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A NOVEL METHOD TO IMPLEMENT THE BEST STRUCTURE OF DISTRIBUTION SUBSTATIONS FOR INCREASED OPERATION RELIABILITY AND SAFETY

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INTRODUCTION

The reconstruction or the revitalization of distribution substations gives the possibility to introduce very powerful gears, and as a result, to simplify the circuit diagrams. Taking into account these tendencies, the problem of developing a systematical method for establishing the optimal structure of distribution substations for increasing the operation reliability and safety emerges.

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

These data can be very useful in assessing the reliability of the existing topology as well as in the strategies for later development of the electrical supply network. 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 building new power lines and/or assembling new (auto)transformers which would carry out to the elimination of the critical nodes and/or of the critical branches in the network).

Concerning the circuit diagrams, we can specify:

- a node is entirely reserved by a diagram with two collecting buses;
- 100% reservation of the branch connection can be implemented as (i) diagrams having a circuit breaker per circuit and transfer bus, (ii) more circuit breakers per circuit without transfer bus or by (iii) plugging charts without collecting buses (polygonal diagrams).

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The paper presents an original method that, using the determination of critical equipments (systems of buses, transformers, power lines), indicates the best (minimal) structure of distribution substation circuit diagrams.

1. DETERMINATION OF CRITICAL EQUIPEMENTS

In this paper, the term “equipment” will be used having the meaning of bus system, (auto)transformer or power line with all their elements.

For the determination of critical equipments we resort to the association of a graph to the electrical supply network. The following specific terminology used in the paper is according to Toadere (6):

Graph: a finite set of dots called vertices (or nodes) connected by links called branches (or arcs);
Path: a sequence of consecutive branches in a graph;
Cycle: A circuit is a path which ends at the vertex it begins;
Connected graphe: 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;
Critical branch *(isthmus):* a branch that if removed produces a graph with more connected components than the original graph;
Multigraph: a graph with multiple branches between the same vertices.

The modeling of the electrical supply network is carried out so that the bus systems are taken for vertices (electric nodes, Duşa and Vaida (3)) of the (multi)graph, while the power lines and the (auto)transformers are considered as branches. By realizing this model, the finding of critical equipment is reduced to the determination of (multi)graph critical nodes (articulation points) and branches (isthmuses), Chindriş and Tomoiagă (2).

The revealing of the critical equipments can have an excellent practical interest because it highlights the weak points of the network (those that can separate it in sub-networks). Knowing the critical equipments, 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). As regarding the latter aspect, for the elimination of a critical branch of (auto)transformer type, the solution can 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 does not represent the subject of this paper. In both cases, the costs of construction and/or acquisition of new power lines and (auto)transformers are quite great and we can consider the corresponding solutions only in long-term development strategies.

The paper presents an original method that, using the finding of critical equipments (bus systems, transformers, power lines), indicates the best (minimal) structure of distribution substation circuit diagrams.

1.1. Determination of Critical Nodes

The problem can be solved by two methods:

a) Classic method, of complexity $O(n^2)$, with the following stages:
- it eliminates, one by one, each node and its incidental branches;
- it is checked if the obtained (multi)graph is still connected;
- if the (multi)graph is not anymore connected, then the node is critical.

b) Optimal method (the Tarjan algorithm), of complexity $O(2n)$:
- it arranges the (multi)graph by levels (figure 1), with the starting node on the first level;
- the graph is traversed *depth first*: from a node, the itinerary is continued to the first node of proximity;
- a node k is not critical if for each branch of advance (k, j) [the branch which binds a node with another placed on an immediately higher level], from the node j one can arrive on a lower level than the node k;

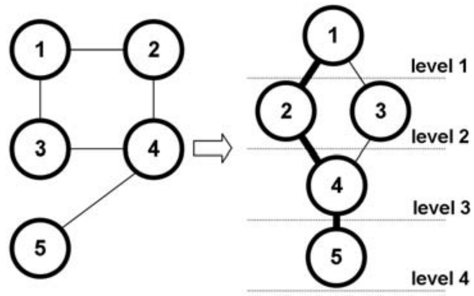
- the node from where one begins the course (node 1) represents an exception from this rule, because it is located on the lower level. This disadvantage can be compensated by a new course of the graph, having for starting point another node.

1.2. Determination of Critical Branches

It can be solved by two methods, in a similar way:

a) Classic method, of complexity *$O(n^2)$:*
- it eliminates, one by one, all branches;
- it is checked if, in every case, the obtained (multi)graph is still connected;
- if the (multi)graph is not more connected, then the branch is critical.

b) Optimal method, of complexity *$O(2n)$:*
- the (multi)graph is arranged by levels and *depth first* traversed;
- the branches of advance (*n-1*, where *n* is the number of the nodes) are checked if they belong to a cycle; the branches that do not satisfy this condition are critical branches.



a ***b***

Figure 1. Ordering of the graph by levels: *a* - initial graph*; b* – graph by levels

The optimal method is based on the following observation: the critical branches are those that do not belong to any cycle, and an branch of return (it joins together a node of a higher level with another of a lower level) cannot be critical (because it would close a cycle).

For the comprehension of this approach, figure 1 presents the ordering by levels of a graph where the branches of advance are indicated in bold. The depth first course of the graph is in order 1-2-4-5-3-1; the node 4 and the branch (4, 5) are critical. For details concerning the implementation of these algorithms see Tarjan (5), Toadere (6), Zaharia (7).

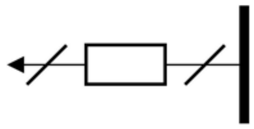
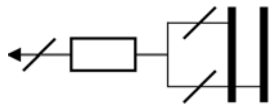
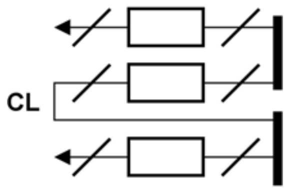
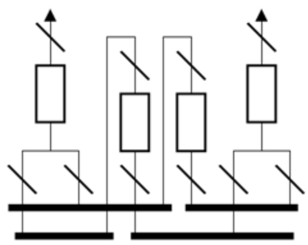
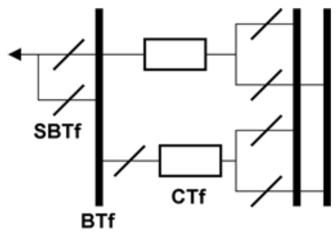
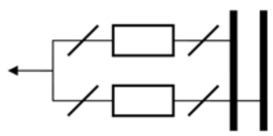
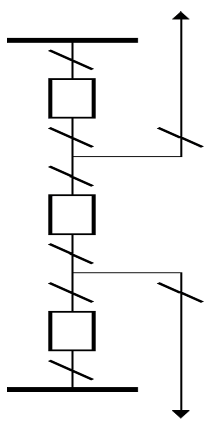
2. CIRCUIT DIAGRAMS

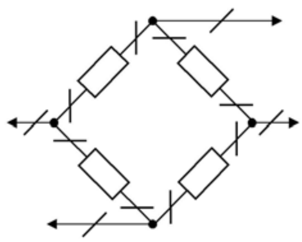
A circuit diagram represents an electric node where the constructive parts of the electrical supply networks that "bring" (sources) and/or "carry out" (towards the destinations) the electric power are linked. In theory, an electric node can be implemented in two forms: with collecting buses (one or more)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

The analyze of the circuit diagrams presented in this table allows the followings assessments:
- the fault of a bus switchgear (**SB**) brings out the unavailability of the related bus and equipment; consequently, the B and/or C2 diagrams should be used;
- the fault of a circuit breaker (**Q**) makes impossible the connection of the equipment to the node; the solution consists in the use of the diagrams D, E, F or G;
- the fault of the power line (**SL**) or transformer (**ST**) switchgear disconnects the equipment from the node. One proposes 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 $years^{-1}$, Staicu and Stoicescu (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”, assure 100 % reservation of the connection to the node.

From the above presented appreciations, 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.

TABLE 1 - circuit diagrams

Type	Circuit diagram		Short considerations
	Designation	Figure	
0	1	2	3
A	Simple collecting bus diagram		The whole node becomes unavailable if a fault occurs; the most faults consist of the bus switchgear (SB) unavailability.
B	Two collecting buses diagram		If a bus fails, all the equipments 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 reserved almost 50 % (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 a better flexibility.
D	Transfer bus diagram		If an equipment 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 breaker per circuit		The diagram does not require any BTf, CTf or SBTf, but for two connected equipments an additional circuit breaker is necessary. Diagrams with 1.33 circuit breakers per circuit (4 circuit breakers for *3* equipments) also exist, Duşa and Vaida (3). These diagrams are very promising, especially if they contain the modern *compact* or *combined* circuit breakers, Staicu and Stoicescu (4).

0	1	2	3
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

3. 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 authors. The logic diagram of this algorithm is presented in figure 2.

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 an branch; this matrix does not contain zero elements, Toadere (6).

As regarding the logic diagram, in figure 2 the steps “determination of critical nodes” and “determination of critical branches” have been located on the same level to suggest that the order of their execution is not important. The steps are realised by the algorithms presented in chapter 1.

The optimal structure of the circuit diagrams is find out in three stages:

a. for each normal electric node, the minimal diagram containing a collecting bus and a circuit breaker per circuit, for each connected equipment, is established;
b. for each critical node, the diagram with two collecting buses and a circuit breaker per circuit, for every connected equipment, 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.

The algorithm was implemented in the visual environment programming language *C++Builder* that, thanks to its graphic interface, ensures an extreme lightness in the use, Calvert (1).

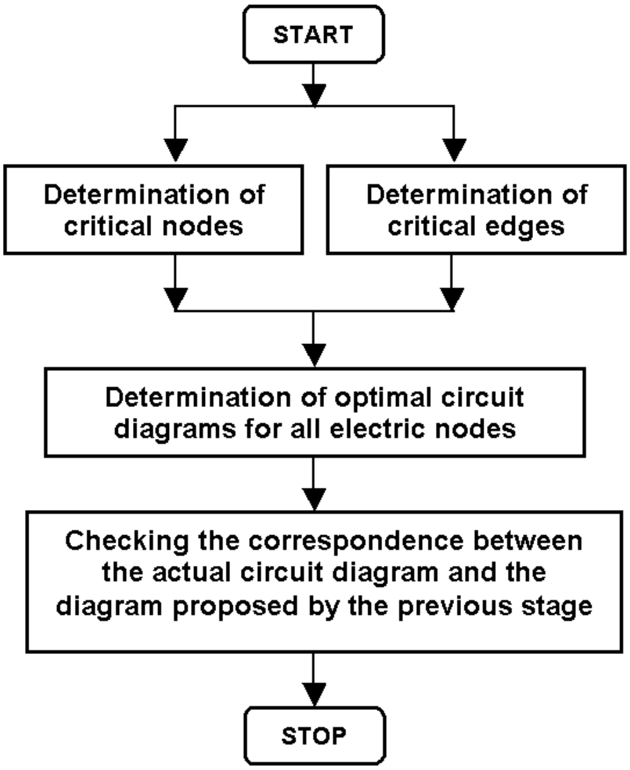


Figure 2. SEN algorithm – logic diagram

TABLE 2 - multigraph represented by the lists of the branches

Branch	Node *i*	Node *j*
1	1	2
2	2	3
3	3	5
4	3	6
5	3	7
6	3	7
7	3	21
8	4	6
9	4	7
10	4	11
11	6	15
12	7	8
13	7	8
14	7	17
15	9	10
16	9	10
17	9	11
18	9	13
19	9	14
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25	17	19
26	19	20
27	21	22

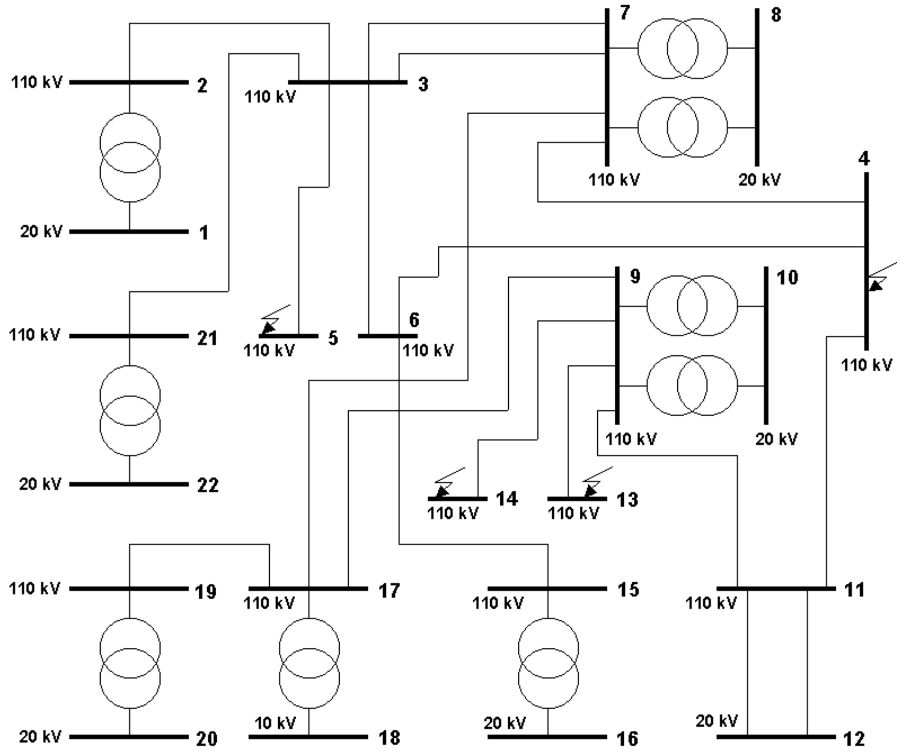

Figure 3. Electrical supply network - general diagram

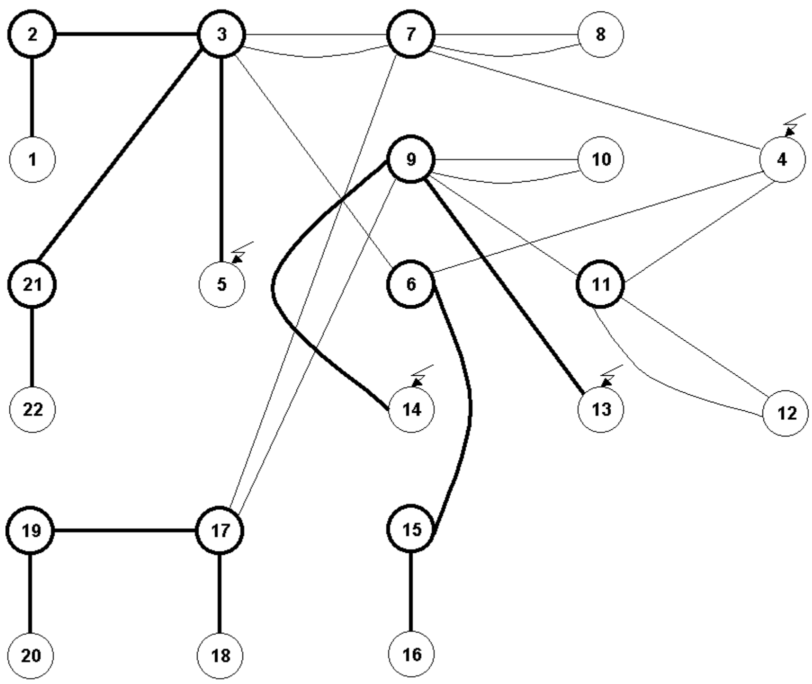

Figure 4. Multigraph associated with the electrical supply network

TABLE 3 - critical nodes of multigraph

Node	***i***	2	3	6	7	9	11	15	17	19	21

TABLE 4 - critical branches of multigraph

Branche		*1*	*2*	*3*	*7*	*11*	*18*	*19*	*23*	*24*	*25*	*26*	*27*
Node	***i***	1	2	3	3	6	9	9	15	17	17	19	21
	j	2	3	5	21	15	13	14	16	18	19	20	22

TABLE 5 - optimal circuit diagrams

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

4. CASE STUDY

As an example, the algorithm was implemented to the electrical supply network presented in figure 3; the attached graph is geometrically represented in figure 4 and by lists of the branches in TABLE 2. The software indicates 10 critical nodes (TABLE 3), 12 critical branches (TABLE 4) and the optimal circuit diagrams (TABLE 5); the critical equipments are presented in bold in figure 4.

Because the software is applied to known circuit diagrams of the network, it also indicates the correspondence between the actual circuit diagram and the suggested optimal diagram – TABLE 5. In particular, for node *2* where the existing diagram is B type (TABLE 1) this one does not correspond with the optimal diagram, because the last one requires, supplementary, more than one circuit breaker per circuit for branches *1* and *2*.

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

CONCLUSION

The paper presents an original algorithm (and a dedicated software) aiming to determine the optimal structure of the connection diagrams in the electric substations.

The proposed method is not heuristic but is based on demonstrated mathematical concepts. Evan if it does not decide the final circuit diagrams (these will be established after the technical-economical calculus), the method indicates, for each case, the necessary number of collecting buses and the necessary number 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 nowadays trend is to give them up, the algorithm can be also used to indicate in which conditions one can eliminate the transfer bus without putting in danger the safety in operation of the electrical supply network.

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