A New Concept for a Fully Transparent Distribution Management System

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***Abstract*— Ergonomically designed distribution management systems (DMSs) become more important as distribution grid operators and municipal utilities are assigned with new complex tasks and more stringent requirements. A state-of-the-art survey carried out of existing DMS revealed considerable innovation potential. This paper will present a new concept how a DMS can be designed completely transparent.**

***Index Terms*— Distribution management system, distribution grid, human operator, transparent data architecture.**

I. INTRODUCTION

IN the last sixty years, the continuously increasing demand of electric energy has resulted in more and more widely extended interconnected power grids, which can only be reliably controlled and managed with an appropriate power system control strategy and technology. With the liberalized electricity market, which among other things led to an increased cost pressure, the extensive environmental and legal restrictions and the general resistance to new power plants and high-voltage transmission lines, the power supply companies are assigned to new tasks and have to fulfill partly diverged requirements concerning

- Supply security and reliability
- Quality
- Economy
- Environmental impact

To meet all these requirements, economically planned, sufficiently scaled and environmentally acceptable power grids and power plants are essential. The grid control system with which these electric power systems will be controlled is almost as important. In fact, the power system control technology becomes more important as the power supply companies have to satisfy stringent requirements and are faced with more complex tasks, like explicated in [1].

The importance of an ergonomically designed grid control system was also recognized with the transmission system blackouts of the last years. The analysis of these blackouts confirmed that some transmission control systems were obsolete or not consistently ergonomically designed so they didn't support the human operators as desired. For example, a mistakable visualization of the actual system state was one of three principal reasons causing the system collapse of the SBB power grid on June 22nd 2005, like reported in [2].

The knowledge of the transmission system's importance for a secure and reliable electric power supply caused a transition from traditional supervisory transmission control systems to integrated energy management systems (EMS) in about the last fifteen years. In contrast, slight attention was paid to distribution systems. However, during the last years, more regard has been paid to distribution systems due to several reasons. Like accurately reported in [3], the following ones are important to mention:

- The advent of distributed generation: Distribution grids are no longer purely passive load systems due to installed small hydro power plants, cogeneration plants, photovoltaic plants or wind power plants. Hence, their operation becomes more complex.
- Changes of the possible topology: Additional cables, circuit breakers and load switches or even distribution substations have to be connected with the existing distribution grid when new loads have to be supplied. According to [3], changes of the possible topology are more frequent in distribution systems than in transmission systems.

The above mentioned reasons also indicate the importance of modern distribution control systems. During these recent years, in which distribution grids were focussed, their control systems migrated from rather traditional supervisory distribution control systems to integrated distribution management systems (DMS).

This paper is organized as follows. Section II emphasizes the importance of an ergonomically designed DMS. The results of a carried out state-of-the-art survey are described in Section III. Section IV covers criteria for a transparent data architecture. In Section V the new concept for a fully transparent DMS is presented by introducing the so called transparency matrix. The final Section VI contains the conclusions. A subsequent appendix explains the mathematical background of the presented transparency matrix.

II. IMPORTANCE OF ERGONOMICALLY DESIGNED DMS

To date, there exists no grid control system which could control the operation of an electric power system completely automatically. The human operator decides on many of the significant matters: Based on the received information from the control system and with his technical knowledge and working experience, he determines what has to be done or not. Therefore, the operator ”closes” the so called supervisory control loop, respectively he is very much ”in the loop”. As a consequence, EMSs and DMSs have to take the cognitive abilities in reception and processing of sensory stimuli of human beings into account.

This work has been supported by Rittmeyer AG Switzerland.

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III. STATE-OF-THE-ART OF DMS

A state-of-the-art survey of existing DMS has been carried out by the authors. Especially, well-known on the market available DMS have been analyzed by product trainings, demos, brochures, fact sheets or booklets.

The results of the state-of-the-art survey showed that functions of modern DMS generally can be divided into two main groups:

- Base system functions
- Applications

The former fulfill the basic requirements of the control system like interacting with the distribution system. The latter serve to support the human operator and to carry out extended tasks of the control system. In the following, base system functions and applications which can be found in state-of-the-art DMS are briefly described.

A. Base System Functions

According to [4], base system functions on their part can be divided into two subgroups:

- Supervisory control and data acquisition (SCADA)
- Control room operations management (CROM)

SCADA functions provide real-time monitoring and control of the distribution network, for example by making set point changes on distant local controllers, opening or closing switches, monitoring alarms or gathering measurement information.

CROM functions contain all facilities provided to the human operator in the control room. Therefore, most of the CROM functions have to be strictly ergonomically designed, like for instance the human machine interface (HMI) or the control room graphics system (CRGS).

Since in modern distribution management systems SCADA functions and CROM functions are closely integrated, base system functions are often just referred to as SCADA or enhanced SCADA functions.

B. Applications

The second main group contains the application-oriented calculation tools which serve to support and to aid the human operator. Whereas SCADA and CROM functions are similar or even identical in remote supervisory control systems for different applications like water supply, wastewater treatment, gas or electricity, the functions of the second group strongly depend on the application or rather on the process to be supervised. As accurately described in [4], applications can be divided into different modules, for instance in

- Advanced applications (ADVAPPS)
- Outage management system (OMS)
- Trouble call management (TCM)

Unfortunately, the collectivity of all applications is sometimes called DMS. But this is not really accurate, since applications alone don't constitute an independent control system. *Distribution management functions* would be the better denomination.

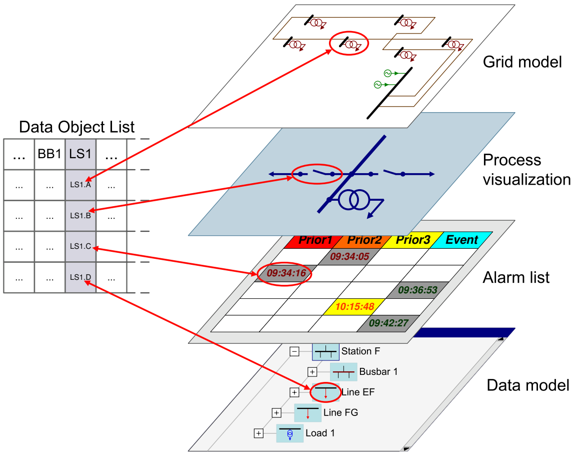


Fig. 1. Data architecture of a transparent distribution management system.

C. Possible Improvements of State-of-the-Art DMS

Based on the carried out state-of-the-art survey the authors believe that there is a need for a fully integrated DMS with a transparent data architecture. State-of-the-art DMS are almost exclusively custom-made solutions. They require a high degree of project implementation work which could strongly affect the quality of the finished systems. At present, the following tasks are part of the implementation work:

- Linking data objects and graphical elements
- Assigning data to reports
- Connecting substations's process variables and data objects of the control system

This type of work is often error-prone and has to be redone after every small configuration change. Thus, configuration changes are cumbersome and time-consuming.

IV. FULLY TRANSPARENT DATA ARCHITECTURE

In order to avoid the shortcomings mentioned in the previous section, the aim is to develop a future DMS with a fully transparent data architecture. Such a distribution control system with a complete transparent data structure allows the adaption to the specific costumer installation with minimal effort and under guaranty of maximal consistency. Thus, errors done by project implementation work or by commissioning can be avoided as far as possible.

Basis of a transparent system architecture has to be a standardized and object-oriented design. Independent of the specific composition of the costumer installation, there should be an attempt to provide a comprehensive library with standard objects. These data objects consequently orientate by real objects of the plant and assure a long-term robust modelling.

Like pictured in Fig. 1, not only a data model belongs to a data object, but also

- Visualization elements
- Operating elements
- Alarm elements
- Log and archiving elements
- Grid model

Based on the grid model, advanced applications like load flow calculations, short-circuit calculations or even outage management functions can be executed. Whether a new object is built or an existing one is deleted, the system consistency should always be guaranteed. Due to the object-oriented architecture, data objects of the library can be adapted to the local structural conditions without endangering the system's consistency at any time.

A. *Criteria for a Transparent Data Architecture*

Before developing the concept for a transparent data architecture, criteria for transparency have to be derived. The concept to be developed will then have to reflect these derived transparency criteria. Careful considerations about how transparency can be judged yield the six following criteria:

1. *Unique data file*
   Basic requirement of every transparent data architecture is the existence of a unique data file or a unique data base. This unique file or unique data base contains all data objects with all their attributes. There should be no other data file or data base having stored information of data objects. Therefore, the unique data file has to contain topological and structural data as well as graphical and geographical data. Besides, it should store event lists, alarm lists and log book information, type, component and element information.
2. *Consistency*
   One of the most important transparency criteria is data consistency: Updates done in one program should update all other views or programs automatically.
3. *Expandability*
   Since a power grid can be enlarged by introducing new substations or lines, it is important that the data base or data file can be easily expanded at any time.
4. *Filterability*
   On the other hand the concept of an unique data file requires that the file or data base is filterable so that every program can read out just the data it needs.
5. *Flexibility*
   Another important criterion is flexibility in the sense that the control system can easily be adapted to the specific costumer installation. Therefore, a library with standardized functions will be needed. Most of the applications should then be independent of costumer installations and the adaptation to a specific costumer installation or an unusual composition should be easy.
6. *Interoperability*
   Information between data objects is often exchanged. For instance, for topological interlocking tests it is necessary that state information of switches being in relation to each other can be exchanged. Hence, information should be exchanged directly without complicated message functions.

V. THE TRANSPARENCY MATRIX

The study of Fig. 1 gave the authors the idea of introducing the so called transparency matrix: All data objects are stored in a matrix where each data object of the distribution control system is placed in one column of this matrix. In every element of the column, one attribute of the data object is stored. To unambiguously address all data objects and their attributes, the first column comprises the name of the attributes and the first row comprises the identifier of the data objects as pictured in Fig. 3.

A. *Structure of the Transparency Matrix*

To describe the structure of the transparency matrix in detail, the distribution grid pictured in Fig. 2 is taken as an example: It contains the medium voltage (MV) source substation and six distribution substations connected by seven lines. Each distribution substation holds a distribution transformer connected with loads on the low voltage level. The transparency matrix mapped in Fig. 3 stores all data objects of the MV source substation and the three distribution substations laying within the dark-red dashed frame of Fig. 2.

The most important part of the transparency matrix is the block matrix in the upper part highlighted with a red frame: This block matrix is an incidence matrix, which has to represent the grid model or rather the grid topology in a manner it can later be used for load flow or topological calculations. In its rows the incidence matrix contains the nodes of the distribution network. Therefore, busbars, which are the real nodes of the power grid, are presented twice in the transparency matrix:

- Once as a data object with all its attributes stored in a transparency matrix column
- and once as a grid node in a row of the incidence matrix.

This could be verified by inspection of the transparency matrix shown in Fig. 3. Besides the grid nodes, the incidence matrix contains so called partition nodes in its rows. For their mathematical derivation the interested reader is referred to appendix I.

B. *Managing Topologies with the Transparency Matrix*

Each interconnected power grid has a limited, but large number of possible connections. The collectivity of all possible connections is referred to as *possible topology*. In a given operation state, only a subset of the possible connections are in use since the usage of *all* possible connections would not be reasonable. The topology resulting of the used connections at a particular time is the so called *actual topology*. In distribution grids, one goal of power system management and control is to maintain a certain grid topology over longer periods of time. Only during disturbances or maintenance work another topology is in use and directly after their correction respectively their completion the switchable connections are switched back to the specific grid topology, the so called *regular topology*.

Since according to [5], the DMS has to manage all these three topologies, the transparency matrix has to express which

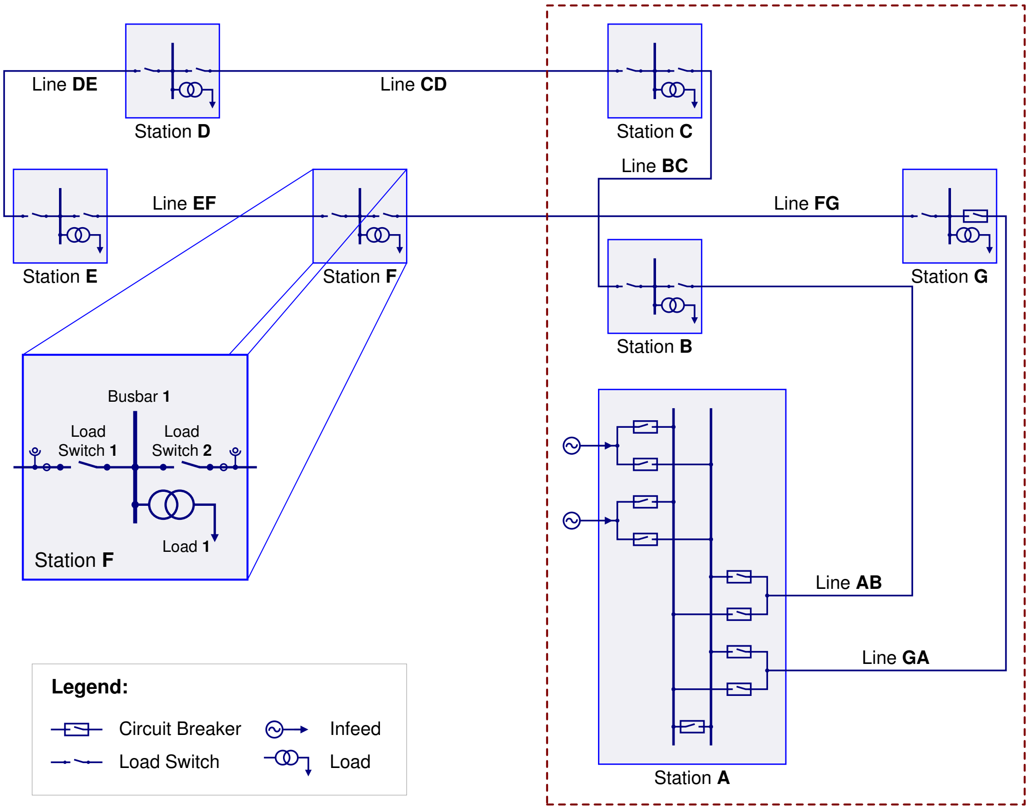
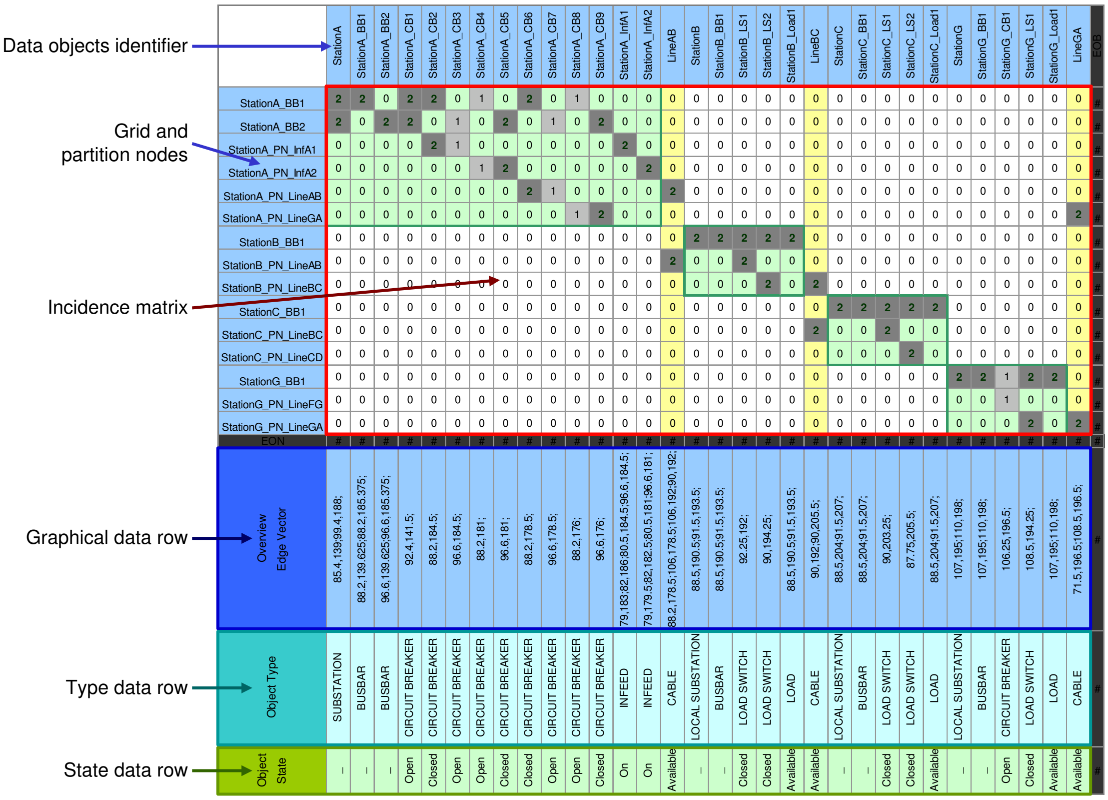
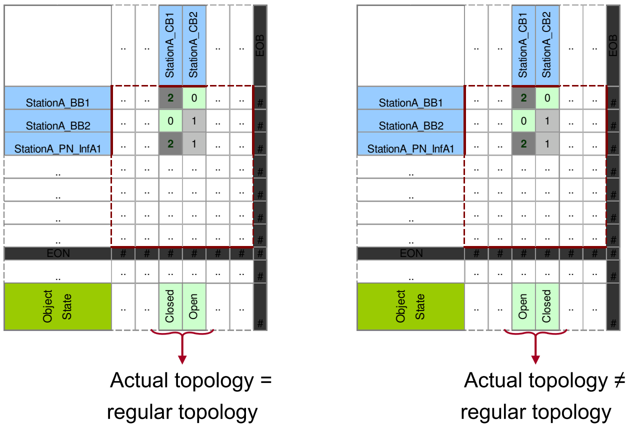


Fig. 2. The test distribution grid with seven substations and seven lines.



	StationA	StationA_BB1	StationA_BB2	StationA_CB1	StationA_CB2	StationA_CB3	StationA_CB4	StationA_CB5	StationA_CB6	StationA_CB7	StationA_CB8	StationA_CB9	StationA_InfA1	StationA_InfA2	LineAB	StationB	StationB_BB1	StationB_LS1	StationB_LS2	StationB_Load1	LineBC	StationC	StationC_BB1	StationC_LS1	StationC_LS2	StationC_Load1	StationG	StationG_BB1	StationG_CB1	StationG_LS1	StationG_Load1	LineGA	EOB
StationA_BB1	2	2	0	2	2	0	1	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	#
StationA_BB2	2	0	2	2	0	1	0	2	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	#
StationA_PN_InfA1	0	0	0	0	2	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	#
StationA_PN_InfA2	0	0	0	0	0	0	1	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	#
StationA_PN_LineAB	0	0	0	0	0	0	0	0	2	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	#
StationA_PN_LineGA	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	#
StationB_BB1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	#
StationB_PN_LineAB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	#
StationB_PN_LineBC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	#
StationC_BB1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	0	0	0	0	0	0	#
StationC_PN_LineBC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	#
StationC_PN_LineCD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	#
StationG_BB1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	1	2	2	0	#
StationG_PN_LineFG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	#
StationG_PN_LineGA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	#
EON	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#
Overview Edge Vector	85.4,139;99.4,188;	88.2,139.625;88.2,185.375;	96.6,139.625;96.6,185.375;	92.4,141.5;	88.2,184.5;	96.6,184.5;	88.2,181;	96.6,181;	88.2,178.5;	96.6,178.5;	88.2,176;	96.6,176;	79,183;82,186;80.5,184.5;96.6,184.5;	79,179.5;82,182.5;80.5,181;96.6,181;	88.2,178.5;106,178.5;106,192;90,192;	88.5,190.5;91.5,193.5;	88.5,190.5;91.5,193.5;	92.25,192;	90,194.25;	88.5,190.5;91.5,193.5;	90,192;90,205.5;	88.5,204;91.5,207;	88.5,204;91.5,207;	90,203.25;	87.75,205.5;	88.5,204;91.5,207;	107,195;110,198;	107,195;110,198;	106.25,196.5;	108.5,194.25;	107,195;110,198;	71.5,196.5;108.5,196.5;	#
Object Type	SUBSTATION	BUSBAR	BUSBAR	CIRCUIT BREAKER	CIRCUIT BREAKER	CIRCUIT BREAKER	CIRCUIT BREAKER	CIRCUIT BREAKER	CIRCUIT BREAKER	CIRCUIT BREAKER	CIRCUIT BREAKER	CIRCUIT BREAKER	INFEED	INFEED	CABLE	LOCAL SUBSTATION	BUSBAR	LOAD SWITCH	LOAD SWITCH	LOAD	CABLE	LOCAL SUBSTATION	BUSBAR	LOAD SWITCH	LOAD SWITCH	LOAD	LOCAL SUBSTATION	BUSBAR	CIRCUIT BREAKER	LOAD SWITCH	LOAD	CABLE	#
Object State	–	–	–	Open	Closed	Open	Open	Closed	Closed	Open	Open	Closed	On	On	Available	–	–	Closed	Closed	Available	Available	–	–	Closed	Closed	Available	–	–	Open	Closed	Available	Available	#

Fig. 3. Transparency matrix of part of the test distribution grid which is surrounded with a dark-red dashed frame.



a) b)

Fig. 4. a) The actual topology is the same as the regular topology due to the switch states. b) The actual topology differs from the regular topology due to the actual switch states.

node and which branch are incident, but also if their incidence is actual, regular or just possible. The possible and regular topology can be stored in the incidence matrix by using numbers 0 to 2. The value of an incidence matrix element $[i, j]$ is defined as follows:

0: node i and branch j are **never** incident.

1: node i and branch j are incident in the *possible topology*:

> There is a possible connection between node i and branch j.

2: node i and branch j are incident in the *possible* and *regular topology*:

> There is a possible and in regular situations used connection between node i and branch j.

For the determination of the actual topology, the DMS has to consider all switch states. It is assumed that the switch states are stored and updated in the state data row of the transparency matrix. Hence, the topology determination algorithm needs to check the state data row like diagramed in Fig. 4: The state of a specific switchable device has to be checked if its data object column contains a **1** or **2** in the incidence matrix.

For example, the switch state **Closed** together with a **2** in the incidence matrix means that the concerning switch is in its *regular state* like sketched in Fig. 4 a).

Contrary, the switch state **Open** together with a **2** in the incidence matrix means that the concerning switch is not in its *regular state*. As consequence, the *actual topology* of the distribution grid differs from its *regular topology*. This situation is pictured in Fig. 4 b).

C. The Transparency Matrix's Benefits

The main benefit of the transparency matrix is that it fulfills all initially derived transparency criteria:

1. *Unique data file*
   The transparency matrix can be stored in a unique data file or be mapped on a unique data base: The transparency matrix contains all data objects with all their attributes. First of all, it comprises topological data as well as graphical data. In addition, it can store event lists or log book information. Hence, there is no need for another data file or data base having stored data object information.
2. *Consistency*
   The transparency matrix forces data consistency: Each program or view uploads its needed information from the transparency matrix. Changes generated in one program are saved back to the transparency matrix. Therefore, all other programs or views are updated automatically when uploading their required information from the transparency matrix.
3. *Expandability*
   The transparency matrix is expandable: A new data object can be added by inserting a new column. New attributes can be added to the control system by inserting a new row in the transparency matrix.
4. *Filterability*
   The transparency matrix is easily filterable: Columns of not needed data objects or rows of not needed attributes can just be ignored.
5. *Flexibility*
   The transparency matrix is flexible. It can handle standardized types and functions as well as costumer-specific ones. If needed, another row containing a special costumer-specific attribute can be inserted in the transparency matrix.
6. *Interoperability*
   The transparency matrix easily enables interoperability. Information can be exchanged directly between the data objects.

Besides fulfilling all transparency criteria, the transparency matrix has further beneficial features:

– The manner how the grid topology is connected with the data objects makes the transparency matrix a promising concept.
– The transparency matrix is easy to understand and can be read like a map.
– The transparency matrix or rather the special form of the incidence matrix allows the control system to manage the different topologies in an efficient way.
– Similarities between different data objects are well apparent in the transparency matrix, namely in the row containing the concerning attribute.

VI. CONCLUSIONS

In this paper, a concept for a fully transparent DMS has been presented. Although the transparency matrix is more a model than a real software solution to store object data, it is an important concept. The final software implementation of the transparency matrix will eventually be done in a data base.

The presented transparency matrix can be used as basis for application-oriented algorithms. For instance, the transparency matrix's filterability allows to derive a condensed matrix from it. The latter presents the actual topology of the distribution grid in a condensed form: Only lines and busbars which are in use will be considered. Hence, this condensed matrix is an ideal grid model for load flow calculations.

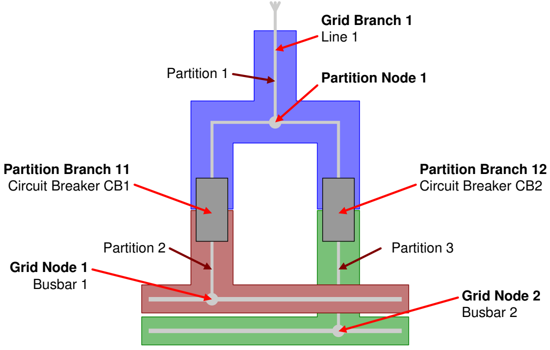


Fig. 5. Partition nodes and branches of a double busbar with an infeed with two circuit breakers.

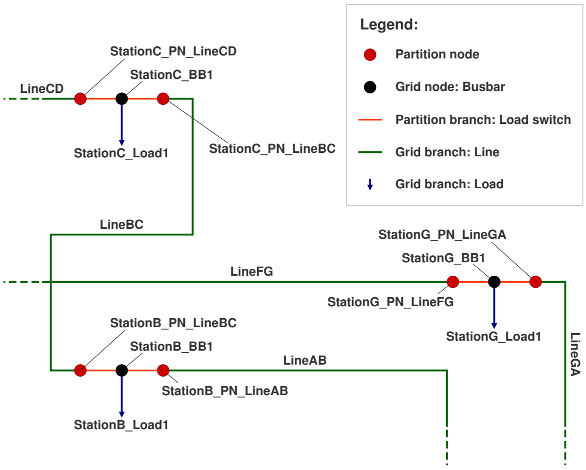


Fig. 6. Mathematical view of three local stations of the test distribution grid. Besides grid nodes and grid branches, this view contains partition nodes and partition branches.

APPENDIX I
PARTITIONS BRANCHES AND PARTITION NODES

Grid branches and grid nodes[1] are almost never fix connected to each other: As shown in Fig. 5, grid nodes, e.g. busbars, and grid branches, e.g. lines, are connected or disconnected over switching devices, e.g. circuit breakers. The actual state of such a switchable device defines which grid node is connected to which line. Hence, there is a need for introducing a sort of branches and nodes between the grid nodes and grid branches so that all possible switch states, that means all states in which the power grid can be found, can be mapped on the resulting mathematical graph structure.

From a mathematical point of view, switching devices are like *active* branches. That's why for every switching device of the power grid a so called *partition branch* has to be introduced. Since branches are always connected by nodes, so called *partition nodes* have to be introduced between partition branches adjacent to a grid branch or between two adjacent partition branches. Fig. 6 shows the mathematical graph structure of a part of the test distribution grid resulting when the partition branches and the partition nodes are introduced. This view of the power grid is called the mathematical view.

Summarized, the following properties are valid for partition branches respectively partition nodes:

Partition Branches:

- Are connectable branches (mathematical view)
- Are real active grid elements or rather switching devices like
  - Circuit breakers
  - Load switches
- Belong to two different partitions
- Can have a voltage across themselves

Partitions Nodes:

- Are nodes connecting partition branches (mathematical view)
- Are real junctions between switching devices
- Are neither grid components nor grid elements
- Belong to just one partition
- Have one electric potential

As already shown in Fig. 3, the introduced partition nodes appear in the incidence matrix like normal grid nodes. The only difference is that a partition node only appears in a row and doesn't appear in a column of the transparency matrix. The cause therefor is that a partition node is just a mathematical object and not a real existing data object.

The reason why these introduced branches and nodes are named partition branches respectively partition nodes becomes obvious when studying Fig. 5: For a double busbar with an infeed, the different partitions are highlighted with colors. Partitions are location and voltage dependent parts of grid components like explained in [1]. Together with the charted partition nodes and partition branches it becomes evident that different partitions are separated by partition branches and that every partition contains one node. Therefore, the given names partition branches and partition nodes are reasonable.

ACKNOWLEDGMENT

The authors want to thank Bernhard Müller, Christoph Bücheler, Mathias Hartmann and Gerhard Nigg of Rittmeyer AG for valuable and stimulating discussions.

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[1] For a detailed definition of grid branches, grid nodes, partitions and grid elements the reader is referred to [1]