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PLC based Structure for Management and Control of Distributed Energy Production Units

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1. Introduction

Renewable Energy consists of energy generated from natural and unlimited sources, which include, among others, wind, solar, biomass and hydroelectricity. These energy sources, unlike the fossil fuels, do not contribute to the greenhouse gas emissions, namely the carbon dioxide emissions, and do not suffer from depletion as well.

The global environmental alertness to protect Earth from the devastation of global warming has widespread, and consequently, governments' incentive policies have driven to a massive investment in renewable energy, namely wind power. These incentives not only avoid a direct competition between clean energy and the one obtained from the conventional technologies, but also minor the damages on environment and mitigate human activity impacts on ecosystems. The continuous growth of the world demand has conducted to an increase of the total electricity power installed capacity, including renewable energy.

The European electricity grid is one of the largest power systems in the world. Due to economies of scale it has always been advantageous to increase its size. Most of the European countries are synchronously connected to his grid. This means that the frequency in all of these interconnected countries is identical (in steady-state). The vast majority of the electricity in this grid is produced with large synchronous generators. Due to environmental, economical and geopolitical reasons there will be a shift in the production of energy. More and more distributed generation will be integrated in the system, some of which have significantly different characteristics when compared to the existing large synchronous generators (Doherty et al., 2005).

There should always be a balance between the supply and the demand of electricity. Any deviation results in a change of the frequency of 50Hz. A set of ancillary services is in use to control the frequency, and therefore the power balance of the grid.

In order to confront the variable or even stochastic behavior of the Renewable Energy Sources (RES), usually not meeting the electricity grid's demand, the adaptation of an appropriate Energy Storage System (ESS) is thought to be essential. On the other hand, storage techniques are faced with controversies mainly referring to the high initial cost rates, the additional transformation losses and the noteworthy environmental impacts, largely depending on the correlation between the type of technology used and the selected site (Denholm & Kulcinski, 2004).

Additionally, the common instability of electrical grids and the requirement for complete control over the quality of the electrical energy provision (Papathanassiou & Boulaxis, 2005), (Lund & Munster, 2003), set some serious obstacles in the dynamic exploitation of RES in autonomous electrical networks, this leading to the introduction of an upper limit of instantaneous RES contribution equal to a pre-described percentage (e.g. 30%) of the corresponding electricity demand.

To confront the problem described, several authors have every so often proposed alternative supply concepts such as water-pumping solutions, hydrogen storage, battery schemes and hybrid systems (Kaldellis, 2007), (Kaiser, 2007).

The system studied in this paper, illustrated in Fig. 1, supports the prior exploitation of RES in collaboration with state of art internal combustion engines set to operate in the range of minimum specific fuel consumption (maximum efficiency), while the ESS adopted is used to meet the satisfaction of power quality issues. In case of energy surplus, the excess amounts of energy are used to charge the ESS. When increased load demand and low RES production rates appear, the energy content of ESS is used and, if necessary, the programmed control of the thermal power stations calls for the back-up engines to set on.

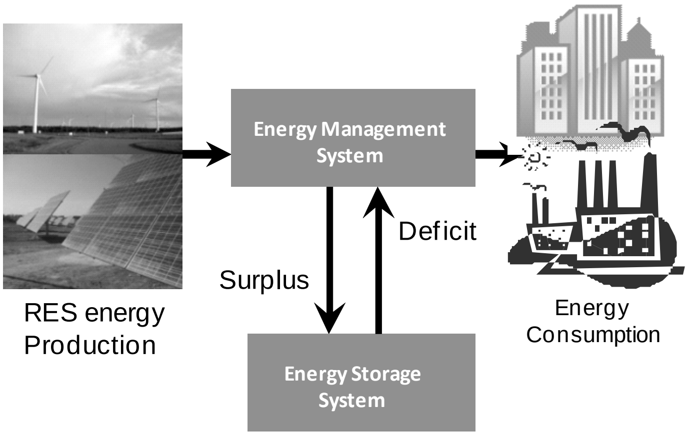


Fig. 1. RES production system integrated with ESS units

Today, the improvements in system communications have stimulated the implementation of distributed systems. These distributed systems are then usually managed by a centralized supervisory platform, commonly known as a SCADA system (Supervisory Control And Data Acquisition). This strategy reaches different fields, from agriculture, to industry, building automation, etc (Figueiredo & Botto, 2005), (Figueiredo & Sá Costa, 2007). An optimal-performance supervisory system has the objective to allocate the minimal needed power generation to the traditional power plant in order to produce the electricity at a minimal economic cost.

This paper presents a supervisory system to monitor and control energy production and consumption, in an optimized way. The developed system consists of a network of

Programmable Logic Controllers (PLC), controlling locally the electricity production in each source, and measuring, in a real time base, the power consumption and production. The PLC network is parameterized according to the traditional Master-Slave requirements, using the PROFIBUS communication (Siemens, 2001). A SCADA system is implemented in order to supervise the entire PLC network.

This monitoring and control strategy is simulated based on the requirements of the renewable energy park that is being assembled in Évora University. This experimental park is founded by an European project (PETER) with Évora University – Portugal and Extremadura University – Spain. The PETER park is a renewable energy park that plans to include a photovoltaic unit (10 KW), a wind generator (1KW) and a biomass unit (75KW).

2. System Model

The power plant studied in this paper is composed by several production units, spatially distributed, with different energetic sources: RES (Photovoltaic, Wind, Biomass), and oil-based thermal power stations for back-up purposes. Additionally this system contains also ESS systems. The electrical schematics of the developed multiple power-source system, with an ESS (battery) is illustrated in Fig. 2.

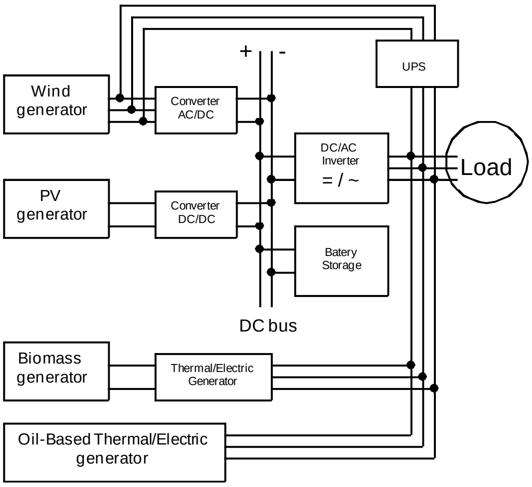


Fig. 2. Electrical schematics of multiple power generation

This paper develops a methodology that can be used with anyone of the several ESS available in the actual market. In fact, the choice of the proper ESS to fit to a specific application depends mainly on the storage requirements. Table 1 shows the most usual ESS systems and their applicability range dependent on load demand (Kaldellis et al., 2007).

In the specific application simulated in this paper (PETER Park) the ESS Pumped Hydro received a particular emphasis as this park is located in an agriculture land with strong irrigation requirements. The usual developed technology used for the pumped hydro is illustrated in figure 3.

TABLE 1
COMMON ENERGY STORAGE SYSTEMS (ESS)

ESS Type	***Power Supply range***
Flywheels	ca. 100KW
Li-ion batteries	100KW to 1MW
Lead-acid batteries	100KW to 10MW
Na-S batteries	100KW to 10MW
Fuel cells	100KW to 10MW
Flow batteries	100KW to 10MW
Pumped hydro	1MW to 100MW
CAES	1MW to 100MW

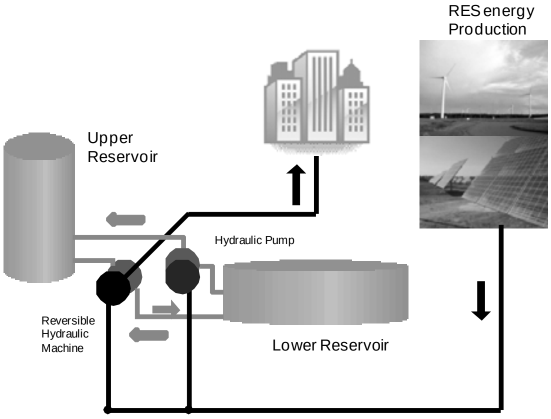


Fig. 3. ESS – Pumped Hydro

Each power source is connected to the central management platform through a typical PLC master-slave network. The master PLC communicates with a SCADA system that enlarges the system communication capabilities, allowing on-line monitoring and control, events recording, alarm management, etc.

In each power unit there exists a slave PLC, which is connected to the master PLC through a Profibus network. This power unit PLC monitors and controls the on-line power delivery to the electric grid. Similarly each ESS has a slave PLC controlling the income/outcome energy in the system.

3. Control Strategy

The developed strategy is implemented through a traditional cascade controller. The inner-loop control is performed by a PLC network controlling locally each power plant. The outer-loop is managed by a SCADA supervisory system.

Each PLC hosts several control programs whose selection is made either locally, via an

HMI (Human Machine Interface) or remotely, via the Master PLC. The Master PLC is connected to the server PC, via RS232/ MPI Siemens protocol, where the SCADA application is running.

The server PC is simultaneous a SCADA server and an internet server, as the implemented SCADA application is web enabled. All process variables are available at the SCADA PC as these variables are on-line available through a Profibus/ DP connection protocol (Siemens, 2001a).

3.1 SCADA Outer-Loop Controller

A Supervisory Control and Data Acquisition (SCADA) System is used as an application development tool that enables system integrators to create sophisticated supervisory and control applications for a variety of technological domains, mainly in the industry field. The main feature of a SCADA system is its ability to communicate with control equipment in the field, through the PLC network. As the equipment is monitored and data is recorded, a SCADA application responds according to system logic requirements or operator requests.

In the developed control strategy, the SCADA application performs the outer control loop of the energy plant system. At this outer loop several complex control structures can be used to manage the overall system dynamics.

In this paper an optimal allocation of production resources is performed taking into account the minimization of the operational costs, what usually corresponds, in an hybrid power system, to the minimization of the supplied power from the oil-based thermal stations. Both instantaneous power demand and power supply are on-line monitored in the developed energy management system.

Considering the application developed in this paper (isolated production/consumption system) the on-line monitoring of the power demand is performed by reading the power delivered at the output of the main electric panel.

In order to guarantee the stability and quality of the electric power delivered, a set of Energy Storage Systems and back-up oil-based thermal power stations are integrated in the production system.

Assuming that the projected hybrid power plant had been optimal designed (Shaahid & Elhadidy, 2008), the role of the platform here developed is basically to minimize the energy supplied by the oil-based back-up power units. We use the potential of the SCADA supervisory platform to integrate the monitoring of the real production figures on the optimization problem.

The selected functional to allocate the proper electricity production to each power unit is presented below (eqs. 1 to 7):

$$\min J = \sum_i c_{PVi} y_{PVi} + \sum_j c_{windj} w_{windj} + \sum_l c_{oill} w_{oill} \tag{1}$$

Subjected to:

$$\sum_i y_{PVi} + \sum_j y_{windj} + \sum_l y_{oill} + \sum_n y_{ESSn} \geq y_{demand} \tag{2}$$

$$y_{ESSk} \leq y_{\max k} \tag{3}$$

$$E_{\max k} \geq y_{ESSk} \times \Delta t_k \tag{4}$$

$$0 \leq y_{PVk} \leq y_{PVkact} \tag{5}$$

$$0 \leq y_{wink} \leq y_{windkact} \tag{6}$$

$$0 \leq y_{oilk} \tag{7}$$

where:

c_{PVi} = production cost associated with PV plant i;

c_{windi} = production cost associated with Wind plant i;

c_{oili} = production cost associated with oil-based thermal plant i;

y_{PVi} = requested Watt-power to be supplied by PV plant i;

y_{windi} = requested Watt-power to be supplied by wind plant i;

y_{oili} = requested Watt-power to be supplied by oil-based thermal plant i;

y_{ESSi} = requested Watt-power to be supplied by energy storage system i;

y_{demand} = total Watt-power demand;

y_{maxk} = max available Watt-power to be supplied by energy storage system k;

E_{maxk} = max available Joule-energy to be supplied at an average rate of y_{ESS}, by a time periode of Δt, for the ESS k;

y_{PVkact} = instantaneous available Watt-power at the PV plant k;

$y_{windkact}$ = instantaneous available Watt-power at the wind plant k;

Analysing the minimization criterion, it is clear that the change at the instantaneous available watt-power from the RES (y_{PVkact}, $y_{windkact}$) implies the energy re-balance of the entire system. In fact when it happens a power surplus (production greater than consumption), the Energy Storage Systems are being charged ($y_{ESSk} <0$). When the demanded power exceeds the RES production, the difference has to be covered by additional requirements on ESS supply ($y_{ESSk} >0$) or oil-based thermal systems production ($y_{oilk} >0$).

The optimization algorithm implemented for the energy management, at the SCADA outer loop control, could not be implemented directly on the SCADA system, as this complex controller needs mathematical operations that are not present at usual available SCADA systems. In this paper we developed a strategy to couple the SCADA system with the MATLAB software (Mathworks, 2005).

The communication between SCADA and MATLAB was performed using the DDE protocol (Dynamic Data Exchange). This communication protocol, developed in the 90's but still very common, permits the exchange of data between two independent running software programs (Client and Server).

In the developed application the MATLAB software was the Client, as it initiates the communication, and the SCADA software was the Server, as it responds to Client's requests.

Among the different information formats supported by DDE protocol, the TEXT format was selected as this format was supported by both software: SCADA and MATLAB.

Figure 4 illustrates the communication flow that was developed to implement the optimization algorithm at the Outer loop control (eqs. 1 - 7). In this figure we see the coexistence of four different communication protocols (LAN, DDE, MPI, PROFIBUS) working simultaneously at different levels of the developed platform.

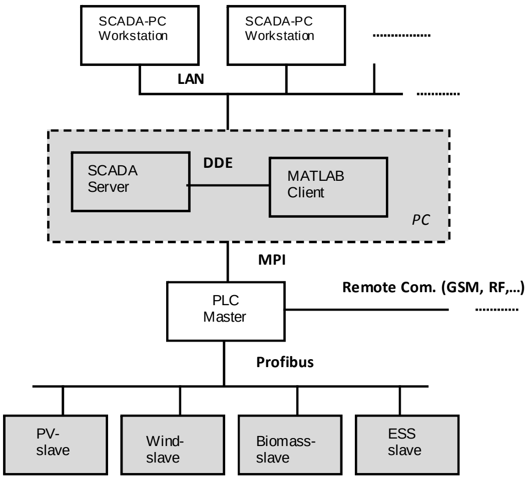


Fig. 4. Communication's Architecture for the built Prototype

3.2 Local PLC Inner-Loop Controller

At the inner loop of the developed strategy (PLC level), several algorithms had been developed. These algorithms were built using the Grafcet methodology - Sequential Function Chart. The designed algorithms were implemented using the Ladder Diagram language (Siemens, 2001b).

The main purpose of the developed programs associated with the RES stations is the monitoring of the electric power generated.

4. Experimental Setup

The developed application to monitor and control automatic Power Plants had been implemented on an experimental setup with the following software and hardware requirements.

The PLC network implemented had four PLCs: one PLC for each Power unit (PV-slave, Wind-slave, Biomass-slave, ESS-slave). Figure 4 shows the architecture of the built Prototype. This prototype aims to test the developed energy management system to be implemented in the future Peter park.

The PETER park plans to integrate a photovoltaic production unit (10 KW), a wind generator (1KW) and a biomass unit (75KW). In this park, the biomass plant will play the role of the controllable power production unit.

4.1 Software Requirements

The software used for the PLC programming was the Siemens Simatic Step 7 (Siemens, 2000). The Scada system was developed over the platform Siemens WinCC (Siemens, 2005).

4.2 Hardware Requirements

Figure 5 shows an overview of the implemented prototype. Referring hardware characteristics each PLC (Master and Slaves) was composed by the following Siemens modules:

Slot1 = Power supply PS 307-2A

Slot2 = Processor CPU 315-2DP

Slot4 = Communication module CP 342 -5

Slot5 = Digital card DI8/DO8xDC24V/0,5A

Slot6 = Digital card DI8/DO8xDC24V/0,5A

Slot7 = Analogue card AI4/ AO2x8/ 8bit

Additionally, the Master PLC has a modem for GSM communication that provides the system capacity to communicate through the mobile phone network.

The sensors used to monitor the generated and consumed electric power/ current are a set of AC/DC current transducers, coupled to energy analysers, with Profibus communication. In our case the energy meters used were the family Siemens SIMEAS P.

The power generation of the considered RES units, was simulated through 2 DC-power supplies, and 1 AC-Power supply, which simulated the power output from the DC-converters and the AC-generator illustrated in fig. 2. The power amplitude was externally changed.

5. Results

The main objective of the performed tests was to evaluate the compatibility of the several communication protocols present in the developed application (LAN, DDE, MPI, PROFIBUS).

The obtained results show mainly the information made available at the several developed Graphical User Interfaces (GUI) of the application.

The optimization problem described in eqs. 1 to 7, was solved through the MATLAB Optimization Toolbox, using the standard algorithm "fmincon" (Mathworks, 2005).

The SCADA system used to implement this monitoring and control strategy permits the selective access to the application, depending on the user's responsibility degree. In this paper we developed three user levels: Operators, Supervisors and Administrators.

Several SCADA menus were built. The main characteristic of a SCADA Menu is to be simple, explicit and quick on transmitting the information to the operator or to the System Administrator.

Two of the developed Graphical User Interfaces (GUI) are shown in figs 6 and 7.

As this SCADA platform is web enabled, all the GUI displayed data is also on-line accessible through the internet.

In fig. 6 it is shown an overview of the complete Power Plant production, with the main information regarding the consumption and the production on several distributed power units (PV, Wind, Biomass). The on-line available information, referring actual data from each power unit is: actual values and maximal daily values for Voltage, Current, Power and efficiency ratio (actual Value/max. Value). In fig. 7 it is shown the GUI relative to one of the power units. In this case this figure shows the available information for the PV-power generator, concerning the several integrated sub-systems.

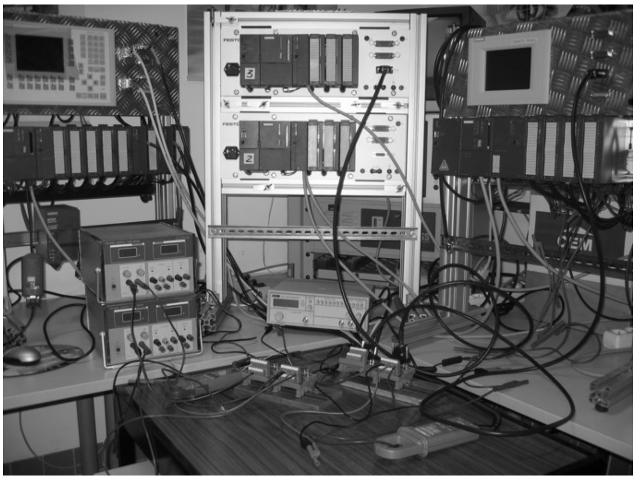
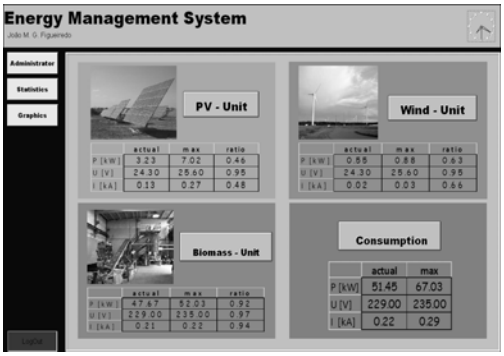


Fig. 5. . Implemented Prototype to test the energy management system



PV - Unit

	actual	max	ratio
P [kW]	3.23	7.02	0.46
U [V]	24.30	25.60	0.95
I [kA]	0.13	0.27	0.48

Wind - Unit

	actual	max	ratio
P [kW]	0.55	0.88	0.63
U [V]	24.30	25.60	0.95
I [kA]	0.02	0.03	0.66

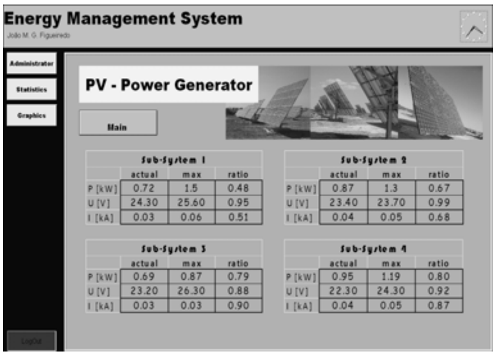
Biomass - Unit

	actual	max	ratio
P [kW]	47.67	52.03	0.92
U [V]	229.00	235.00	0.97
I [kA]	0.21	0.22	0.94

Consumption

	actual	max
P [kW]	51.45	67.03
U [V]	229.00	235.00
I [kA]	0.22	0.29

Fig. 6. GUI: overview of the complete Power Plant Production



Sub-System 1

	actual	max	ratio
P [kW]	0.72	1.5	0.48
U [V]	24.30	25.60	0.95
I [kA]	0.03	0.06	0.51

Sub-System 2

	actual	max	ratio
P [kW]	0.87	1.3	0.67
U [V]	23.40	23.70	0.99
I [kA]	0.04	0.05	0.68

Sub-System 3

	actual	max	ratio
P [kW]	0.69	0.87	0.79
U [V]	23.20	26.30	0.88
I [kA]	0.03	0.03	0.90

Sub-System 4

	actual	max	ratio
P [kW]	0.95	1.19	0.80
U [V]	22.30	24.30	0.92
I [kA]	0.04	0.05	0.87

Fig. 7. GUI: Photovoltaic Power Generation

6. Conclusion

The energy management system developed in this paper is composed by several production units, spatially distributed, with different energetic sources: Renewable Energy Sources –

RES (Photovoltaic, Wind, Biomass), Oil-based thermal power stations and Energy Storage Systems - ESS.

The developed strategy is implemented through a traditional cascade controller.

The inner-loop control is performed by an industrial PLC network, controlling locally each power plant. The outer-loop is managed by a SCADA supervisory system.

In this paper an optimal allocation of production resources is performed taking into account the minimization of the operational costs. Both instantaneous power-demand and power-supply are on-line monitored in the developed energy management system.

The developed strategy is simulated, based on the requirements of the new renewable energy experimental park (PETER), that is being implemented at the University of Évora - Portugal.

7. References

Denholm P., Kulcinski, G. (2004). Life Cycle Energy Requirements and Greenhouse Gas Emissions from Large Scale Energy Storage Systems. *Energy Conversion Manag. 2004, 45(13-14), pp. 2153-2172.*

Doherty, R., Lalor, G., O'Malley, M. (2005) "Frequency control in competitive electricity market dispatch"; IEEE Trans. on Power Systems, vol 20, nº3, pp. 1588-1596

Figueiredo, J., M. Botto (2005). Automatic Control Strategies Implemented on a Water Canal Prototype. *Proc. 16th IFAC World Congress, Praha, Czec Republic*

Figueiredo, J., Sá da Costa J. (2007). A Concept for an Operational Management System for Industrial Purposes. *Proc. IEEE Intl. Symposium on Intelligent Signal Processing, Madrid, Spain, ISBN 1-4244-0830-X/07, 2007 IEEE*

Kaiser, R. (2007). Optimized Battery-Management System to Improve Storage Lifetime in Renewable Energy Systems. *J. Power Systems 2007, 168, pp. 58-65.*

Kaldellis, J. (2007). An Integrated Model for Performance Simulation of Hybrid Wind-Diesel Systems. *Energy 32 (2007), pp. 1544-1564*

Lund, H., Munster, E. (2003). Management of Surplus Electricity – Production from a Fluctuating Renewable-Energy Source. *Appl. Energy 2003, 76(1-3), pp. 65-74.*

Mathworks (2005). *Matlab Simulink 7.1* (R14), Mathworks, 2005.

Papathanassiou St A., Boulaxis N. (2005). Power Limitations and Energy Yield Evaluation for Wind Farms Operating in Island Systems. *Renew Energy 2005, 31(4), pp. 457-479.*

Shaahid, S., Elhadidy, M. (2008). Economic Analysis of Hybrid Photovoltaic-diesel-battery power systems for residential loads in hot regions – A step to clean future. *Renewable and Sustainable Energy Rev 12 (2008), pp. 488-503.*

Siemens (2000). *System Software for S7-300 and S7-400 – Reference Manual*, SIEMENS 08/2000; A5E00069892-02

Siemens (2001a). *Simatic Net – NCM S7 for Profibus/ FMS.* SIEMENS 12/2001.

Siemens (2001b). *Simatic S7-300 – Ladder Logic (LAD) for S7-300,* SIEMENS, 2001.

Siemens (2005). *Simatic WinCC V6.0 SP2*, SIEMENS, 2005.