is also underdetermined. The corresponding consumers will then be substituted, until one of them is switched separately in time from the other. Equations (7) and (8) exemplify the composition of the resulting equations of systems.

Case 1:

$$m\left\{\underbrace{\begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{pmatrix}}_{{}^{j}\underline{Z}_{\mathrm{GJ}}}\right. \cdot \begin{pmatrix} P_1 \\ \vdots \\ P_n \end{pmatrix} = \begin{pmatrix} {}^{1}E/{}^{1}T \\ \vdots \\ {}^{m}E/{}^{m}T \end{pmatrix} \qquad (7)$$

$\rightarrow P_2$ unknown, because not switched

Case 2:

$$m\left\{\underbrace{\begin{pmatrix} 1 & \begin{bmatrix} 0 & 0 \end{bmatrix} & 0 & \cdots & 0 \\ 0 & 1 \;\; 1 & 0 & \cdots & 0 \\ 0 & 0 \;\; 0 & 1 & \cdots & 0 \\ \vdots & \vdots \;\; \vdots & \vdots & \ddots & \vdots \\ 0 & 0 \;\; 0 & 0 & \cdots & 1 \end{pmatrix}}_{{}^{j}\underline{Z}_{\mathrm{GJ}}}\right. \cdot \begin{pmatrix} P_1 \\ \begin{bmatrix} P_2 \\ P_3 \end{bmatrix} \\ P_4 \\ \vdots \\ P_n \end{pmatrix} = \begin{pmatrix} {}^{1}E/{}^{1}T \\ \begin{bmatrix} {}^{2}E/{}^{2}T \\ {}^{3}E/{}^{3}T \end{bmatrix} \\ {}^{4}E/{}^{4}T \\ \\ {}^{m}E/{}^{m}T \end{pmatrix}$$

$$\rightarrow m\left\{\underbrace{\begin{pmatrix} 1 & [0] & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & [0] & 0 & \cdots & 1 \end{pmatrix}}_{{}^{j}\underline{Z}_{\mathrm{GJ}}}\right. \cdot \begin{pmatrix} P_1 \\ [P_2^*] \\ P_4 \\ \vdots \\ P_n \end{pmatrix} = \begin{pmatrix} {}^{1}E/{}^{1}T \\ \left[({}^{2}E+{}^{3}E)/({}^{2}T+{}^{3}T)\right] \\ {}^{4}E/{}^{4}T \\ \\ {}^{m}E/{}^{m}T \end{pmatrix} \qquad (8)$$

$\rightarrow P_2 + P_3 = P_2^*$, only switched simultaneously so far

With ongoing operation time, the initialized system matrix is enriched with information, from which data on the consumption of individual consumers can be calculated in the described two-stage process.

6. TECHNICAL IMPLEMENTATION

The functionality of the described algorithms shall be exemplified in the following sequence of operation. Four consumers are connected to a central energy meter. An underlying freely located special function shall determine the individual power rating P_1, P_2, P_3, P_4 of each consumer by applying the described algorithm. The following switching sequence shall be performed:

$$\begin{aligned} {}^{1}\underline{Z}(t_0 \le t < t_1) &= (0 \quad 0 \quad 0 \quad 0) \\ {}^{2}\underline{Z}(t_1 \le t < t_2) &= (1 \quad 0 \quad 0 \quad 0) \\ {}^{3}\underline{Z}(t_2 \le t < t_3) &= (1 \quad 0 \quad 0 \quad 1) \\ {}^{4}\underline{Z}(t_3 \le t < t_4) &= (1 \quad 1 \quad 1 \quad 1) \\ {}^{5}\underline{Z}(t_4 \le t < t_5) &= (0 \quad 1 \quad 1 \quad 1) \\ {}^{6}\underline{Z}(t_5 \le t < t_6) &= (0 \quad 0 \quad 1 \quad 1) \\ {}^{7}\underline{Z}(t_6 \le t) &= \ldots \end{aligned}$$

Figure 2 symbolizes the described state transitions and the coherent steps that are performed by the algorithm to determine the power rating of each individual consumer.

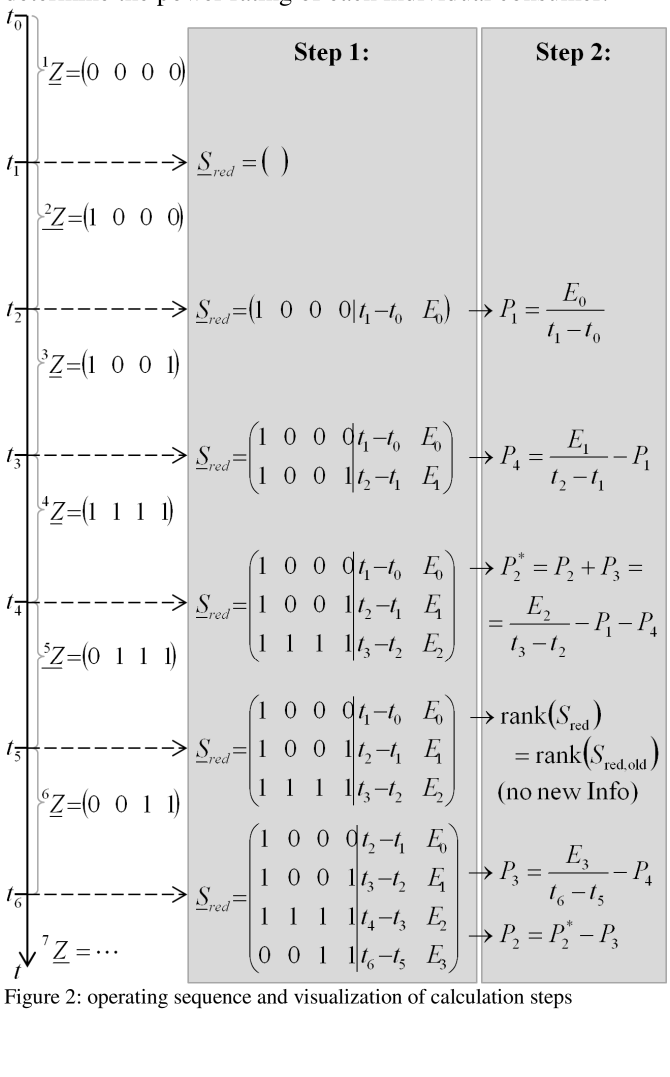

Figure 2: operating sequence and visualization of calculation steps

Figure 3 shows a part of a SmallCAN installation, with a main unit and power source (top left), the energy evaluation system (top right), including the evaluating special function and current and voltage safety check, and an array of consumers (bottom), of which four are used to exemplify the described algorithm's functionality. The resulting power rating is depicted next to the corresponding consumer.

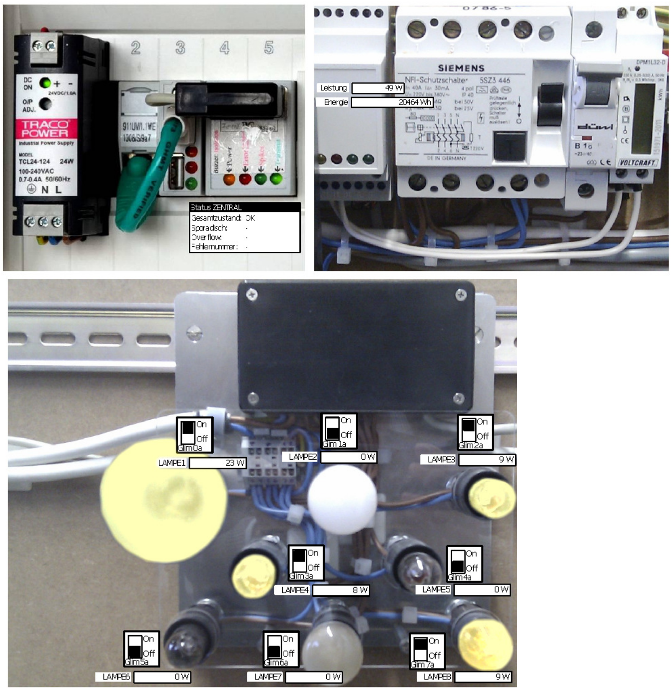

Figure 3: A minimalistic SmallCAN installation

7. SUMMARY AND OUTLOOK

The presented method provides a cost-effective way of measuring the electric energy in buildings and is therefore particularly attractive for private households. It enables the determination of the current energetic state of any building in order to optimize and later evaluate the chosen operating strategy. The long-term observation of the determined parameters can be used to observe and detect wear and aging effects of consumers and give warnings if critical values are exceeded.

The combination of energy consumption measurement and the application of intelligent control algorithms in form of software agents enables a local load management that could for example identify the reserve to the maximum power available and react accordingly to ensure network stability. This topic will gain importance in the future, when energy supply of electric vehicles will be carried out over the electric networks instead of fossil fuels.

8. REFERENCES

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