THE IDENTIFICATION OF CRITICAL EQUIPMENT AND OPTIMUM CONFIGURATIONS FOR ELECTRICAL SUBSTATIONS

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ABSTRACT

The reconstruction or revitalization of electrical substations gives the possibility to introduce very powerful new switch gears, and as a result, to simplify the substation circuit diagram. Taking into account these tendencies, the authors propose a systematical method for establishing the optimal structure of electrical substations for increasing the operational level of reliability at the lowest economic cost. The graph theory is used to solve this particular problem. A (multi)graph will be associated to the network under study, where the bus system are taken for nodes, while the power lines and the (auto)transformers are considered as branches. By developing this model, the task of finding the critical equipment is reduced to the determination of (multi)graph critical nodes (articulation points) and critical branches (isthmuses). The paper presents an original method that, using the determination of critical equipment (systems of buses, transformers, power lines), indicates the most appropriate (minimal) structure for electrical substation circuit diagrams.

Index Terms - Electrical Substation, Critical Equipment, Graph Theory, Circuit Diagram

INTRODUCTION

In order to facilitate the reconstruction and revitalisation of distribution substations a methodology for optimisation of the circuit diagram has been developed.

To solve this particular problem, the authors propose the implementation of some methods specific to the graph theory. For this aim, a (multi)graph will be associated with the analyzed network. In the specified (multi)graph the bursars are considered as nodes, while the power lines and (auto)transformers are considered as branches. By realizing this model, the goal of finding the critical equipment is reduced to the determination of (multi)graph critical nodes (articulation points) and critical branches (isthmuses).

This information can be very useful in assessing the reliability of the existing topology as well as in forming strategies for later development of the electrical supply network. Identifying the critical equipment, allows the structure of the circuit diagrams in the substations, or the topology of the entire network, to be re-evaluated (by building new power lines and/or assembling new (auto)transformers which would result in the elimination of the critical nodes and/or of the critical branches in the network). The first issue represents the goal of this paper.

Referring to Table 1, the following terms are specified:

- a node is entirely reserved by using a diagram with two collecting buses;
- the branch connection can be reserved by:
  - (i) diagrams having a circuit breaker per circuit and transfer bus;
  - (ii) more circuit breakers per circuit without transfer bus;
  - (iii) plugging charts without collecting buses (polygonal diagrams).

CRITICAL EQUIPMENT – CRITERIA FOR IMPLEMENTING THE BEST STRUCTURE OF ELECTRICAL SUBSTATIONS

In this paper, the term “equipment” will be used for a bus system, as well as for (auto)transformer or a power line, with all its elements.

For the determination of critical equipment, we associate a graph to the electrical supply network. The following specific terminology used in the paper is according to [6]:

Graph: a finite set of dots called vertices (or nodes) connected by links called branches (or arcs);

Connected graph: a graph is connected if there is a path connecting every pair of vertices;

Critical node (articulation point): a vertex that if removed (along with all branches incident with it) produces a graph with more connected components than the original graph;

Content is final as published with the exception of pagination.
Recommended Citation: "Mircea Chindris, Bogdan Tomoiagă, Philip Taylor, Liana Cipcigan: The Identification of Critical Equipment and Optimum Configurations for Electrical Substations. Universities Power Engineering Conference, 2006. UPEC '06. Proceedings of the 41st International; 10/2006, ISBN 978-186135-342-9"
Digital Object Identifier: http://dx.doi.org/10.1109/UPEC.2006.367759

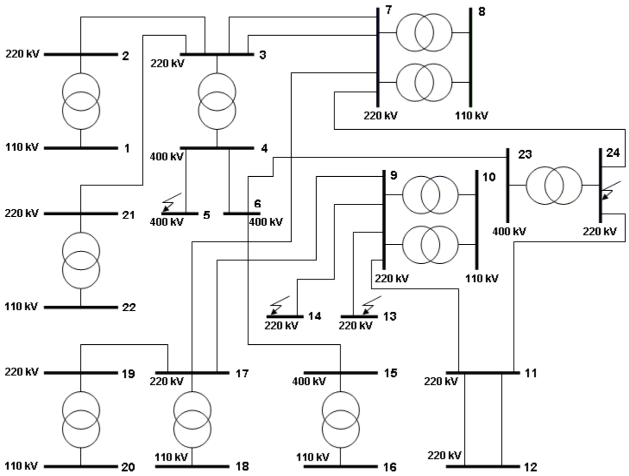


Figure 1 Electrical supply network (general diagram)

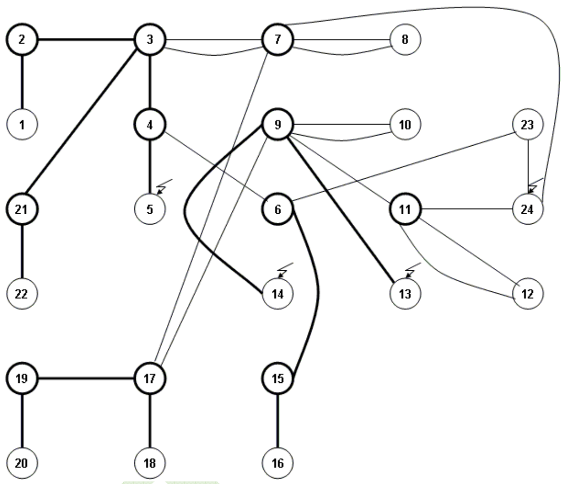


Figure 2 Multi-graph associated with the electrical supply network

Critical branch *(isthmus):* a branch that if removed produces a graph with more connected components than the original graph;

Multi-graph: a graph with multiple branches between the same vertices.

In the modelling process of the electrical supply network the bus systems are considered for vertices (electric nodes, [3]) of the (multi)graph, while the power lines and the (auto)transformers are considered as branches. Realising this model, the finding of critical equipment is reduced to the determination of (multi)graph critical nodes (articulation points) and branches (isthmuses).

Different authors (e.g. Tarjan) propose algorithms for solving these particular graphs' problems [1, 2]. In Figure 1 an example of an electrical supply network is presented along with the attached graph (Figure 2) where the critical equipment is indicated in bold.

Identification of the critical pieces of equipment could have an important practical interest as it highlights the weak points of the network (those that can be separated into sub-networks). Knowing the critical equipment, we can reconsider either the structure of the circuit diagrams in the substations, or the topology of the entire network (by creating new power lines and/or by assembling new (auto)transformers which would carry out to the elimination of the critical nodes and/or branches in the network). With regard the second aspect, for the elimination of a critical branch of (auto)transformer type, the solution could be the introduction of an additional (auto)transformer. The determination of the optimal solution for the elimination of the power line type critical branches and of the critical nodes can be much more complex and is beyond the goal of this paper.

In both cases, the costs of the construction and/or acquisition of new power lines and (auto)transformers are quite high and we can consider the corresponding solutions only in long-term development strategies.

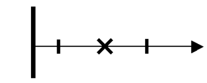
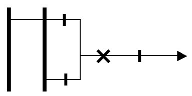
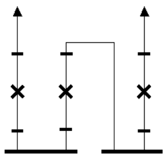
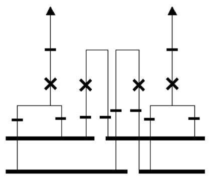
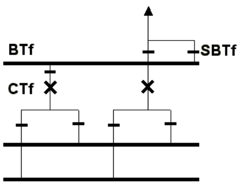
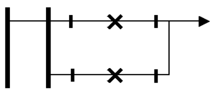
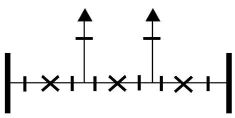
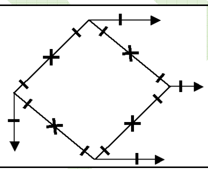
CIRCUIT DIAGRAMS

A circuit diagram represents an electric node where are linked the constructive parts of the electrical supply networks that "bring in" (sources) and/or "carry out" (towards the destinations) the electric power. In theory, an electric node can be implemented in two forms: with collecting buses (one or more) or without collecting buses (a group of circuit breakers and switchgears in various connections) [3]. In Table 1 are presented some main circuit diagrams and their possible practical implementation.

The analysis of the circuit diagrams presented in Table 1 allows the following assessments to be made:

- the failure of a bus switchgear unit (**SB**) brings out the unavailability of the related bus and equipment; consequently, the B and/or C2 diagrams should be used;
- the failure of a circuit breaker makes it impossible to connect the equipment to the node; the solution consists of the use of diagrams D, E, F or G;
- the failure of the power line (**SL**) or transformer (**ST**) switchgears disconnects the equipment from the node. It is proposed to abandon the **SL** or **ST** and the implementation of diagram F with *combined* circuit breakers (according to CIGRE, the failure probability of this circuit breaker is 0.01 years^{-1} [4]). On the other hand, **SL** and **ST** are less vulnerable than **SB**, because they work only when the served equipment is withdrawn from the system;
- the diagrams D, E, F and G, named "diagrams with more than one circuit breaker per circuit", reserve 100 % the connection to the node.

Table 1 Circuit diagrams

Type	Circuit diagram		Brief description of considerations
	Designation	Figure	
A	Simple collecting bus diagram		The whole node becomes unavailable if a fault occurs; most faults consist of the bus switchgear (SB) unavailability.
B	Two collecting bus diagram		If a bus fails, all the equipment connected to it can be passed to the other bus and the node is entirely reserved.
C1	Diagram with longitudinally divided simple collecting bus		The node is almost 50 % reserved (depending on the number of the equipments connected to each section). If a fault occurs on a section, the equipments connected to the other section bus will remain in service (the longitudinal coupler – **CL** disconnects the failed area).
C2	Two longitudinally divided collecting buses		In practice, the diagrams with two collecting buses can have one or two longitudinally divided buses, leading to improved flexibility.
D	Transfer bus diagram		If a circuit breaker fails, the equipment remains connected through the transfer bus (BTf) and transfer coupler (CTf). This diagram asks for some additional transfer elements: a bus, a coupler and a bus switchgear (SBTf) for every equipment connected to the node.
E	Diagram with 2 circuit breakers per circuit		The equipment remains connected to the node even if a circuit breaker becomes unavailable (this solution is not economic taking into account the circuit breaker cost).
F	Diagram with 1.5 circuit breakers per circuit		The diagram does not require any BTf, CTf or SBTf, but for two connected equipment an additional circuit breaker is necessary. Diagrams with 1.33 circuit breakers per circuit (4 circuit breakers for *3* equipments) also exist [3]. These diagrams are very promising; especially if they contain the modern *compact* or *combined* circuit breakers [4].
G	Polygonal diagram		With the same number of circuit breakers as the connected equipments, the solution assures the integral reservation of the node and of the equipment connections to the node

Based on this analysis, the following conclusions can be highlighted:

- a critical node needs the use of two collecting buses;
- a critical branch imposes a connecting system with more than one circuit breaker per circuit;
- for a node with incidental critical branch, the solution consists of two collecting buses with more than one circuit breaker per circuit.

DETERMINATION OF CIRCUIT DIAGRAMS OPTIMAL STRUCTURE

In order to decide the critical equipment and the optimal structure of the circuit diagrams in electric substations, the algorithm *SEN* (Safety in the operation of the Electrical supply Network) was developed by the authors. The logic diagram of this algorithm is presented in Figure 3.

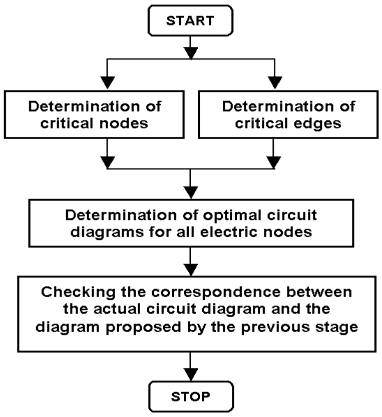


Figure 3 SEN algorithm (logic diagram)

In most of the cases, the matrices of nodes adjacency or nodes-branches incidence are used to represent the graph associated with an electrical supply network. However, in the implementation of the SEN algorithm, the representation using the branches lists was preferred as a power system node is only linked with a small part of the other system nodes (it results a *rare graph*, i.e. the associated matrix contains many zero elements). Consequently, the graph associated to the electric network can be described by a matrix with *m* lines and 2 columns (*m* is the number of the branches), each column indicating the two ends of a branch; this matrix does not contain zero elements [6].

In the logic diagram presented in Figure 3, the steps named "determination of critical nodes" and "determination of critical branches" has been located on the same level; that means that the order of their execution is not important.

The optimal structure of the circuit diagrams is established in three stages:
A) For each normal electric node, the minimal diagram containing a collecting bus and a circuit breaker per circuit is implemented;
B) For each critical node, the diagram with two collecting buses and a circuit breaker per circuit, is imposed;
C) For each node which has incidental critical branches, the diagram with two collecting buses is compulsory; besides, every critical branch has to contain more than one circuit breaker per circuit.

Table 2 Multi-graph represented by the lists of the branches

Branch	Nodes		Critical	
	i	*j*	*Nodes*	*Branches*
1	1	2	*2*	*1*
2	2	3	*3*	*2*
3	3	4	*4*	*6*
4	3	7	*6*	*7*
5	3	7	*7*	*9*
6	3	21	*9*	*18*
7	4	5	*11*	*19*
8	4	6	*15*	*24*
9	6	15	*17*	*25*
10	6	23	*19*	*26*
11	7	8	*21*	*27*
12	7	8		*28*
13	7	17	-	-
14	7	24	-	-
15	9	10	-	-
16	9	10	-	-
17	9	11	-	-
18	9	13	-	-
19	9	14	-	-
20	9	17	-	-
21	11	12	-	-
22	11	12	-	-
23	11	24	-	-
24	15	16	-	-
25	17	18	-	-
26	17	19	-	-
27	19	20	-	-

C++ *Builder* programming environment was used for implementing the proposed algorithm [7].

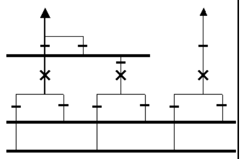
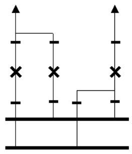
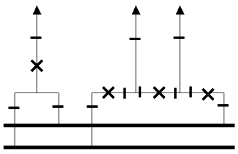
CASE STUDY

The developed algorithm was applied to the electrical supply network presented in Figure 1; its attached graph is represented by lists of the branches in Table 2. Based on the analysis the *SEN* algorithm indicates 10 critical nodes, 12 critical branches (Table 2) and the optimal circuit diagrams (Table 3).

Optimal circuit diagrams

Node	Existing diagram	Suggested optimal diagram	Does the existing diagram correspond to the optimal one?
2	B	B plus more than 1circuit breaker for branches 1, 2	NO
3	B	B plus more than 1circuit breaker for branches 2, 3, 7	NO
6	D	B plus more than 1circuit breaker for branch 11	YES
7	D	B	YES
9	D	B plus more than 1circuit breaker for branches 18, 19	YES
11	B	B	YES
15	A	B plus more than 1circuit breaker for branches 11, 23	NO
17	G	B plus more than 1circuit breaker for branches 24, 25	YES
19	A	B plus more than 1circuit breaker for branches 25, 26	NO
21	B	B plus more than 1circuit breaker for branches 7, 27	NO

Table 4 New circuit diagrams

Type	Designation	Figure
D1	Diagram with transfer bus diagram combined with B type diagram	
E1	Diagram with 2 circuit breakers per circuit combined with B type diagram	
F1	Diagram with 1.5 circuit breaker per circuit combined with B type diagram	

For an existing power system, the algorithm also indicates the correspondence between the actual structure and the suggested optimal diagram. For example, the existing diagram of type B for the node 2 does not correspond to the optimal one because the latter requires more than one circuit breaker per circuit for branches*1* and *2* – Table 3.

We have to specify that in order to establish the optimal diagram of the source (4, 5, 13, 14) and destination (1, 8, 10, 12, 16, 18, 20, 22) nodes, it is necessary to consider their links with other networks (upstream for source nodes and downstream for destination nodes) to find out, in this context, if they are critical and/or possesses incidental critical branches.

The obtained results have also suggested new circuit diagrams presented in Table 4.

CONCLUSIONS

This paper presents an original algorithm (and some dedicated software) which aims to determine the optimal structure of the connection diagrams in electric substations.

The proposed method is not heuristic and is based on verified mathematical concepts. The method does not decide the final circuit diagrams (they will be established after the technical-economical assessment), but indicates, for each case, the necessary number of collecting buses and of circuit breakers per circuit (for every circuit).

The data provided by the algorithm are useful for the safety level assessment in the operation of the current diagrams, as well as for the choice of the optimal circuit diagram in the stage of a new electrical network design.

Because many existing substation diagrams with collecting buses are built with transfer buses, and the current trend is to give them up, the algorithm can also be used to indicate in which conditions one can eliminate the transfer bus without putting in danger the operational safety of the electrical supply network.

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