UNIVERSITY POLITEHNICA OF BUCHAREST
DOCTORAL SCHOOL OF ENERGY ENGINEERING

PH.D. THESSIS SUMMARY

Development and implementation of SCADA systems in power systems

Dezvoltarea și implementarea sistemelor SCADA în sistemele electroenergetice

Author: Eng. Dănuț Adrian POȘTOVEI

Ph.D. Coordinator: Prof. PhD. Eng. Constantin BULAC

COMISIA DE DOCTORAT

President	Prof. PhD. Eng. Sanda Carmen GEORGESCU	from	University Politehnica of Bucharest
Ph.D. Coordinator	Prof. PhD. Eng. Constantin BULAC	from	University Politehnica of Bucharest
Reviewer	Prof. PhD. Eng. Ioana FĂGĂRĂȘAN	from	University Politehnica of Bucharest
Reviewer	Prof. PhD. Eng. Marcel ISTRATE	from	Technical University “Gheorghe Asachi” from Iași
Reviewer	Prof. PhD. Eng. Mihai GAVRILAȘ	from	Technical University “Gheorghe Asachi” from Iași

Bucharest
2022

THESSIS CONTENTS

KEYWORDS

Power system, SCADA, DCS, EMS, DMS, Human Machine Interface, Bay Control Unit (BCU), PMU (Phasor Measurement Unit), Front End, IEC61850, IEC 60870-5-101, IEC 60870-5-104, Master/Slave, Client/Server, GOOSE, communication protocols, communication architectures, data network, cyber security, data models, protocol conversions, interoperability, process controllers, Hardware In the Loop - HIL, DAS, monitoring, control, regime simulator, Online Voltage Stability Monitoring - OLVSM, synchro phasors, TEST2 system, Voltage Stability Index - VSI, Thevenin equivalent, local measurements, power distance, voltage stability.

EXTENDED SUMMARY

In this period of energy transition, both transmission and distribution operators are facing new challenges, primarily due to the increased penetration of renewable energy sources both in the transmission grid and in the medium and low voltage distribution networks, which leads to an increase in their operational complexity.

In this context, microgrids with their three key characteristics: local, independent, and smart, will be the main driver of growth in the share of renewable energy.

To be able to adapt and react as quickly as possible to these changes, electricity transmission and distribution operators need to adopt a new monitoring and control concept that can forecast as accurately as possible the power that may be available at any given time.

Also, the geographical distribution of electricity generators, which in most cases are located at long distances from consumers, forces operators to diversify and expand electricity transmission and distribution networks, making them more flexible but also more complex.

Another important aspect in the monitoring and control of power systems is the increasing development and integration of HVDC (High Voltage Direct Current) networks, which will lead to increased complexity and the need for advanced estimation and monitoring methods in the operation of ESS using specialized PMUs (Phasor Measurement Units) and SynDCs (Synchronous DC Measurement Units). [2]using the C37.118 protocol [3] [4].

The new monitoring and control concept must be able to process information in real time. This monitoring is carried out at local transmission and distribution station level using SCADA systems and at national level data is centralized in EMS/DMS SCADA systems.

The rapid evolution of technology has made it possible to reduce the production costs of SCADA component equipment, resulting in their widespread deployment. In practice, it is not possible to talk about modernization in the power system without considering the implementation of such a system.

Traditional SCADA systems have focused on monitoring and controlling vital parts of the technological process independently, but modern systems aim to monitor and control the entire technological process, power unit or power transmission or distribution station, ensuring the interconnection of all monitoring and control equipment, providing full visibility of all data at the central level, usually in the control room of the power unit, or power transmission or distribution station.

Modern SCADA systems are characterized by flexibility and scalability and connect the supervised facility to modern IT facilities: remote control, remote access, mobile phone monitoring and cloud archive storage.

In practice, these functions are realized through a set of hardware equipment such as system servers, local controllers, communication networks, Human Machine Interface (HMI) and specific software packages.

Regardless of their evolution, modern SCADA systems continue to provide the same basic functions as traditional ones, i.e., monitoring and controlling a large volume of inputs/outputs, they have evolved towards interconnecting all monitoring and control equipment, ensuring full visibility of all data at the central level, usually in the control room of the power plant, or the power transmission or distribution station [5].

With flexibility and scalability as its main characteristics, where the hardware part is composed of a multitude of autonomous entities, distributed in different physical locations, with local, remote, or dispatcher-controlled operating modes, at the level of each SCADA system there is a software platform that manages the whole ensemble as a unit, making it perceived by the user as a single and coherent system for the entire technological process being supervised.

If in the power generation area, SCADA systems optimize the control and monitoring of technological processes, facilitating human intervention in their management, in transmission and distribution power stations the trend is to monitor and control the entire installation from the territorial or national dispatch level, and upgrades are aimed at operating unmanned installations.

Current IT trends have also not bypassed SCADA systems, even influencing their future developments. Although they are considered closed monitoring and control systems and do not interact much with IT facilities, they must meet increasingly complex energy requirements and be integrated into modern IT systems.

At the level of an electricity transmission or distribution station, not only energy is transferred, but also a large amount of information, which can only be managed by migrating to modern automation systems that can process this data in real time and then transmit it in the specific format to the actors involved in technological processes, such as: Power station operators, National Energy Dispatcher (DEN), Territorial Energy Dispatcher (DET), Remote Control and Plant Supervision Centers (CTSI), intervention and maintenance teams (EI), through the facilities offered by modern IT technologies such as SMS, MMS, Cloud, ERP, etc.

A traditional SCADA system today is seen as a monolith that cannot be changed, with distributed control of the technological process limited by the serial communication network and specific communication protocols. Over the years, hardware, software, and communication architectures have become increasingly complex, but with few exceptions, control is still done using controllers and system servers.

The transmission and distribution of electricity requires that all components are precisely monitored and controlled. This can be achieved by automated systems, and by distributed systems that can ensure the coordination of a large number of technological process equipment without the risk of errors, thus helping operators to work safely and quickly.

Migration to modern SCADA systems is usually driven by poor performance of existing automation processes, high cost of maintenance, lack of components and specialists, and technological barriers that block expansion or integration with new systems. While the benefits of new technology are obvious, this research highlights solutions that both technically and economically justify the choice of a SCADA system solution.

Based on these arguments, the main purpose of this thesis is to establish the basic principles, provide a methodology and provide examples for choosing the optimal solution both for the implementation of a new SCADA system and for the migration from a traditional to a modern system required by the adaptation to current requirements and standards.

In this regard, the thesis pursued three major objectives, namely:

1. Conduct a detailed analysis of the current status, implementations and trends of SCADA systems in transmission and distribution stations.
2. Development of a real-time simulation environment of the Hardware-in-the-Loop (HIL) type, using the Open DSS application developed by EPRI, respectively EPSA (Electric Power Systems Analisys) developed in the Laboratory of Electroenergetic Networks and Systems of the Faculty of Energetics - UPB as regime simulators, together with the system in the SCADA Laboratory of the DSEE Department, Faculty of Energetics - UPB;

3. Proposal of a new EMS SCADA function to monitor and control the voltage stability at a transformer substation designed to supply a consumption area (220/110kV or 400/110kV substation), and development of a simulation

application for this function using local measurements, either classical or provided by PMU devices.

Conclusions and recommendations for the ***development and implementation of SCADA systems in power systems*** resulting from the research conducted during the doctoral studies take into account the specific requirements of the beneficiaries, applicable domestic and international energy standards, budgetary constraints of such investments, hardware and software limitations of SCADA systems, integration of some equipment or systems, cyber security and low impact of the controlled technological process for future development and expansion.

In order to achieve the objectives of my doctoral research and to have a support as close as possible to the operation of a transmission substation, I actively participated in the concept, design, implementation and testing of the command-control-protection system, at the "University POLITEHNICA Bucharest", "Faculty of Energy Engineering", "Department of Electroenergetic Systems", of the SCADA Laboratory, whose equipment and realization were provided by companies working in the field of energy, such

as the national transmission operator CNTEE Transelectrica SA, as well as with the contribution of SIEMENS Energy, Siemens Romania SRL and Eneroptim SRL. The laboratory fully reproduces the functionality of an existing SCADA system in a 220/110 kV power station, being a modern multi-level dynamic modelling solution. [6] [7] [8] [9] [10] [11]. The proposed interface represents a new solution for the realization of a real-time Hardware-in-the-Loop (HIL) simulation environment, using Open DSS and EPSA applications developed in the Laboratory of Electric Power Networks and Systems at the Faculty of Energetics - UPB as regime simulators, together with a SCADA system currently used in the power stations of various transmission and distribution operators in Europe and Africa and Asia, with very good performance in terms of accuracy in the acquisition and processing of status and measurement signals from the system.

The concept implemented in the SCADA laboratory highlights the flexibility of real-time modelling of many types of energy systems, both transmission and distribution and complex Microgrid networks. This approach has significant advantages compared to real field tests, with the possibility to simulate most types of faults in power systems.

The dissertation consists of 6 chapters, plus an important bibliographical study.

Chapter 1, "INTRODUCTION" is the introductory part of the paper where the concept of SCADA system is defined, the evolution and trends of modern SCADA systems used in power generation, transmission and distribution processes are presented.

Chapter 2, "CURRENT STATUS, DEVELOPMENTS AND TRENDS OF SCADA SYSTEMS" defines the concept and characteristics of SCADA systems, the history of the development and implementation of SCADA systems in power engineering and the current state of research in the field.

Chapter 3, "STRUCTURE, GENERAL METHODOLOGY AND IMPLEMENTATION STRATEGIES OF SCADA SYSTEMS IN ELECTROENERGY", presents architecture, structure, general methodologies, and implementation strategies of SCADA systems in electric power systems. Also in this chapter, the general framework for monitoring and control of technological processes in electricity transmission and distribution using SCADA systems is described.

Chapter 4, "REAL-TIME MONITORING AND CONTROL TECHNIQUES FOR ELECTROENERGY SYSTEMS WITH SCADA SYSTEMS MODELLED HARDWARE IN THE LOOP", presents real-time monitoring and control techniques for electric power systems with SCADA systems modelled hardware-in-the-loop. An integrated solution for a 220/110 kV power station modelled Hardware-in-the-Loop is also presented, highlighting the real-time functionality of the control architecture and the benefits of this integrated solution.

Chapter 5, "MIGRATION OF SCADA SYSTEMS TO ADAPTIVE SYSTEMS WITH REAL-TIME MONITORING AND CONTROL", discusses the EMS functions of system automation supported by SCADA and the importance of using synchronous meters (synchro phasors) in power systems, both as stand-alone metering systems and integrated into SCADA systems. The last part of the chapter proposes a new EMS SCADA function for monitoring and controlling voltage stability at a transformer substation designed to supply a consumer area (220/110kV or 400/110kV substation) and presents the results obtained with the application developed to simulate this function. The software developed in the

MATLAB environment is attached to the platform in the SCADA Laboratory, uses the EPSA program for regime simulation and local data (voltage and active and reactive powers) provided by the HIL platform. Based on this information, the monitoring function assesses the risk of voltage instability triggering and, if necessary, activates the preventive or corrective functions that are required (alarm, load shedding, blocking of the regulation of the plots, etc.). The software has been tested using the TEST2 system.

Chapter 6, "CONCLUSIONS", presents the conclusions drawn from the theoretical and practical aspects of the research carried out, as well as the author's contributions.

GENERAL CONCLUSIONS

In the current socio-economic context, digitalization and energy infrastructure play a key role in a country's development and progress. It is therefore necessary to develop and widely implement digital management, monitoring, and control systems (SCADA) in the complex process of electricity generation, transmission, and distribution.

Although the development of SCADA systems has been, and continues to be, driven by the interests of individual equipment vendors, and

has been carried out in a closed system, in the future, from the perspective of the benefits to users (reduced implementation and training costs), they must evolve towards open and standardized systems, without proprietary vendor features.

A first step in this direction was the adoption of IEC61850 as the single communication protocol by all vendors. The main benefit of this standardization is to reduce the cost of integrating monitoring and control equipment from different SCADA system suppliers.

In addition to the adoption of a common communication protocol, SCADA systems need to move towards standardization of process architectures and HMI technology. At present the lack of such standardization is a barrier to the development of these systems.

The migration to modern SCADA systems will allow the use of common automation technologies available to all suppliers, which means better interoperability and greater compatibility with both modern IT facilities and the business environment.

SCADA systems allow the use of digital technologies and the development of powerful algorithms for the implementation of management and control functions within EMS platforms because:

- Digital systems are more accurate and flexible;
- command/control algorithms can be changed without having to shut down the system;
- Digital systems require lower installation and maintenance costs;
- digital data, stored in electronic files, is easily accessible to various applications that allow the extraction of information needed to produce reports and present the

operational status of the system in graphical form that is easy to interpret by operators in command-and-control centers;

- are flexible in terms of design and development/expansion, reliable and easy maintenance;
- loss of connection to the communications network does not implicitly result in complete loss of SCADA system capability because distributed units can continue to operate without significant loss of function for moderate or extended periods of time.

Research conducted during the development of the PhD thesis highlights that maintaining two or more SCADA systems with different technologies operating in parallel is, on the one hand, an additional drain on resources with implementation and operation and, on the other hand, limits future development or expansion.

The paper represents new research in the literature in the field, providing a theoretical and practical basis for future studies on SCADA systems, the integration of devices for synchronized phase measurement, i.e. PMU and PDC units, into the IEC61850 network of the laboratory, and the realization of adaptive automation schemes with real-time monitoring and control.

PERSONAL CONTRIBUTIONS

The current state of development of SCADA systems used in power systems allows for complex IT solutions, which offer the possibility to implement advanced estimation, monitoring and control techniques that respond efficiently to both normal and disturbed operating regimes.

The PhD thesis addresses the complex problem of developing and implementing SCADA systems in power systems and is structured in two parts. In the first part, an analysis of the status and strategies for the development/implementation of SCADA systems in electro-energy systems was carried out considering two cases. In the first case it was considered that the migration to a modern SCADA system will be achieved partly by maintaining part of the existing system and providing parallel operation of two SCADA systems. In the second case, the hypothesis of implementing a completely new system was adopted as the optimal technical-economic solution.

The second part presents the laboratory developed at the Faculty of Energy Engineering of University POLITEHNICA of Bucharest for testing new SCADA technologies and training/education activities, as well as two applications developed using Hardware-in-the-Loop (HIL) technology. The first application addresses the problem of interfacing simulation programs of electro-energy systems with physical equipment in the laboratory (simulation of the data acquisition process). The second application aims at real-time monitoring of voltage stability using local measurements provided by the SCADA system which may include state-of-the-art synchronized measurement (PMU) technologies. This application is proposed as a new function in EMS SCADA systems to trigger preventive or corrective actions in case of alerts or emergency situations.

By writing his PhD thesis entitled ***"Development and implementation of SCADA systems in power systems"***, the author added a number of contributions, briefly presented below:

- Conduct a thorough literature survey on the current state of development of SCADA systems worldwide.
- Conducting a study, updated to 2021, showing the status of implementation of SCADA systems by the transmission operator and distribution operators in our country.

- Carry out a case study on the adoption of the optimal strategy for the development and modernization of SCADA systems considering two modern implementation solutions, in two typical variants, namely:
  - implementation of a modern, comprehensive IEC61850 system;
  - an optimal retrofitting of an existing legacy system, retaining and integrating equipment and solutions from the previous investment.
- Participation in the conception, design, installation, and commissioning of the SCADA Laboratory at the Faculty of Energy Engineering UPB for testing new SCADA technologies and training/instruction activities.
- Implementation of Hardware-in-the-Loop technology in the SCADA laboratory for interfacing power system regime simulation programs with physical equipment in the lab (simulation of data acquisition process and monitoring, command and control functions), concept that can very accurately model a real power system that can simulate different operating regimes and faults in real time for complex transmission, distribution and Microgrid power systems.
- Analysis of the bidirectional data chain and presentation of the impact of the various protocols implemented in the communication between different networks on the data models, highlighting both their association with the real quantities and with additional data (metadata).
- Detailing the complete data model management chain with proposed improvements based on the analysis performed.
- Development of the software interface between the power system regime simulation program and the acquisition and control equipment in the laboratory, integrated into the Grid MonK application to achieve HIL functionality;
- Development of Front End (FE)/Central Point SCADA application that exchanges data with the local SCADA system, adapted to work as a library within GridMonK;
- Adapting the Grid MonK application interface for real-time SCADA functionality;
- Design and implementation of a new EMS SCADA function for monitoring and control of voltage stability at a transformer substation intended to supply a consumption area (220/110kV or 400/110kV

substation), respectively development of a simulation application of this function using classical local measurements or provided by PMU devices, application integrated in the laboratory SCADA system.

To continue the studies presented in the PhD thesis, the following research directions are proposed:

- A new approach to the design of SCADA systems based on three-dimensional data models (IEC 61850), models that are closer to human thinking than to the way computers work, which gives the user a freedom to model process equipment virtually.
- Extending the analysis of the compatibility of data models specific to traditional and modern SCADA systems, with a focus on how to convert between the data models of two different protocols without losing information and ensuring the transfer of additional information (metadata) between the two systems, or how to complete more complex data models in a consistent way with this information.
- Adapting the HIL simulation environment within the SCADA laboratory so that it is possible to report phase measurements to the central SCADA server, which can be achieved by integrating the IEC61850 PMU and PDC units.
- Develop a guide of recommendations for the implementation of SCADA systems in similar power stations but with different implementation strategies.
- Extending the online voltage stability monitoring function to use the results provided by it (VSI indicator values and power distances) in an algorithm for load shedding to prevent voltage instability.

SELECTED BIBLIOGRAPHY

[1] ENTSO-E, ENTSO-G, „TYNDP 2018 Scenario Report,” 2017.

[2] C. Wenge, A. Pelzer, A. Naumann, P. Komarnicki, S. Rabe, M. Richter, „Wide area synchronized HVDC measurement using IEC61850 communication,” IEEE Power and Energy Society, General Meeting, 27 July 2014.

[3] G. Phadke, J. S. Thorp, „Synchronized Phasor Measurements and Their Applications,” Springer Verlag, 2008.

[4] J. R. Carroll, F. R. Robertson, „A Comparison of Phasor Communication Protocols,” Pacific Northwest National Laboratory report, February 2019.

[5] S. Chowdhury, S. P. Chowdhury and P. Crossley, „Microgrids and Active Distribution Networks,” The Institution of Engineering and Technology, 2009.

[6] C. Zambrano, C. Trujillo, D. Celeita, M. Hernandez, and G. Ramos, „Gridteractions: Simulation platform to interact with distribution systems,” IEEE Power and Energy Society General Meeting(PESGM), pp. 1–5, July 2016.

[7] D. Celeita, M. Hernandez, G. Ramos, N. Penafiel, M. Rangel, and J. D. Bernal, „Implementation of an educational real-time platform for relaying automation on smart grids,” Electric Power Systems Research, vol. 130, pp. 156–166, 2016.

[8] D. Martinez, D. Celeita, D. Clavijo, and G. Ramos, „Hardware and software integration as a realist SCADA environment to test protective relaying control,” IEEE Industry Applications Society Annual Meeting, pp. 1–8, Oct 2017.

[9] S. Brahma, J. De La Ree, J. Gers, A. Girgis, S. Horowitz, R. Hunt, M. Kezunovic, V. Madani, P. McLaren, A. Phadke, M. Sachdev, T. Sidhu, J. Thorp, S. Venkata, and T. Wiedman, „The Education and Training of Future Protection Engineers: Challenges, Opportunities, and Solutions,” IEEE Transactions on Power Delivery, vol. 24, no. 2, pp. 538–544, April 2009.

[14] B. Camachi, L. Ichim, D. Popescu, „Cyber Security of Smart Grid Infrastructure,” IEEE 12th International Symposium on Applied

Computational Intelligence and Informatics, SACI, Timisoara, Romania, 2018.

[15] R. Botezatu, „Cyber Security for SCADA and DCS systems, ICARE Cybersecurity," Germany, 2016.

[17] ANRE, Autoritatea Națională de Reglementare în domeniul Energiei, „Raport Anual," 2019.

[25] D. A. Poștovei, C. Bulac, I. Triștiu and B. Camachi, „A practical implementation of modern Distributed Control Systems in Electric Power Substations„" 12th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), pp. 1-6, doi: 10.1109/ECAI50035.2, Bucharest, Romania, 2020.

[26] M. Sanduleac, „Tehnologii digitale si sisteme SCADA pentru conducerea sistemelor electroenergetice," Politehnica Press, ISBN 979-606-515-870-2, Bucharest, Romania, 2019.

[27] D. Costianu, N. Arghira, I. Făgărăşan Ioana, S. St. Iliescu, „Standards in Control and Protection Technology for Electric Power Systems," Proceedings of Journal ISOM No. 2 Vol. 2, page 416-427, Bucharest, 2008.

[33] D. A. Poștovei, C. Bulac, I. Triștiu and B. Camachi, „Setting up a Distributed Control System Laboratory," 11th International Conference and Exposition on Electrical and Power Enhineering (EPE), Iasi, 2020.

[60] M. Eremia, H. Criscu, B. Ungureanu, C. Bulac, „Analiza asistata de calculator a regimurilor sistemelor electroenergetice," Editura Tehnica, Bucuresti, 1985.

[81] M. Gavrilaș, „Stabilitatea și controlul sistemelor electroenergetice," Editura Politehnium, 2011.

[82] P. Kundur, J. Paserba, V. Ajjarapu, „Definition and classification of power system stability," IEEE/CIGRE joint task force on stability terms and definitions, et al. No. 3, s.l. : IEEE Transaction on Power Systems, pp. 1387-1401, Vol. 19. DOI: 10.1109/TPWRS.2004.825981., 2004.

[86] Nicoleta Arghira, Sergiu Stelian Iliescu, Conducerea și automatizarea instalațiilor energetice, http://shiva.pub.ro/cursuri/conducerea-si-automatizarea-instalatiilor-energetice.

[96] C. Bulac, M. Eremia, Dinamica sistemelor electroenergetice, Bucuresti: Editura Printech, 2006.

[99] S. Ştefănescu, R. Tîrnovan, Automatiari in Sistemele Electroenergetice, Cluj Napoca: U.T. PRESS, ISBN 978-606-737-367-7, 2019.

[106] Radu-Adrian Tîrnovan, „Protecţii digitale în Sistemele Electroenergetice," U.T. PRESS, ISBN 978-606-737-370-7, CLUJ-NAPOCA, 2019.

[116] P. Kundur, Power System Stability and Control, New York: MacGraw-Hill, Inc., 1994.