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# Information Technologies Supporting Control and Monitoring of Power Systems

***Streszczenie.*** *Praca omawia postęp w zakresie technologii informacyjnych stosowanych do monitorowania i sterowania procesów produkcji i przesyłu energii. W pracy rozważano różne aspekty tej problematyki: architekturę układu sterowania, metody transmisji danych oraz metody sterowania nadrzędnego. Przedstawiono wielopoziomowe architektury systemów informatycznych wspierających sterowanie dystrybucją energii. Omówiono ewolucję metod transmisji danych - w kierunku Ethernetu czasu rzeczywistego. Opisano także model logiczny standardu IEC 61850. Zaproponowano zadania sterowania nadrzędnego poprawiające odporność procesu i zapewniające lepsze bilansowanie pobytu i podaży w systemach DER. (**Technologie informacyjne stosowane do monitorowania i sterowania procesów produkcji i przesyłu energii**)*

***Abstract****. This paper describes advantages of application of IT technologies for monitoring and control of power production and distribution. Various aspects are considered: control system architectures, data transmission methods and supervisory control methods. Multilevel IT architectures supporting control of energy distribution are presented. An evolution of industrial communication towards real-time Ethernet is described. The IEC 61850 logical model of communication supporting exchange of information between substation devices is briefly described. Supervisory control tasks are proposed to increase fault tolerance of power systems, their adaptability and better supply/demand balancing.*

**Słowa kluczowe**: rozproszone systemy sterowania, sterowanie podstacją, protokoły transmisji, IEC61850
**Keywords**: distributed control systems, substation control, IEC 61850, industrial communication

## Introduction

Energy consumption in Europe accounts for a significant part of the budgets of individual and collective users. To meet the European Union target of reducing energy consumption by 20% and increasing energy production from removable sources to 20% in 2020, there is a strong focus on the development and implementation of renewable (wind, solar) and highly efficient energy resources. The progressive dissemination of distributed energy resources (DER), some of them renewable, introduces the concept of active distribution networks. All this is increasing the need of information technologies supporting data exchanges and network automation. Recent developments in micro-processor technology and industrial IT tools have created new possibilities for real-time access to information about the current state and parameters of a power system and a big progress in fast data processing [1]. The fact, that the depreciation of investments made for development of a power distribution monitoring and optimization system can be achieved in a relatively short time through reduction of the power charges is an additional motivation [2].

Example problem is demonstrated in Figure 1. The figure illustrates the control problem arising for a district heating systems. District heating systems are inherently distributed both spatially and with respect to control. A consumer is represented by a substation embedded within the district heating network. A district heating network is basically a collection of autonomous entities, which may result in behaviour that is only locally optimal. For instance, during a power shortage in the network, resource allocation is unfair since consumers close to the heat source will have sufficient amount of heat, while those distantly located will suffer deficiency of heat energy.

District heating systems are facing many changes today. There are several new concepts in heat energy generation, transmission and distribution.

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Distributed generation (DG) concept, well known for electric power systems, also relates a to generation, transportation and accumulation of heat energy. Energy sources are typically renewable sources (RES), like solar collectors, heat pumps, oil/gas boiler or biomass boilers combined with storage systems (accumulation tanks, phase change materials) – by their very nature physically distributed. The problem is similar to DG integration problem: if some designed modules allow powering of buildings from renewable sources, how to apply smooth switching between RES, energy storage units and district heating grids, making energy distribution possible optimal?

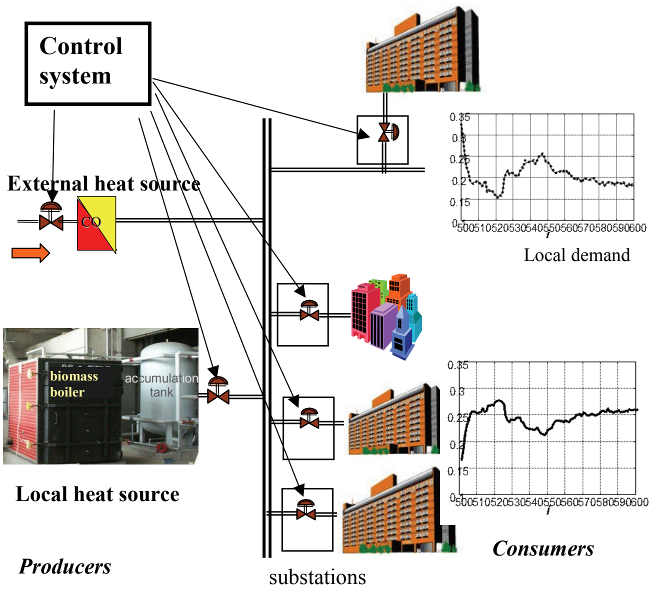


Fig.1. District heating system

The control of a district heating system as a whole, is aimed at minimizing the difference between the current demand for heating energy and the supply. Another observation is that power systems are continuously subject to disturbances. Typical examples of disturbances are sudden changes in load demand, losses of one or more transmission lines, modifications in the system configuration, equipment outages and energy sources failures. Some of the disturbances can be controlled locally, while other require a coordinated, supervisory control actions.

Assume, that it is possible to collect all sensor data from each substation in real time, do all computations necessary for the control of the system at the central computer, and then send control signals to each of the substations. Therefore it will be possible to increase the utilization of resources if only a "global picture" of the system state is available. In the example considered [3], the proposed control and monitoring system has a two-level structure. It consists of the following levels (Fig.2):

**Direct control level** collecting information from the external heating source, local heating source and from substations located in a close distance to the external heating source. The key elements of this control layer are PLC controllers equipped with industrial network interfaces. This level carries out the basic tasks of direct process control: stabilization of temperatures in the heating installations and follow-up tracking of changes in outdoor temperature. Communication between controllers is supported by CAN industrial fieldbus.

**Supervisory control and data acquisition level**. A workstation is serving as a platform for the SCADA (*Supervisory Control and Data Acquisition*) industrial system. The installed SCADA system performs tasks that are typical for a power dispatch unit – acquisition of substations operating data to the databases, visualization of the process status (HMI), as well as detection and reporting of emergency conditions. The main server is also used in this case as a supervisory control platform balancing supply and demand of heat energy for the grid.

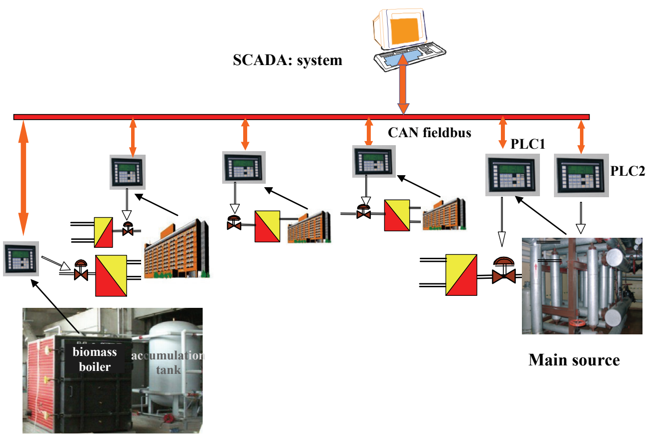


Fig.2. Example of data transmission and control architecture system for a district heating system

This example represents an integrated architecture that is intended to combine two systems typical for power industry: the energy producing/delivery system and the information system. The similar control problems are detected for heat energy production/ distribution systems and electrical energy distribution systems. The coordinated operation and control of distributed energy sources together with storage devices such as flywheels, energy capacitors, batteries, and controllable loads such as water heaters is central to the concept of a DER (*Distributed Energy Recourses*) control. If there is a controlled group of energy sources, sinks and storage devices connected to a LV (*Low Voltage*) grid, but having the possibility of functioning independently ("islanded" option), the problem of MicroGrid coordinated control can be formulated [4].

The information sources can be extended by data acquisition from home metering (*Smart Meters*). Also in this case introductions of information and communication technology to the power supply network is the basic way to improve operational behaviour of the grid. Communication architecture here takes advantage of many technologies available, like radio, high bandwidth network connecting substation and dispatching centres, power line carrier and wireless services like GSM/GPRS.

Most of integrated industrial control systems adopt a multilevel, vertical control hierarchy. Logically, such a system (Fig. 3) is structured in three levels: the direct (process) control level, the supervisory level and the management level [5].

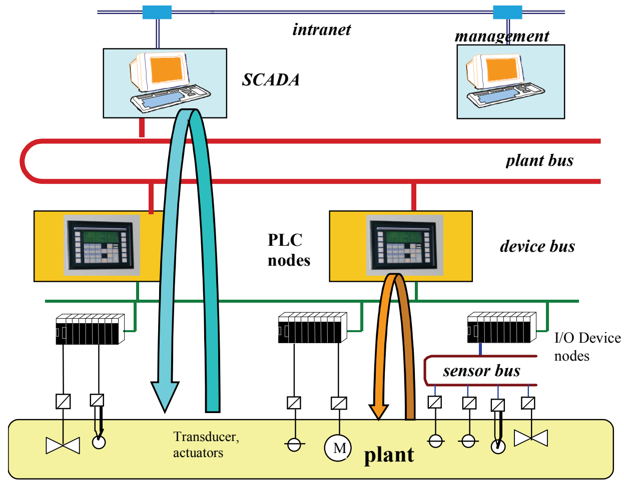


Fig.3. Multilevel structure of an industrial control system

The basic task of the direct (device) control level is to maintain the process states at the prescribed set values. A number of embedded control nodes and Programmable Logical Controllers (PLC) are used as the front-ends to take the control tasks. DSP based UAD system [6] or substation controller Relion® 670/650 from ABB [7], which integrates the protection and control functionality with Ethernet communication technology based on the IEC 61850 international standard, are good examples of specialized front ends applied for substations.

High speed networks and fieldbuses are implemented at the direct control level to exchange in real time the information between front-ends and the device controllers and, vertically, with the supervisory control level [8]. This architecture has the advantage of locating the hard real-time activities as near as possible to the equipment. The principal role of device level substation control is to stabilize the system state, i.e., to prevent the system state from transitioning from secure to emergency state, over the widest range of operating conditions.

The supervisory level comprises workstations providing high-level control support, database support, graphic man-machine interface, network management and general computing resources. Classically, the supervisory level calculates set points for controllers according to the defined criteria. More complex mathematical models of the process can be employed at this level to find the optimal steady-state, by solving on-line optimisation and identification tasks. Due to the rapid development of computer technology, there is growing scope for more advanced close-loop algorithms (predictive control, repetitive control) located at this level. However, increasing computational efficiency of PLCs at the device level supported by high performance networks transferring data and control signals vertically gives more flexibility to the designer. The control loops can be handled by local, device–level controllers, and also by the supervisory controllers (Fig.3). It should be noted that upper level loops usually offer shorter computational time due to the higher efficiency of the workstations.

**Distributed control and real-time networks**

Power systems are by their nature physically distributed. Thus, if one aims at monitoring and control approach based on knowledge about the current state of the system, the sensors data must be collected via a distributed transmission system.

*Distributed Control Systems* (DCS) can be considered a special case of digital control, as data is sent through the network periodically, in units called packages. Therefore, any signal continuous in time must be sampled to be carried over the network. Real-time assumptions are as important for Distributed Control Systems as for any other computer controlled systems. Hence, there are similarities between Distributed Control Systems and real-time digital control systems due to sampling effects. The most challenging problem with DSC that need to be properly addressed are time delays. A network induced delays occurs while sending data among nodes connected to the shared data transmission medium of limited throughput. Network-induced delays may vary depending on the network load and *Medium Access Protocol* (MAC). Lack of access to the communication network is an important constraint compared to lack of computer power or time errors of the real-time operating system. It is well known that time delays can degrade the performance of the control system or even destabilize the system.

Especially, the following effects are observed in Distributed Control Systems [8]:

- variable computation-induced delays,
- variable network induced delays,
- data loss, caused by packet dropouts.

Generally, distributed control often introduces some additional dynamics and temporal non-determinism. Therefore, novel methodologies should be developed, for stability analysis of DCS and optimise the performance. Study and research on communications and networks to make them suitable for real-time DCS, such as routing control, real-time protocols, congestion reduction, codesign of networking and controllers are referred as *Control of network.* Developing of control strategies and control systems design over the network to minimize the effect of adverse network parameters on DCS performance, such as network delay is referred as *Control over network.*

Following the *control of network* approach, effects of the network configuration on the performance of the control system have been studied and different improvement have been proposed [1]. At the physical level the network topology typically cannot be chosen freely but is subject to many practical constraints such as cost and reliability considerations. For example, the real-time performance of industrial Ethernet network depends strongly on the way the devices are allocated to the individual switches in the network**.**

Current communication systems for automation implement different protocols. This is a substantial disadvantage, leading to the need to use vendor-specific hardware and software components, which increase installation and maintenance costs. Moreover, presently used fieldbus technologies make vertical communication across all levels of the automation systems difficult. Gateways need to be used to establish connections between different kinds of fieldbus systems used in the lower levels, and Ethernet used in the upper level. Desire to incorporate a real-time element into some standard network solution has led to the development of different real-time Ethernet solutions, called as Real-time Ethernet [9]. Ethernet provides unified data formats and reduces the complexity of installation and maintenance, which, together with the substantial increase in transmission rates and communication reliability over the last few years, results in its popularity in the area of industrial communications. Ethernet, as defined in IEEE 802.3, is non-deterministic and, thus, is unsuitable for hard real-time applications. The medium access control protocol, CSMA/CD can not support real-time communication because a back-off algorithm for collision resolution is used. With CSMA/CD it can not be determine in advance how long the collision resolution will take.

Different real-time Industrial Ethernet solutions were proposed, such as PROFINET, EtherCAT, Ethernet/IP, IEC61850 and many more [10]. The conditions for the industrial use of Ethernet are described by international standard IEC 61 784-2 Real Time Ethernet, but also by some specific norms dedicated for power systems. For example: International Data Object Models for Distributed Energy Resources (DER) (IEC 61850-7-420).

To employ Ethernet in an industrial environment, its deterministic operation must first be assured. This can be accomplished in several ways. Coexistence of real-time and non-real time traffic on the same network infrastructure remains the main problem. This conflict can be resolved in several ways:

- by embedding a fieldbus or application protocol on TCP(UDP)/IP – the fieldbus protocol is tunneled over Ethernet, and full openness for "office" traffic is maintained. For example, Common Industrial Protocol (CIP) has implementations based upon Ethernet and the IP protocol suite (e.g.: EtherNet/IP, DeviceNet, or ControlNet). This group of protocols has the largest conformity to the Ethernet TCP/IP standard and can thereby use standard hardware and software components,
- by introducing data flow optimizations, whereby the realtime data bypasses the TCP/IP stack and thus considerably reduces the latency time in the node and increases the achievable packet rate,
- by using application protocol on TCP/IP, direct MAC addressing with prioritization for real-time, and hardware switching for fast real-time. This approach is used in applications that require maximum latency in the range 1ms, e.g. Profinet RT2. For his class of protocols strong restrictions are imposed on the use of standard hardware components - there is necessity to install special components, like dedicated switches.

All these specific techniques allow a considerable improvement of the network performance, especially in the terms of determinism. The following parameters are covered by the network performance metrics:

- latency (delay) – the amount of time required for a frame to travel from source to destination,
- jitter – a measure of the deviation of the latency from its average value,
- loss rate – the probability that an individual packet is lost during the transmission (mainly dedicated to wireless systems),
- capacity (bandwidth) – the amount of digital data transferred per time unit.

Table 1 gives example parameters of three versions of the Ethernet - based ProfiNet network.

Table.1. ProfiNet Parameters

| Profinet Class | (*latency*) | (*jitter*) |
|---|---|---|
| non RT | ≥ 100ms | ≥ 100% |
| RT 1 | ≥ 5ms | ≥ 15% |
| RT 2 | ≥ 250 μs | ≥ 0.4% |

* RT – Real Time

## IEC61850 real-time data transmission model

A major trend in substation automation is the closer integration of control and protection functions [12]. The development of digital relays over the past 25 years has been paralleled by the installation of advanced IED's (IED - *Intelligent Electronic Device*) in substations.

The IED is a generic term for intelligence and communication that can be designed into any field device and can serve multiple functions. IEDs implement the software applications that can analyze local conditions and make preprogrammed data processing. These IEDs should also interact with each other either within a substation (generating protection signals to circuit breakers) or on feeders. These control actions can greatly enhance response times, improve local conditions, and minimize outages.

Power utilities and DER manufacturers recognized the growing need to have one international standard that defines the communication and control interfaces for all DER devices, particularly for IED devices. The IEC61850 standard defines the systems and communication networks to be use in electrical substation automation, however the phrase "sixty-one-eight-fifty" has become a synonym for the next generation substation with a higher degree of integration, greater flexibility, open communication networks replacing dedicated protocols, plug-and-play functionality and other advantages. The IEC61850 standard specifies several aspect related with communications between substation controllers, and the supervisory level stations. The standard applies standardized device models using names instead of custom object numbers and indexes and the standardized configuration language (SCL).

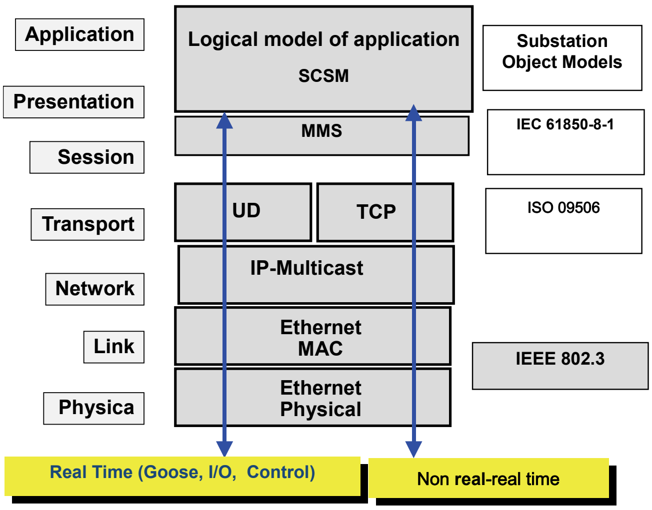


Fig.4. IEC 61850 protocol model

Using the term "protocol" in relation to IEC 61850 is not quite correct. It is rather a logical model of communication defined over existing protocols (including Ethernet). The parts 7-3 and 7-4 of IEC61850 comprise the Substation Object Models. These two Parts of the IEC 61850 specifications describe the object models as abstract objects, and only the last parts of the standard describes "Specific Communication Service Mapping (SCSM)" onto a particular set of protocols. The IEC 61850 also defines, DER-specific logical nodes like generation devices, storage devices, fuel cells, microturbines, photovoltaics and combined heat and power.

In the case of Ethernets protocol the structure to describe IEC 61850 (Fig.4) is the ISO's 7-layer communication model, and the basic protocols chosen for the layers are Ethernet (Data link layer), IP (Network layer), TCP (Transport layer), and MMS (Manufacturing Messaging Specification) as SCMS protocol (Application layer). Two highest levels constitute the "information model". The Network and Transport Layers use TCP/IP protocol to send messages between one or more devices. At these layers, messages used by all higher levels are encapsulated. TCP/IP encapsulation allows a node on the network to embed a message as the data portion in an Ethernet message. The encapsulation technique uses both the TCP and UDP layers of the TCP/IP suite and provides the method that allows substation object models to be implemented transparently on top of Ethernet and TCP/IP model.

Currently deployed Ethernet links have 100Mbps or 1Gbps capacities. Even though this may seem a big progress in comparison to an old serial-communications systems, the IEC61850 standard defines the special messages (GOOSE), with traffic prioritization option. In this way, traffic with different levels of priority, coexists in the same physical network. The IEC61850 standard specifies that the maximum transfer time of a message in a network must not exceed a certain time depending on its priority. For instance, type I messages (e.g. triggering) require a total transmission time below 3 milliseconds.

## Supervisory control

The most common model for distributed control systems is centralized system. An argument for centralized approaches for problems as complex as the management of power systems (where a large number of state variables, parameters and constraints should be taken into account), is that solutions based only on local approaches often lead to a lack of system fault tolerance, and adaptability. An argument against a centralized approaches is that solutions based on local data processing can be received more quickly. Therefore, semi-distributed approach, were the control is distributed to clusters of substations, can be considered (Fig.5).

More specific supervisory tasks can be formulated for district heating systems, for DER systems or substations supervisory control. In any case a hierarchical control scheme architecture comprising two or three different control levels will be assumed, as proposed in Figure 5. For this example the substation control architecture includes:

- Local Substation Controllers and DER Controllers,
- Master Station (SCADA),
- Supervisory Management System.

In [11] the following variables sensed in the substation and transmitted to Master Station are recommended: voltage at output bus, phase, power factor at output bus, phase, total voltage harmonic distortion at output bus, amount of time the voltage is in a given range (tolerance zone); amount of time the output voltage is below the given boundary (alert zone).

Master Station supported by the SCADA system provides such functions as data concentration, alarm and event logging and substation HMI. Master Station is also responsible for the controllable loads regulation with regards to the Supervisory Management System demand.

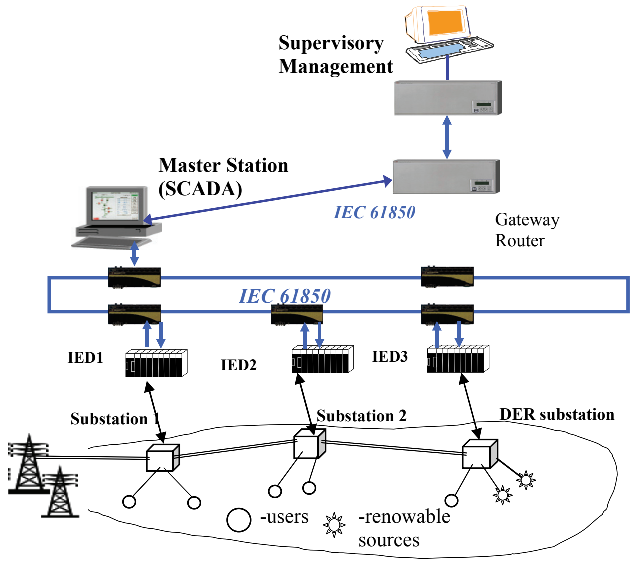


Fig. 5 Example of a communications architecture for a DER plant

Intelligent metering in this IT infrastructure could lead to more sophisticated management and control of distributed generators, storages and loads at the supply and demand side of the network. This enables *active network management.*

The following task can be defined for the Supervisory control level [11]:

**Load management:** The supervisory level determines a set of control decisions by applying the cost objective against the constraints, and the dynamic state of grid. The decisions are translated into specific DER actions such as on/off control and power reference set-points. The optimisation process is performed periodically to follow the evolving dynamics of the grid. It includes the functions like load prediction for short-term operational control and planned power cuts scheduling. It involves coordinating the timing and selection of dispatchable DER with the non-dispatchable ones (such as renewable resources) to minimize energy cost or emission cost. Expected supply/demand throughout the grid can predicted based on historical data and weather forecasts. In the case of Microgrid control: determining the amount of power that the Microgrid should draw from the central distribution system, thus optimizing the local production capabilities.

**Advanced integrated and coordinated protection**. This includes the functionality like fault location and isolation, contingency planning for disrupted electric power, autorestoration and contingency analysis. Results into improvement of the service reliability.

**Coordinated Volt/VAR control schemes**. Benefits of these implementations are reduces losses especially for peak demands (better utilization of generation capacity) and improvement of power quality.

**Equipment monitoring and diagnostics**: This includes the functionality like detection and localization of line faults or detection of faulty operation of transformers, voltage regulators, distributed generators, power electronic devices and remotely controlled capacitor banks. Performing this task results in to extension of equipment lifetime, reduction of capital and maintenance expenses.

## Conclusions

The progressive penetration of distributed energy resources is increasing the need of information technologies supporting data exchanges and network automation. Developments of data transmission technologies and industrial IT tools offer new possibilities for real-time accessing information about states of a large scale power system. The standardisation of data transmission protocols, monitoring and control of the power distribution systems for normal and abnormal conditions are key issues to enable an effective deployment of these new technologies. It should be noted that the similar control problems are detected for heat energy production/ distribution systems, electrical DER systems or poligeneration systems.

A semi-distributed approach, were the data acquisition and control functionality is distributed to clusters of substations, has been described. For the proposed architecture the data flow is supported by Industrial Ethernet network (IEC 61850 standard). The IEC 61850 standard can be considered as result of incorporating some real-time improvements into standard Ethernet TCP/IP network solution. It is a part of evolution in industrial communication towards real-time Ethernet.

To increase system fault tolerance, adaptability and to improve supply/demand balance several supervisory control tasks were proposed. The proposed approach will enhance efficiency and productivity of a utility, and will provide quality and reliable supply to the consumers.

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## REFERENCES

[1] Gupta R.A., Chow M.-Y., Networked Control System: Overview and Research Trends, IEEE Transaction on Industrial Electronics, 57 (2010), 2527–2535
[2] Grega W. Kołek K., Sterowanie nadrzędne węzłem cieplnym *(Supervisory control of heating station),* Pomiary, Automatyka, Robotyka, 16 (2002), n. 7/8, 18-24
[3] [3] Grega W., Bania P., Heating System Control In Commercial Buildings with Peak Demand Adjustment, in *Proc. of IASTED Conference Energy And Power Systems*, Krabi, (2005), 64-69
[4] Hatziargyriou N., Asano H., Iravani R., Marnay C., Microgrids, *IEEE Power and Energy Magazine*, 5 (2007), 78 –94
[5] Grega, W., Multilevel Control under Communication Constraints, In: *Proceedings of 2010 IEEE International Symposium on Computer-Aided Control System Design,* Yokohama, Japan (2010), 1176 – 1181
[6] Lisowiec A., Nowakowski A., Kołodziejczyk Z., Miedziński B., E-diagnozowanie energetycznych sieci rozdzielczych. *Przegląd Elektrotechniczny*, 85 (2009), n. 9, 232-235
[7] Transformer voltage control Relion 670 and 650 series, *ABB Products*, http://www.abb.com/product/
[8] Grega W., Robust Networked Control, *Robust Control,* v.1 (2011), Bartosiewicz A. (ed.), InTech (2011)
[9] Felsner M., Real-Time Ethernet – Industry Prospective, *Proceedings of the IEEE*, 93 (2005), n.6. 1118- 1129
[10] CoNeT/Co-operative Network Training, www.conet-eu.net
[11] Ayala S, M. Botura, G., Jr. Maldonado A, O.A. , Ai automates substation control, *Computer Applications in Power, IEEE*, 15 (2002), n.1, 41 –46
[12] Skeie T., Johannessen S.,Brunner C., ETHERNET in Substation Automation, *IEEE Control Systems*, 22 (2002), 43-51

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