Robust Topology Determination Based on Additional Substation Data from IEDs

M. Kezunovic[1], *Fellow IEEE*, T. Djokic, T. Kostic[2], *Member IEEE*

***Abstract*—This paper describes an approach for more robust power system topology determination using additional substation data currently not available through Supervisory Control and Data Acquisition (SCADA). This new approach uses additional data from multiple Intelligent Electronic Devices (IED) located in substations. The additional data relates to the same measurements as taken by Remote Terminal Units (RTU) as well as the measurements not "seen" by RTUs at all. By utilizing redundant data, performing time correlation between analog and contact data, and examining the historical data, the proposed approach significantly increases accuracy of topology determination and makes the outcome reliable under multiple measurement contingencies.**

***Index Terms*—Topology processor, Substation IEDs, SCADA, RTUs, Measurements, Disturbance recorder, Digital relay, Circuit breaker monitor.**

I. Introduction

THIS paper addresses a very important problem in today's Energy Management System (EMS) designs, namely the problem of robust determination of power system topology [1]. The power system topology determination has long been recognized as a key to a successful execution of many EMS functions such as State Estimation, Load Flow, Stability Assessment, and Supervisory Control and Data Acquisition [2]. The errors in the outcomes can have significant impact on both the operator actions and results of automated EMS functions [3].

To avoid erroneous outcomes, we are proposing the use of additional data available from variety of Intelligent Electronic devices (IEDs) in substations [4]. While today's solutions for topology determination rely exclusively on the use of data collected by Remote Terminal Units (RTU) of a Supervisory Control and Data Acquisition (SCADA) System, the future solutions can significantly be improved by taking into account data from other IEDs that are connected to sources of substation signals and provide additional and/or redundant data about the topology [5,6].

II. Topology determination problem

Topology processors are important in an EMS system, since many of the functions rely on the topology state produced by the topology processor. However, it is difficult to make the topology processor reliable under different operating conditions of a power system. Determining power system topology very accurately using SCADA information only is not always possible. Topology information in SCADA lacks redundant measurements that would help improving the robustness of the decision-making outcome. RTUs are not designed to track the analog measurements and status changes closely. Due to an overwhelming amount of measurement points, only reporting by exception for analog signals and monitoring of selected or grouped contacts is implemented.

As an overall consequence of the limited measurements available through SCADA, decisions about correct power system topology are sometimes impaired. The incorrect topology determination can lead to diverging State Estimator, erroneous load flow computation, and inadequate stability assessment. Operator actions may be affected by the mentioned software producing incorrect results and/or by operator's inability to have a correct visual representation of the topology [7].

III. Improved Robustness of Topology Determination

Additional and redundant data from multiple IEDs can be used to improve robustness of topology determination. IEDs of interest in this study are Digital Fault Recorders (DFRs), Digital Protective Relays (DPRs), and Circuit Breaker Monitors (CBMs) [8]. Those IEDs provide multiple measurements of the same values. All the mentioned IEDs measure:

- Phase currents
- Circuit breaker control circuitry contacts "A" and "B"
- Relay trip signal

Those redundant data may be utilized to verify accuracy of the measurements. The additional signals recorded by IEDs are:

- Internal circuit breaker control signals, recorded by CBM, providing additional insight into CB operation;
- Transients, recorded by DFR, describing behavior of phase current under switching and fault clearing events; and,
- Internal protective relay logic signals, captured by DPR, explaining details of the initial relay action as well as the follow up trip/close, autoreclosing and breaker failure actions of the breaker.

[1] M. Kezunovic and T. Djokic are with Texas A&M University, U.S.A. (e-mail: kezunov@ee.tamu.edu, djtanja@tamu.edu)
[2] T. Kostic is with ABB Switzerland, Corporate Research, Baden-Daettwil, Switzerland (e-mail: tatjana.kostic@ch.abb.com, respectively).

M. Kezunovic, T Djokic, T. Kostic, "Robust Topology Determination Based on Additional Substation Data from IEDs", PowerTech 2005, Sankt Petersburg, June 2005.

If the mentioned redundant as well as the additional analog and contact measurements were available to SCADA, it would be possible to determine power system topology more accurately by combining all the data. Table 1 shows types of signals monitored by DFRs, CBMs and DPRs.

TABLE 1. DESCRIPTION OF THE TYPES OF SIGNALS FOR DFRS, DPRS, AND CBMS

Digital Fault Recorder	Digital Protective Relay	Circuit Breaker Monitor
"A" and "B" contacts	"A" and "B" contacts	"A" and "B" contacts
Phase currents	Phase currents	Phase currents
Relay trip signal	Relay trip signal	Trip and close initiate
Recloser timing signal Breaker failure initiate Comm. scheme signals	Recloser timing signal Breaker failure initiate Comm. scheme signals	Trip and close currents "X" and "Y" coils DC supply

If data recorded by the mentioned IEDs were stored in a substation database, improved robust topology determination can be obtained using additional and redundant data through the following analysis [8]:

- *Time correlation between analog and contact data.* It is well known that a change in topology is followed by a change in the analog signals "seen" at different points in the network. Digital Fault Recorders (DFRs) are capable of tracking both analog (voltages and currents) and contact (status) information from circuit breakers. By combining this information and drawing the cause–effect conclusions one can confirm whether a breaker has opened/closed by monitoring the expected changes in the associated analog signals.
- *Functional correlation.* Associating the recorded signals with the specific action that the relay was engaged in can yield additional information about the circuit breaker status. Digital Protective Relays (DPRs) record both input signals (currents and voltages) as well as automatic control actions on the breaker. Monitoring the sequence of such signals gives the actual final open/close positions of the breaker, and hence allows one to check the actual outcome of the CB status against an expected one.
- *Switching sequence check.* Many switching actions are initiated by commands that cause a change in control circuitry contacts of the switching or control equipment. By using data captured by Circuit Breaker Monitors (CBMs) one can verify if the initiated switching sequence has been completed as expected since the deviation in the expected sequence can easily be observed by looking at a possible deviation in the CB control circuit signals.

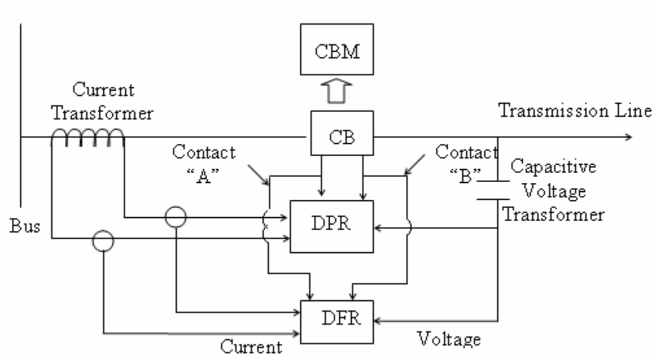

Figure 1. Typical connection of substation IEDs to a circuit breaker

Figure 1 illustrates how a circuit breaker (CB) may be connected to DFR, CBM and DPR. Again, it should be observed that a number of CB signals that are collected by various IEDs shown in Figure 1 are redundant and are typically not "seen" by a RTU of the SCADA.

IV. THE NEW APPROACH TO TOPOLOGY DETERMINATION

The accuracy of topology information may be improved by:

- Using additional and redundant data from different IEDs,
- Establishing a clear temporal relationship in the data analysis, and
- Taking advantage of the time-series analysis of historical data.

Table 2 shows factors affecting the accuracy of topology information in the case of circuit breaker monitoring [9].

TABLE 2. FACTORS AFFECTING THE ACCURACY OF INFORMATION IN THE CASE OF CIRCUIT BREAKER MONITORING

Multiple data sources	Temporal analysis	Historical assessment
CB monitors: control circuit signals, vibration, gas pressure	Sequence of control signal initiations and changes in circuit breaker status	Number of operations and assessment of the opening/closing times
Digital fault recorders: "A" and "B" contacts, phase current changes	Sequence and correlation of changes of the status contacts and CB currents	Consistency of "A" and "B" contacts and their reliability
Protective relays: duty cycle currents, $I^2 \bullet t$	Timing of CB operations and current interruptions	Assessment of the duty cycle over long time

Further discussion in the paper will provide details on how the required data may be captured and processed to yield the expected benefits in determining power system topology in a more reliable and robust way.

M. Kezunovic, T Djokic, T. Kostic, "Robust Topology Determination Based on Additional Substation Data from IEDs", PowerTech 2005, Sankt Petersburg, June 2005.

A. *Example substation*

One example of robust topology determination using similar and redundant information recorded by different IEDs installed in one substation can be shown on the breaker-and-a-half substation configuration shown in Figure 2.

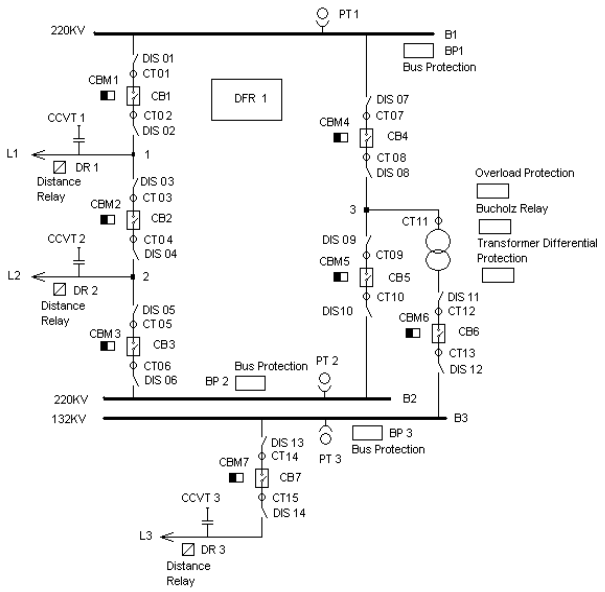

Figure 2. Breaker-and-a-half substation configuration

The substation has seven digital relays, seven circuit breaker monitors (CBMs) and one digital fault recorder (DFR). Each of the 15 devices records a number of data on an event. It has been assumed that files from the devices are available in COMTRADE format. The summary of the data analyzed is given in Table 3.

TABLE 3. SUMMARY OF INFORMATION USED FROM IED FILES

Device	Description
Relay	- Analog values of three phase voltages and currents - Digital status of logic operand – breaker trip signal
CBM	- Trip initiate - Close initiate - X Coil signal - Y Coil signal - “A” contact - “B” contact - Control DC Voltage - Yard DC voltage - Trip coil - Close coil current - Three phase currents
DFR	- Analog current and voltage values from all instrument transformers - Relays’ trip signals - Circuit breakers’ status signals

B. *Algorithm*

If we make assumption that after an event files from IEDs that recorded the disturbance are available for analysis then following analysis can be perform on those files. Figure 3 shows the proposed algorithm for determining circuit breaker statuses using redundant data from IED files.

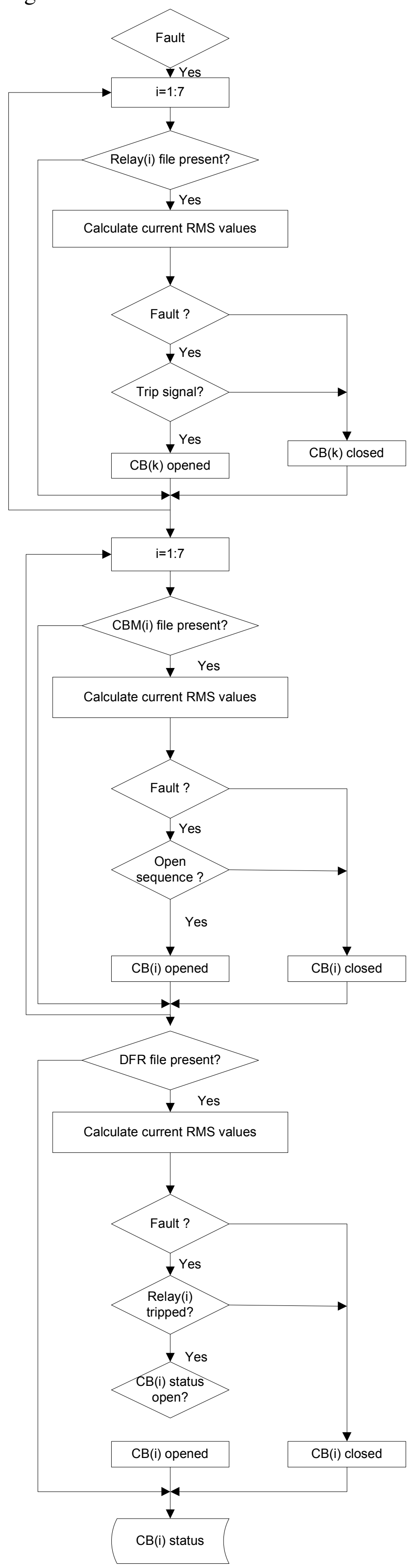

Figure 3. Algorithm for determining circuit breakers’ statuses

M. Kezunovic, T Djokic, T. Kostic, “Robust Topology Determination Based on Additional Substation Data from IEDs”, PowerTech 2005, Sankt Petersburg, June 2005.

The algorithm consists of three steps, each step aimed at a verification of the CB status based on data received from one of the three devices that have captured the status change: DPR, CBM, and DFR. In the first step, data from DPR is analyzed to determine if the relay has initiated CB action. If so, then based on the relay actions, and subsequent expected CB action, a hypothesis about the final CB state is derived [9]. The rest of the checks given in Figure 3 are aimed at verifying the hypothesis. In the next step, data from CBM is collected and analyzed. A complex analysis that compares the trip or close initiate with a pre-specified follow-up sequence of changes in other control circuitry contacts is performed to determine if the intended action is completed correctly [10]. The final check is associated with verification of circuit breaker currents, which should be interrupted if the breaker has opened or initiated if the breaker has closed. Verifying the observations recorded by substation DFR does the final check. The analog signals are analyzed first to determine which circuit was involved in CB operation. After that, based on both analog and contact measurements, a sequence of CB switching is analyzed and a final confirmation of the CB status is confirmed [11].

The portion of the algorithm that is not shown in Figure 3, and which is needed, is associated with the verification of the overall substation switching state after the switching state of each breaker is known. This step is rather trivial and requires an update of the overall substation database that contains both the substation topology and associated states of each breaker.

C. *Simulation environment*

Figure 4 shows simulation environment in which DFR, CBM and DPR oscilography files, for breaker-and-a-half substation configuration can be simulated. Using this simulation environment, different test cases can be simulated. A number of tests will be conducted in the future to verify various performance aspects of the proposed solution.

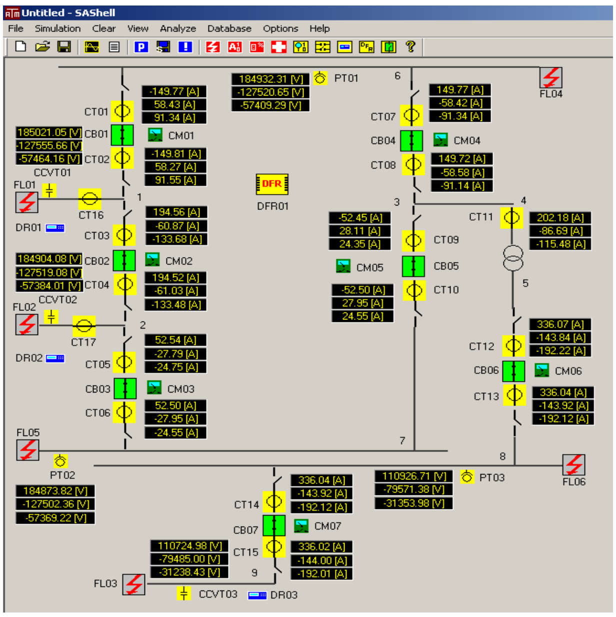

Figure 4. Simulation environment

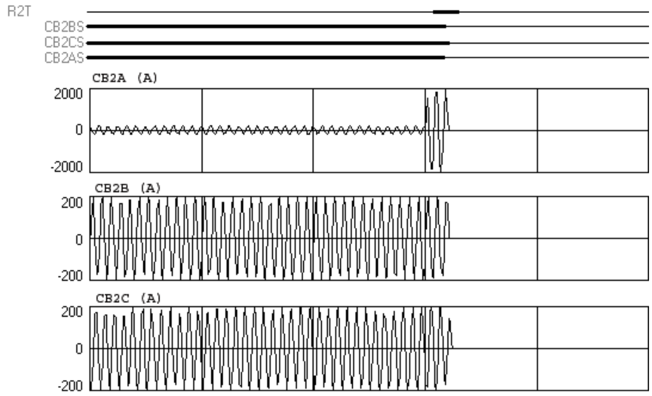

Figure 5. Simulated waveforms and signals

A signal processing module is designed to extract features from the waveforms and evaluate operation of the circuit breakers. From the waveforms that represent current value and relay trip signal and breaker status signal, captured by DFR, the signal processing module can conclude, following the algorithm, that circuit breaker 2 was opened after the event (Figure 5).

V. IMPLEMENTATION ISSUES

To be able to implement this concept, several important practical issues need to be resolved, of which we briefly discuss the following two:

- Substation database intelligent processing for the extraction of "right" information [12], and,
- Interfacing between SCADA and substation IEDs using the standards IEC 61850 [13] and IEC 61970 [14].

A. *Substation database intelligent processing*

The problem of creating the necessary database is schematically illustrated in Figure 6.

From Figure 6, it appears that the IED data can be collected in a common substation database, processed to achieve the desired compatibility among different data formats and recording features of the involved IEDs, and then used to extract required information for different uses. Figure 6 also illustrates that the extracted information, including the results of the improved topology processing, may be made available to different kinds of applications, intended for different kinds of users in a utility organization, for both real-time operation functions (e.g., substation operators in a manned substation, controls centre operators) and different back-office users (protection engineers, maintenance engineers, planners, asset managers, etc.).

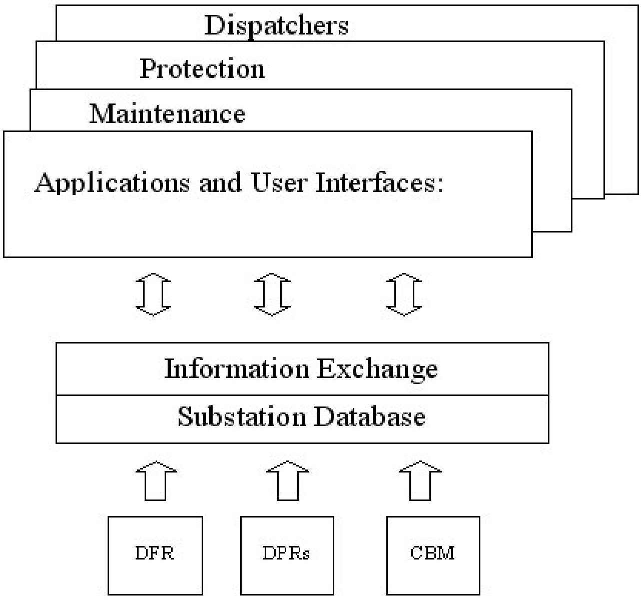

Figure 6. Substation database integration

B. *Data integration using IEC standards*

The results of the improved topology processing provide the highest benefit in the context of applications used to support the real-time operation of the power system. A simplified communications architecture of the control systems in substations and control centers is shown in Figure 7. This is the context (real-time operation) in which IEC 61850 and IEC 61970 (which are recently adopted international standards for substations and control centers, respectively) can support data exchange in a standardized way. The implementation issue that relates to data interfacing using the two IEC standards is discussed in detail in [15,16]. In particular, several possible integration scenarios are identified, and the possible usage of the data models of the two standards and the way to exchange the data are described. Figure 7 shows an example of the data models for the circuit breaker position, according to the respective IEC standards. Data model mapping between the two standards at the substation equipment level has been reported in [15], as well as different issues encountered during the development of a prototype that supports a semi-automatic conversion between the two data formats.

It can be observed from Figure 7 that, besides providing a substation database, one possible approach may be to bring the data directly to the real-time DB at the EMS level and perform the database integration between SCADA and substation IED data at that level.

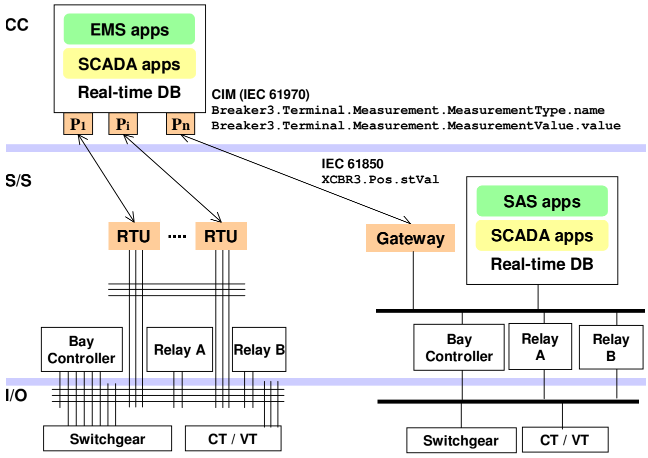

Figure 7. Communications between control centre and substation with an example of data model for circuit breaker position in IEC 61970 and IEC 61850

VI. CONCLUSIONS

In this paper, we have proposed a method for robust topology determination, based on redundant data available from IEDs in a substation. We have also discussed the benefits of such a method for other topology processing applications in the control systems of a utility. Finally, we have briefly mentioned data exchange issues that are to be addressed when incorporating the proposed robust topology processing into the existing control systems.

Several conclusions can be drawn based on the discussions given in the paper:

- Using additional data from substation IEDs can significantly enhance the accuracy and robustness of the SCADA topology processor.
- The implementation database issues need to be carefully evaluated to decide whether substation-based or centralized-based is the best approach.

VII. ACKNOWLEDGEMENTS

The work reported in this paper was funded by ABB Corporate Research Center in Baden-Daettwil, Switzerland.

REFERENCES

[1] M. Kezunovic, and A. Abur, "Data Integration and Information Exchange: Impact on Future Substation and EMS Applications and Related Implementation Requirements", EPRI Technical Report#1010898, May 2004.

[2] T. E. Dy Liacco, "Real-time computer control of power systems", Proc. IEEE, vol. 62, no.7, pp.884-891, July 1974.

[3] U.S.-Canada Power System Outage Task Force," Final report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," April 2004.

[4] M Kezunović, "Data Integration and Information Exchange for Enhanced Control and Protection of Power Systems," *Hawaii International Conference on Systems Science*, Waikoloa Village, HI, January 2003.

[5] M. Kezunovic, A. Abur, A. Edris, D. Šobajic, "Data Integration/Exchange Part I: Future Technical and Business Opportunities," IEEE Power & Energy Magazine pp. 14-19, Mar/April 2004.

[6] M. Kezunovic, A. Abur, A. Edris, D. Šobajic, "Data Integration/Exchange Part II: Future Technical and Business Opportunities," IEEE Power & Energy Magazine pp. 24-29, May/June 2004.
[7] A. Abur, H. Kim and M. Celik, "Identifying the Unknown Circuit Breaker Statuses in Power Networks", *IEEE Transactions on Power Systems*, Vol.10, No.4, November 1995.
[8] M. Kezunovic, "Integrating Data and Sharing Information from Various IEDs to Improve Monitoring, Condition-based Diagnostic, Maintenance, Asset Management, and Operation Tasks", in Proc. EPRI Substation Equipment Disturbance Conf., New Orleans, Louisiana, Feb. 2004.
[9] M. Kezunovic, X. Luo, "Automated Analysis of Protective Relay Data," 18thInternational Conference on Electricity Distribution-CIRED, Turin, Italy, June 2005.
[10] M. Kezunović, G. Latiško, Z. Ren, D. Sevcik, J. Lucey, E. Koch, W. Cook, "Automated Analysis of Circuit Breaker Operation," *17th International Conference on Electricity Distribution – CIRED 2003*, Barcelona, Spain, May 2003.
[11] M. Kezunovic, P. Spasojevic, C. Fromen, D.R. Sevcik, "An Expert System for Transmission Substation Event Analysis," *IEEE Transactions on Power Delivery*, Vol. 8, No. 4, pp 1942-1949, October 1993.
[12] M. Kezunovic, H. Taylor, "New Solutions for Substation Sensing, Signal Processing and Decision Making," Hawaii International Conference on System Sciences HICSS-37, Waikoloa Village, HI, January 2004.
[13] IEC 61850: Communications Networks and Systems in Substations, International Standard, 2003.
[14] IEC 61970: Energy Management System Application Programming Interface (EMS-API), International Standard. Part 301: Common Information Model (CIM) Base, 2003. [Online] Available (model view): http://www.cimuser.com
[15] T. Kostic, C. Frei, O. Preiss, M. Kezunovic, "Scenarios for Data Exchange using Standards IEC 61970 and IEC 61850," presented to the UCA User Group, Cigré 2004, Paris, France, September 2004 ([Online] Available: http://sharepoint.ucausersgroup.org/archives/Paris%2004/Scenarios%20for%20Data%20Exchange%20Paper%20-%20Tanja%20Kostic.pdf).
[16] M. Kezunovic, T Djokic, T. Kostic, "Automated Monitoring and Control Using New Data Paradigm," Proc. of HICSS-38, January 3-6, 2005, Big Island, Hawaii.
[17] T. Kostic, O. Preiss, C. Frei, *Towards the Formal Integration of Two Upcoming Standards: IEC 61970 and IEC 61850*, in Proc. of 2003 LESCOPE Conference, pp. 24-29, May 2003.

M. Kezunovic, T Djokic, T. Kostic, "Robust Topology Determination Based on Additional Substation Data from IEDs", PowerTech 2005, Sankt Petersburg, June 2005.