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Bus Split Contingency Analysis Implementation in the NetVision DAM EMS

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***Summary* — Implementation of the bus coupler outage scenarios, commonly known as bus splitting, in the NetVision DAM energy management system (EMS) contingency analysis is presented in this paper. In order to identify the bus coupler branches in the network model, the existing topology processor was upgraded. The description of the topological algorithm for detection of the bus couplers is given. Based on the topology analysis results, calculation subnodes are created. Calculation model was modified in order to include the bus couplers and the subnodes as the new calculation objects. These modifications are fundamental for the introduction of the bus coupler outages in the contingency analysis. Implications of the bus coupler outages on the load flow mathematical model are discussed. Implemented NetVision DAM solution for the analysis of such outage scenarios is presented.**

***Keywords* — power system, contingency analysis N-1, bus coupler outage, bus splitting**

I. Introduction

Reliable security assessment is one of the most important tasks in the power system control and planning. Such security assessments are most often based on the results of the contingency analysis calculations for the power system stationary state. The main objective is the identification of outages which could cause the violation of the power system operational constraints. Most often the N-1 criterion, in which only the single element outages are analysed, is used. However, in certain cases multiple outages are also taken into account (N-k criterion), especially the case of simultaneous outage of two power system objects (N-2 criterion).

Contingency analysis is based on the sequential load flow calculations for the pre-defined outage scenarios. Generally, such scenarios include outages of the overhead transmission lines, high-voltage power cables, transformers, synchronous generators and compensation devices. On the other hand, outages of elements that are not explicitly and unambiguously represented in the commonly used bus-branch power system calculation model, such as the bus coupler circuit breakers, are analysed to a much lesser extent.

The inclusion of the bus coupler outages, also commonly known as the bus splitting events, in the contingency analysis is becoming more and more important, due to the increasingly frequent circuit breakers misoperations [1], [2] or malicious cyberattacks [3] – [7]. The bus coupler circuit breakers states determine the topological interpretation of the switchgear, and therefore the overall mathematical (calculation) model of the power system [8]. The node-breaker representation includes detailed modelling of all the substation components. The bus couplers are usually modelled as (near) zero impedance lines [9] - [11], and their implementation in the contingency analysis is similar to the line outage calculations. However, the node-breaker model typically involves sparse matrices of much larger dimensions due to the significant increase in the number of the nodes [12]. The bus-branch model, on the other hand, lacks the detailed substation information, and cannot directly include the bus split event in the contingency analysis [12]. However, because of its simplicity and efficiency, it is still a most commonly used EMS model.

Additionally, the bus-branch model can be modified in order to implement the bus coupler circuit breaker switching actions. The bus coupler outage scenario has a specific impact on the mathematical interpretation of the transmission grid topology state (i.e. bus admittance matrix), considering it requires the change in the number of the bus-breaker model calculation nodes. Therefore, the analysis of such scenarios requires the application of different mathematical models, in comparison with the conventional outages, i.e. outages of elements such as the transmission lines or the transformers.

Modifications of the topological processor are required in order to enable the detection of the active bus couplers, i.e. active circuit breakers which represent the connection between the two active busbars. If such bus coupler is detected within the station voltage level, new subnodes are created and assigned to the corresponding calculation node. These subnodes represent only the potential calculation nodes which, in the case of the bus coupler outage, become real, and are used as such in the contingency analysis calculations.

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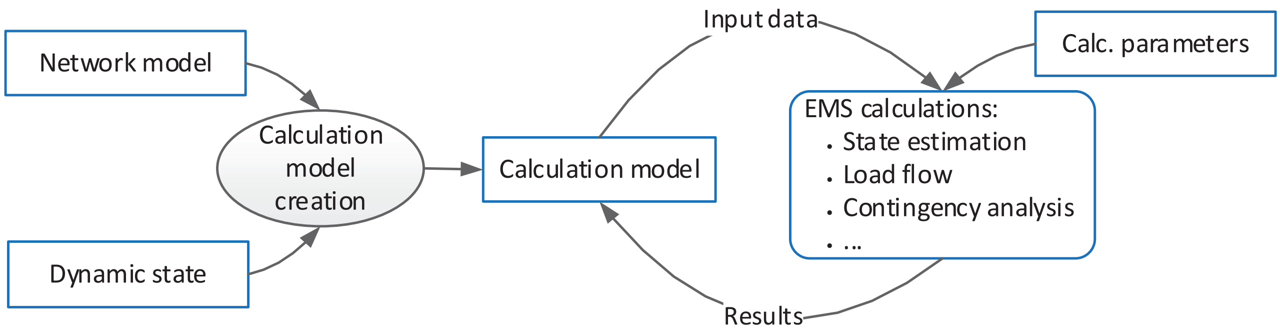

Fig. 1. Basic architecture of the NetVision DAM EMS

II. Power system modelling

All calculations in the NetVision DAM EMS are based on the so-called calculation model, which basically represents the mathematical bus-branch interpretation of a single power system stationary state [13], [14]. The fundamental architecture of such model is very simple, as it consists solely of calculation nodes and branches. Calculation nodes represent mathematical equivalents of the parts of the network which have the same electrical potential. Typically, a node represents a substation of a certain nominal voltage which includes a group of interconnected sections and fields with the substation objects such as busbars, breakers, disconnectors, etc. Nodes are interconnected by branches. Branches represent power system objects such as the transmission lines, the transformers and the high voltage power cables. Other power system elements, such as the shunt compensation devices or the fixed impedance loads, are also modelled as branches, incident with a single node and the ground.

NetVision DAM calculation model is created using the two data sources: the network model, and the dynamic data (Fig. 1). The network model is a detailed, hierarchical and topologically organized representation of all existing power system elements. In comparison with the calculation model, it contains significantly larger data set. As such, it is generally unsuitable for the direct use in the calculations. Therefore, it represents a main source of fixed data (parameters) required for the creation of the calculation model objects. The dynamic state includes all the real process data, measurements and signals collected from the transmission grid using the SCADA system. The working topology of the analysed grid is created using the topology processor, based on the collected breaker and the disconnector states. Topology is created using the depth first search (DFS) algorithm, firstly on the substation level, and then the network level. After the topology is created, the SCADA measurements are preprocessed and joined with the corresponding calculation model objects. Finally, they are used for the creation of the input data vectors for the EMS calculations. Therefore, the calculation model is completely defined by the three data groups: the topological state, the fixed parameters of the power system elements, and the input data measurements.

III. Bus coupler identification

The result of the topological analysis is a graph model, which is a mathematical model consisting of nodes and branches. Each branch connects two nodes, and can be classified as oriented or non-oriented. The graph model and the standard graph algorithms have been upgraded for the needs of the transmission grid modelling and analysis. The basis for all the graph analysis in the NetVision DAM is the DFS algorithm, which, in its fundamental form, detects the connected graph parts, that is the connectivity components [16], [17]. The connectivity components are the sets of the connected graph nodes, which are used to create the dynamic model nodes. Modified algorithm detects bridges, separation nodes, blocks containing loops, connecting paths, etc.

From each substation voltage level, a corresponding graph is formed, in which the circuit breakers and the disconnectors represent branches connecting the graph nodes (external nodes, grounding, buses, etc.). Unlike the station topology, the network topology is defined by the graph in which the branches represent the transmission lines, high-voltage cables and transformers incident with the external station nodes. Other objects, such as the generators, loads and shunt compensators, are also connected to the external station nodes.

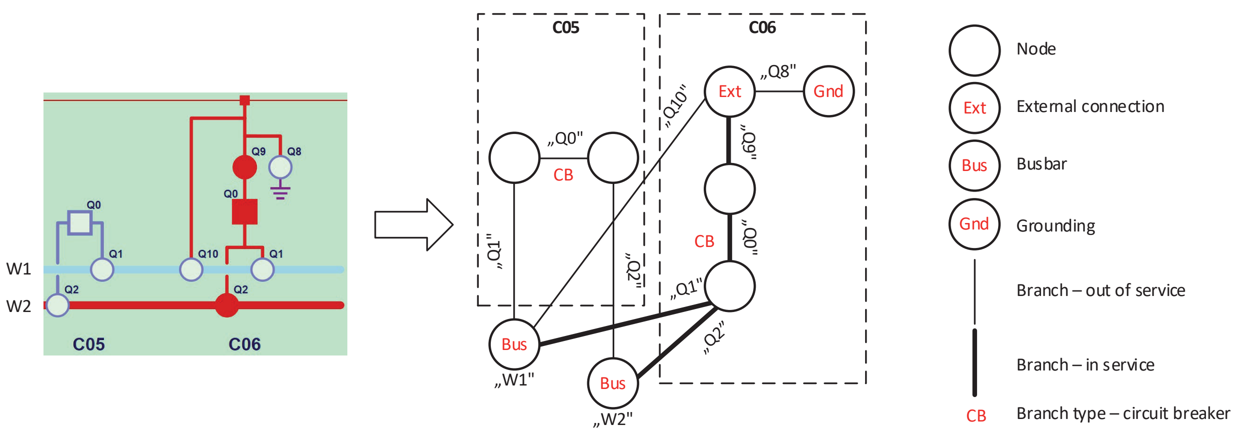

Fig. 2. Section of a single-line station scheme and the corresponding graph

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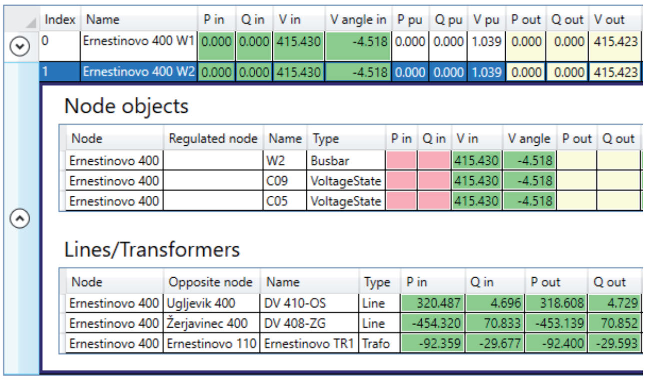


Fig. 3. Calculation subnodes for Ernestinovo 400 kV calculation node

NetVision DAM topology processor has been upgraded in order to detect the bus coupler paths within the substation graph. The modified DFS algorithm can be described in two steps:

1. Connection paths from each external connection point to busbars are detected. Branches leading from the external connection points to the busbars are marked as potential bus coupler paths.
2. Using the marked paths (step 1), connection paths from each busbar to another are detected. If a path includes a circuit breaker branch, it is declared a bus coupler.

First step is necessary in order to detect paths which represent disconnectors within bays which are not used as bus couplers.

After the DFS algorithm detects the connection components within the substation graph, additional analysis is used for defining the calculation subnodes which are connected by the bus coupler. Each calculation node with detected bus coupler has at least two calculation subnodes.

IV. NetVision DAM contingency analysis

Contingency analysis calculation (N-1/N-2/N-k) is defined as a sequence of load flow calculations for predefined outages of a single or multiple elements which may endanger the operational security of a power system. Taking into account that the number of such outage scenarios can be very large, the speed of response can be considered as another important criterion, in addition to the accuracy, for the assessment of the quality of the contingency analysis calculations. Therefore, the conventional load flow algorithms, such as the Newton-Raphson or the Gauss-Seidel, should not be used for such task. In order to satisfy both conditions, modified versions of the conventional methods are used, in which the reduction of the execution time is achieved at the expense of minimal accuracy loss. Most often, the fast decoupled load flow (FDLF) is used [17].

FDLF is based on several effective simplifications of the standard Newton-Raphson algorithm, where the differences in the models are mostly manifested in the way the Jacobi (sub)matrices are calculated [18], [19]. In the FDLF algorithm, the Jacobi matrix is calculated only once, at the beginning of the iterative calculation. With the assumption of the weak coupling between the active power and the voltage magnitudes, on the one hand, and the reactive power and the voltage angle on the other, Jacobi submatrices J2 ($\partial P/\partial V$) and J3 ($\partial Q/\partial \delta$) are ignored. In this way the basic load flow system of equations can be separated into two independent systems. This assumption derives from several characteristics of the high-voltage transmission grid. Firstly, the phase angle differences between two adjacent nodes are very small ($\cos(\delta_i - \delta_j) \approx 1$). Secondly, the resistance and the reactance ratio (r/x), and the conductance and the susceptance ratio (g/b), are also relatively small ($r/x = g/b \ll 1$). Additional assumption is that the $G_{ij} \sin(\delta_i - \delta_j) \ll B_{ij}$ and the $Q_i \ll B_{ii} V_i^2$. While calculating the voltage angles the voltage magnitudes are usually set to the value of 1.0 p.u. Also, the ratios of the phase shifting transformers are ignored while calculating the voltage magnitudes. The basic mathematical model that follows from the above assumptions is given by the following equations:

$$B' \cdot \Delta\delta = \Delta P / V \tag{1}$$

$$B'' \cdot \Delta V = \Delta Q / V \tag{2}$$

It is important to point out that the Jacobi matrices B' and B" are constant, and are calculated and factorized only once in the calculation (for the conventional outage scenarios).

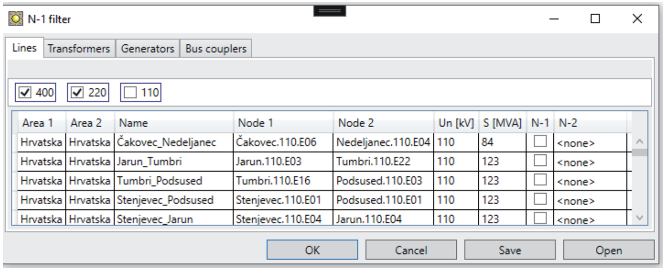


Fig. 4. Defining the N-1/N-2 outage scenarios in the NetVision DAM filter

NetVision DAM contingency analysis is calculated for the predefined N-1 and N-2 outage scenarios using the FDLF algorithm. The outage scenarios are defined using the appropriate contingency analysis filter, similarly for the on-line and the off-line calculations (Fig. 4). Currently, the user can select outages within the four groups of the power system elements: transmission lines and cables, transformers, generators and bus couplers. The filter list contains all the existing transmission grid objects and is created from the network model. Therefore, it does not depend on the analysed dynamic state. Selected objects which are not active in the analysed dynamic state are skipped within the contingency analysis. The same applies for the elements for which it is not possible to obtain the load flow results (i.e. outage of a critical branch separating the grid into two islands).

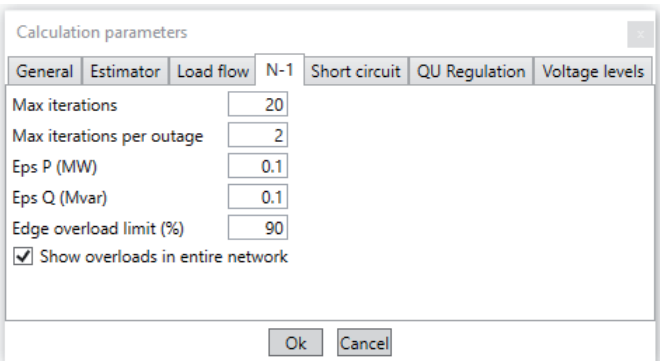
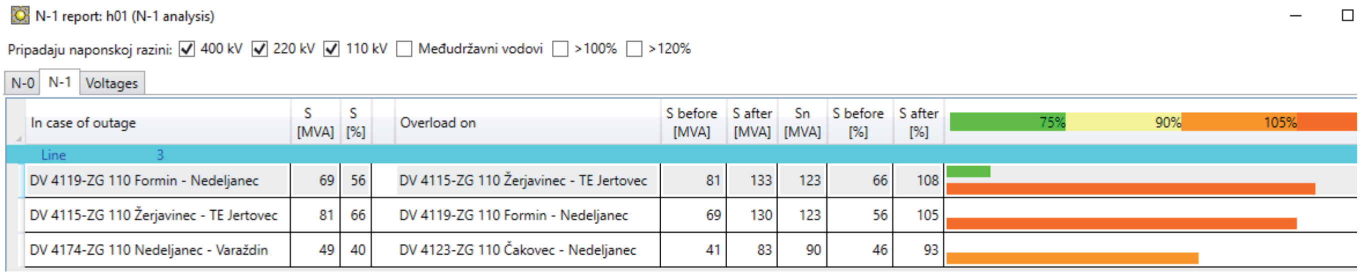


Fig. 5. Contingency analysis parameters in the NetVision DAM

Initial voltage values for each outage are taken from the base state (N-0), while the number of the iterations per outage is limited by the user settings. If the FDLF does not converge within the set



N-1 report: h01 (N-1 analysis)

Pripadaju naponskoj razini: 400 kV 220 kV 110 kV Međudržavni vodovi >100% >120%

N-0 N-1 Voltages

In case of outage	S [MVA]	S [%]	Overload on	S before [MVA]	S after [MVA]	Sn [MVA]	S before [%]	S after [%]	75% 90% 105%
Line 3									
DV 4119-ZG 110 Formin - Nedeljanec	69	56	DV 4115-ZG 110 Žerjavinec - TE Jertovec	81	133	123	66	108	
DV 4115-ZG 110 Žerjavinec - TE Jertovec	81	66	DV 4119-ZG 110 Formin - Nedeljanec	69	130	123	56	105	
DV 4174-ZG 110 Nedeljanec - Varaždin	49	40	DV 4123-ZG 110 Čakovec - Nedeljanec	41	83	90	46	93	

Fig. 6. List of the NetVision DAM N-0/N-1/N-2 alarms

number of iterations, however all the calculated electrical values are within the set boundaries, the calculation continues with the next outage. If some of the values are not within the set boundaries, the calculation continues till the convergence criteria is met. In this way, it is possible to quickly check and eliminate those outages that do not pose a danger to the system.

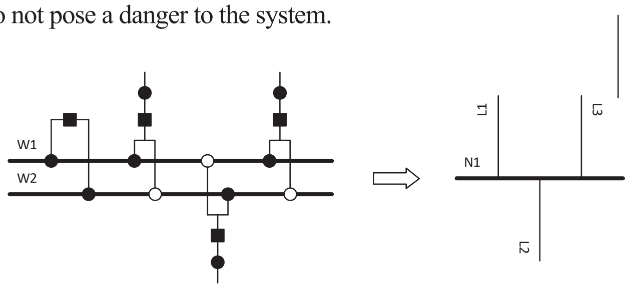


Fig. 7. Topological interpretation of the substation in case of active bus coupler

Calculation results for the outage scenarios in which some of the set constraints are violated are presented in the alarm interface (Fig. 6.). The results include the identification data of the outaged object, the object with the determined constraint violations, including the load flow results before and after the outage.

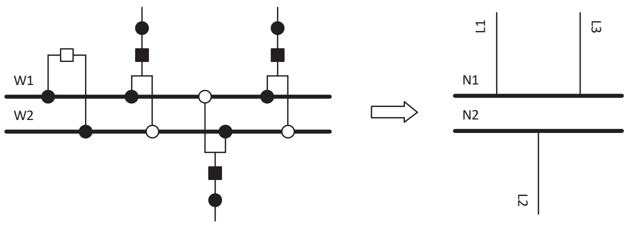


Fig. 8. Topological interpretation of the substation in case of inactive bus coupler

V. Contingency analysis N-1 for bus coupler outages

Bus couplers connect busbar systems in the substation switchgear which have double or multiple busbars. The status of the bus coupler circuit breaker (active/inactive) defines the topological interpretation of the analysed substation state. In case of the active bus coupler (Fig. 7.), the incident busbars W1 and W2 are at the same electric potential, so the result of the topological analysis is only one computational node – N1, incident with three calculation branches L1 – L3.

In case of inactive bus coupler (Fig. 8.), the final result of the topological analysis are two separated calculation nodes – N1 and N2, where N1 is incident with branches L1 and L3, and N2 with branch L2.

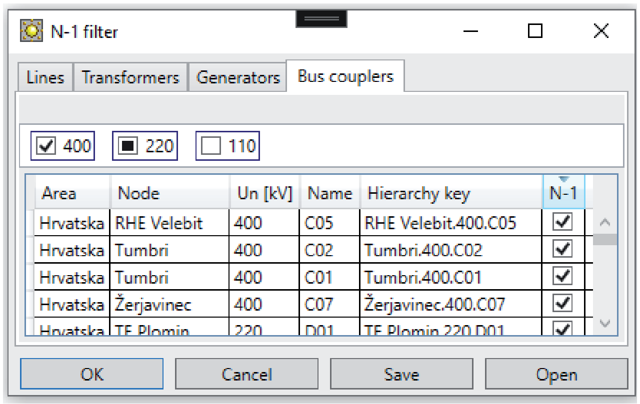


Fig. 9. Defining the NetVision DAM N-1 bus coupler outages

N-1 contingency analysis calculations for the bus coupler outages require a change in the number of the calculation nodes. Therefore, mathematical models are significantly more complex in comparison with other outage scenarios. In addition, standard calculation model does not contain the bus coupler as an independent calculation object, as it is usually an invisible part of the calculation node (Fig. 7.).

Modifications of the NetVision DAM topological processor and the calculation model enabled the identification of the bus couplers and the creation of calculation subnodes. Calculation subnode and the bus coupler data are stored within the extended data of the associated calculation node. In case of a bus coupler outage, the subnodes are transformed from the potential to the real calculation nodes, while the original calculation node is removed from the calculation model. In this way, all the prerequisites for the contingency calculation are provided directly in the calculation model. Bus coupler outages are selected within the filter list, in the same way as all the other N-1 objects (Fig. 9.).

A change in the calculation node list requires a significant modification of the whole calculation model. Considering the implementation issues solely, much simpler approach would be to directly change the dynamic state, i.e. the topology state of the network model, and then create the new calculation model [20], [21]. However, such approach would be burdensome, and would require much longer time of execution. Therefore, it is more acceptable to make such changes directly on the calculation model, by resizing and recalculating (input and output) vectors and matrices Y, B' and B''. Modifications of the vectors and matrices are additionally conditioned by the types of the new nodes (PV, PQ, REF). Modifications of the FDLF model are illustrated by equations (3) and (4).

In case of the bus coupler outage in the node *k* (red), two new nodes (green) are created from the predefined subnodes, and the initial parent node is removed from the model. Initial Jacobi matrices B' and B'' need to be modified and refactored, which is the most demanding and the most time-consuming part of the calculation.

$$B'_{[(n-1)\times(n-1)]}\cdot\begin{bmatrix}\Delta\delta_1\\ \vdots\\ \Delta\delta_k^{(node)}\\ \vdots\\ \Delta\delta_{n-1}\end{bmatrix}=\begin{bmatrix}\frac{\Delta P_1}{V_1}\\ \vdots\\ \frac{\Delta P_k^{(node)}}{V_k^{(node)}}\\ \vdots\\ \frac{\Delta P_{n-1}}{V_{n-1}}\end{bmatrix}\Rightarrow B'_{[n\times n]}\cdot\begin{bmatrix}\Delta\delta_1\\ \vdots\\ \Delta\delta_k^{(subn\ 1)}\\ \Delta\delta_{k+1}^{(subn\ 2)}\\ \vdots\\ \Delta\delta_n\end{bmatrix}=\begin{bmatrix}\frac{\Delta P_1}{V_1}\\ \vdots\\ \frac{\Delta P_k^{(subn\ 1)}}{\Delta V_k^{(subn\ 1)}}\\ \frac{\Delta P_{k+1}^{(subn\ 2)}}{\Delta V_{k+1}^{(subn\ 2)}}\\ \vdots\\ \frac{\Delta P_n}{V_n}\end{bmatrix} \quad (3)$$

$$B''_{[(n-g-1)\times(n-g-1)]}\cdot\begin{bmatrix}\Delta V_1\\ \vdots\\ \Delta V_k^{(node)}\\ \vdots\\ \Delta V_{n-g-1}\end{bmatrix}=\begin{bmatrix}\frac{\Delta Q_1}{V_1}\\ \vdots\\ \frac{\Delta Q_k^{(node)}}{V_k^{(node)}}\\ \vdots\\ \frac{\Delta Q_{n-g-1}}{V_{n-g-1}}\end{bmatrix}\Rightarrow B''_{[(n-g)\times(n-g)]}\cdot\begin{bmatrix}\Delta V_1\\ \vdots\\ \Delta V_k^{(subn\ 1)}\\ \Delta V_{k+1}^{(subn\ 2)}\\ \vdots\\ \Delta V_{n-g}\end{bmatrix}=\begin{bmatrix}\frac{\Delta Q_1}{V_1}\\ \vdots\\ \frac{\Delta Q_k^{(subn\ 1)}}{\Delta V_k^{(subn\ 1)}}\\ \frac{\Delta Q_{k+1}^{(subn\ 2)}}{\Delta V_{k+1}^{(subn\ 2)}}\\ \vdots\\ \frac{\Delta Q_{n-g}}{V_{n-g}}\end{bmatrix} \quad (4)$$

VI. Conclusion

Implementation of the bus coupler outage scenarios in the N-1 contingency analysis requires specific modifications of the calculation model. In order to identify the bus couplers in the network model, the topology processor was upgraded. If the bus couplers have been identified, new calculation objects – subnodes, are created based on the topology analysis results. Subnodes are potential nodes, which transform into real ones when the incident bus coupler is not active. The basic subnode data (i.e. branch and node object incidents) is stored within the calculation node data. In this way, just by modifying the existing calculation model, all the basic prerequisites for the implementation of the bus coupler outages in the contingency analysis N-1 are met. The mathematical analysis of the bus coupler outage scenario requires the modifications of the input matrices and vectors, whereby their dimensions increase due to the increase of the number of the calculation nodes. The need for the refactorization of the Jacobi matrices is the main drawback of this mathematical approach. However, this solution is superior to the alternative in which the calculation model is not modified, but instead created from the scratch, with the status of the analysed bus coupler set to inactive. This approach would require much longer execution time, and as such would therefore be inapplicable.

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