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Identification of Topology Errors with Use of Unbalance Indices and Neural Networks

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Abstract—**The paper deals with identification of topology errors, i.e. identification of incorrect modelling of the physical connections of a power system, which is one of the most important tasks of the real-time modeling of a power system. The paper presents the method, based on utilization of introduced-by-authors so-called unbalance indices and artificial neural networks. Values of the unbalance indices create characteristic sets for different cases of modeling of branches and nodes of the considered power system. In the paper, analyses of the mentioned sets is made. The analysis allows to point out these cases of topology errors, which can be distinguished by examination of values of the unbalance indices. The analysis gives bases for determination of the cases, for which the considered method is efficient. The presented considerations are illustrated by the case study. At the end, the features of the method are summed up.**

***Index Terms*— ART Neural Networks, Estimation, Power Systems, Topology**

I. Introduction

Identification of power-system topology errors (TEs), i.e. identification of incorrect modelling of the physical connections of a power system is one of the more important tasks of the real-time modeling of a power system. This task can be performed with use of the results of state estimation (e.g. [1]-[7]) or independently of this process (e.g. [1], [8]-[15]). In the first case, the methods of identification of topology errors are sophisticated and time consuming. They can fail when there are convergence problems in the state estimation. In the second case, the most important feature of the identification of TEs is that it is independent from results of state estimation, and then independent from the mentioned convergence problems. In the paper, this second case of the identification of TEs is considered. The node-branch model of a power system is assumed.

The aim of the paper is to present results of the next stages of investigations of the identification of TEs with use of the approach which is considered in [15]. The method from [15] uses the idea of so-called unbalance indices whose values create characteristic sets for distinguished TEs. The standardized values of unbalance indices are inputs for artificial neural networks (more precisely, Radial Basis Function networks – RBF networks). In this paper, the approach to identification of TEs, which is considered in the paper [15], is analyzed not only for the cases of consideration of correctness of inclusion or exclusion of the branches from a topology model but also for the cases, in which correctness of connection of a selected branch with each of its terminal nodes in the model is separately taken into account. The correctness of modeling the nodes is investigated, as well. The results of the carried out analysis allow to increase the number of cases in which TEs are identified, using the approach utilized in [15].

II. Theoretical Background of the Method

The considered method is based on the observations that if TE occurs some of the relationships among distinguished quantities in a power system become unfulfilled. It should be emphasized that in many power system applications if a branch is not included in the power system model, the relationships for this branch are not considered, because measurement data for it are not taken into account.

In the analyzed method, relationships for all nodes and all branches are always taken into account. It is independent of the correct or incorrect inclusion of these nodes and branches into the power system model. To have possibility of examination of the mentioned relationships the so-called unbalance indices for nodes and branches are introduced. The nodal unbalance indices are defined as follows [16]:

$$W_{Pk} = \sum_{l \in I_k} P_{kl}, \tag{1}$$

$$W_{Qk} = \sum_{l \in I_k} Q_{kl}, \tag{2}$$

where W_{Pk}, W_{Qk} are unbalance indices for node k for active and reactive power, respectively, I_k is the set of nodes connected to the node k; P_{kl}, Q_{kl} are respectively active and reactive power flows on the branch connecting the nodes k and l (the branch k-l) at the node k.

Unbalance indices for branches are as follows [16]:

$$W_{Pkl} = -W_{Pk} - W_{Pl} + R_{kl} W_{kl}^{u}, \tag{3}$$

$$W_{Qkl} = -W_{Qk} - W_{Ql} + X_{kl} W_{kl}^{u} - W_{kl}^{V}, \tag{4}$$

where: $W_{kl}^{V} = B_{kl}\left(V_k^2 + V_l^2\right)$, V_k, V_l are voltage magnitudes at the nodes k and l respectively; R_{kl}, X_{kl}, B_{kl} are parameters of

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the π model of the branch k-l (Fig. 1); $B_{kl} = B_{lk} = B$, B is a half of the capacitive susceptance of the branch;

$$W_{kl}^{u} = \frac{W_{Pk}^{2} + \left(W_{Qk} + B_{kl}V_{k}^{2}\right)^{2}}{V_{k}^{2}} .$$

The nodal unbalance indices are calculated with use of the measurement data of active and reactive power flows in a power system. For calculation of the branch unbalance indices the nodal unbalance indices are utilized instead of the measurement data of active and reactive power flows.

Values of the unbalance indices for nodes and branches create sets which are characteristic for different TEs.

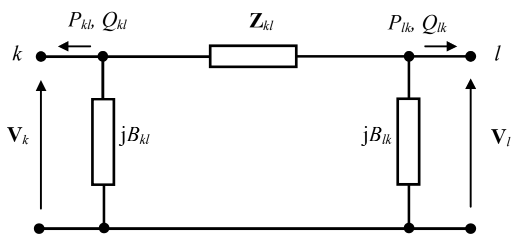

Fig. 1. The assumed π model of the branch. $\mathbf{Z}_{kl} = R_{kl} + \mathrm{j}\,X_{kl}$.

III. Characteristic Sets of Unbalance Indices for Different Topology Errors

In the section, the assumption is made that there are no errors burdening measurement data. In the carried out considerations, the branch k - l and the nearest area of a power network, comprising nodes connected with the nodes k and l through branches, is taken into account.

Further, the area containing:

(i) the node k,
(ii) all the nodes adjacent to the node k (creating the set I_k), from which each is connected with the node k through a branch,
(iii) all the branches connecting the nodes mentioned in (ii) with the node k,

is called as the area A^k.

The branch k - l is in the area A^k as well as in the area A^l.

The unbalance indices for branches and nodes for the here-considered cases are presented in Table I.

A. There are no Errors - Correct Modeling of a Branch

When there are no TEs, for each node in the areas A^k and A^l the unbalance indices are equal to zero. The unbalance indices for any branch in the considered areas are different from zero, but moduli of their values are relatively small.

B. Exclusion Error

When the selected branch k - l is not included in the topology model but in the system it is in operation then the unbalance indices for the terminal nodes of the branch are different from zero. The larger power flows at the ends of the branch the larger moduli of the mentioned unbalance indices.

The unbalance indices for the branch k - l are equal to zero. The unbalance indices for other branches, for which the nodes k and l are terminal (i.e. for the branches in the areas A^k and A^l), are different from zero. These unbalance indices are dependent on the power flows on the branch k - l. Their moduli can be relatively large when the moduli of the mentioned power flows are large.

C. Inclusion Error

When in the power system the selected branch k - l is out of operation but it is included in the topology model, then comparing with the case of correct modeling the power system (subsection A) the mentioned fact does not change the unbalance indices for:

(i) the terminal nodes of the branch $k - l$, and all other nodes in the areas A^k and A^l,
(ii) the branch $k - l$, and all other branches in the areas A^k and A^l.

D. Incorrect Switching-off a Branch at One End in a Topology Model when in the Power System the Branch is in Operation

If in a system a branch is in operation and in the topology model this branch is erroneously connected with the node x, where $x \in \{k, l\}$, i.e. the branch is not connected with the node x, then the unbalance indices for:

(i) the node y, where $y \in \{k, l\}$ and $x \neq y$,
(ii) all the nodes i, where $i \in (I_k \cup I_l) - \{k, l\}$,
(iii) the branches connected with the node y and other one than the branch k - l,

are the same as in the case of correct modeling the power system (subsection A).

Generally, the unbalance indices for the node x and for the branches in the area A^x (also for the branch k-l) have values different from the values, that these unbalance indices have in the case of correct modeling the power system.

It can be noted that when in the system the branch k - l is in operation but it is switched off at one end in a topology model, then after switching off the branch k - l also at the second end in a topology model, all the unbalance indices for the areas A^k and A^l are the same as in the case of exclusion error (subsection B).

E. Incorrect Switching-on a Branch at One End in a Topology Model when in the Power System the Branch is out of Operation

In the considered case, the unbalance indices for all the nodes and all the branches in the areas A^k and A^l are the same as in the case in which there are no topology errors (subsection A), i.e. when in the topology model the branch k-l is switched off at both ends.

F. Incorrect Switching on a Branch at One End in a Topology Model When in the Power System the Branch is Switched on at One End

Ascertainment that a branch is incorrectly switched on at one end in a topology model when in the system the branch is switched on at one end means that in the topology model the branch is switched on at both ends. In this case the unbalance indices for all the nodes and all the branches in the areas A^k and A^l are the same as in the case in which there are no topology errors (subsection A) and in the case of inclusion error.

G. Incorrect Switching-off a Branch at One End in a Topology Model when in the Power System the Branch is Switched off at the Other End

In the subsection, it is assumed that:

(i) in a system, the branch k - l is not connected with the node x, and it is connected with the node y where x, $y \in \{k, l\}$ and $x \neq y$,

(ii) in the topology model, the branch k - l is not connected with the node x and also with the node y.

In the considered case, the unbalance indices for:

(i) the node x,

(ii) all the nodes i, where $i \in (I_k \cup I_l) - \{k, l\}$,

(iii) the branches connected with the node x and other ones than the branch k - l,

are the same as in the case of correct modeling the power system (subsection *A*). The unbalance indices for the branches in the area A^y apart from the branch k-l have values different from the values, that they have in the case of correct modeling the power system. However, usually differences between the mentioned values are relatively small as the power flows on the branch k - l at the node y are usually small.

It can be expected, that the moduli of the unbalance indices for the branch k-l and differences between the moduli of the mentioned unbalance indices and the moduli of the appropriate unbalance indices for the case *A* (when there are no topology errors) are relatively small.

H. Incorrect Switching-on a Branch at One End and Incorrect Switching-off a Branch at Second End in a Topology Model

In the considered case, incorrect modeling a branch at one end at which the branch is switched off in a power system does not implies changes of the unbalance indices for the terminal node in comparison with the correct modeling the branch at this end. However, changes of the unbalance indices can be observed for the second terminal node of the branch. At this end, the branch is also incorrectly modeled and now this fact has influence on values of the mentioned unbalance indices. It should be noted, that in a power system the branch is switched on at the considered end. A result of the existing situation is such a set of the unbalance indices for the nodes

TABLE I
UNBALANCE INDICES FOR BRANCHES AND NODES IN THE AREAS A^k, A^l FOR DIFFERENT CASES

Case	Branches		Nodes	
	x - y	$j - i$	x	y
There are no errors	$W_{Xxy} = \gamma_{Xxy}$, $W_{Xyx} = \gamma_{Xyx}$	$W_{Xji} = \gamma_{Xji}$, $W_{Xij} = \gamma_{Xij}$	$W_{Xx} = 0$	$W_{Xy} = 0$
Exclusion error	$W_{Xxy} = 0$, $W_{Xyx} = 0$	$W_{Xji} = \Gamma_{Xji}$, $W_{Xij} = \Gamma_{Xij}$	$W_{Xx} = U_{Xx}$, $U_{Xx} = F_{Xx}$	$W_{Xy} = U_{Xy}$, $U_{Xy} = F_{Xy}$
Inclusion error	$W_{Xxy} = \gamma_{Xxy}$, $W_{Xyx} = \gamma_{Xyx}$	$W_{Xji} = \gamma_{Xji}$, $W_{Xij} = \gamma_{Xij}$	$W_{Xx} = 0$	$W_{Xy} = 0$
Model: incorrect switching-off the branch at one end (at the node y); System: the branch is in operation	$W_{Xxy} = \Gamma_{Xxy}$, $W_{Xyx} = \Gamma_{Xyx}$	$W_{Xxi} = \gamma_{Xxi}$, $W_{Xix} = \gamma_{Xix}$ $W_{Xyi} = \Gamma_{Xyi}$, $W_{Xiy} = \Gamma_{Xiy}$	$W_{Xx} = U_{Xx}$, $U_{Xx} = 0$	$W_{Xy} = U_{Xy}$, $U_{Xy} = F_{Xy}$
Model: incorrect switching-on the branch at one end (at the node y); System: the branch is out of operation	$W_{Xxy} = \gamma_{Xxy}$, $W_{Xyx} = \gamma_{Xyx}$	$W_{Xji} = \gamma_{Xji}$, $W_{Xij} = \gamma_{Xij}$	$W_{Xx} = 0$	$W_{Xy} = 0$
Model: incorrect switching-on the branch at one end (at the node y); System: the branch is switching-on at one end (at the node x)	$W_{Xxy} = \gamma_{Xxy}$, $W_{Xyx} = \gamma_{Xyx}$	$W_{Xji} = \gamma_{Xji}$, $W_{Xij} = \gamma_{Xij}$	$W_{Xx} = 0$	$W_{Xy} = 0$
Model: incorrect switching-off a branch at one end (at the node y) System: the branch is switched off at one end (at the node x)	$W_{Xxy} = \Gamma_{Xxy}$, $W_{Xyx} = \Gamma_{Xyx}$	$W_{Xxi} = \gamma_{Xxi}$, $W_{Xix} = \gamma_{Xix}$ $W_{Xyi} = \Gamma_{Xyi}$, $W_{Xiy} = \Gamma_{Xiy}$	$W_{Xx} = U_{Xx}$, $U_{Xx} = 0$	$W_{Xy} = U_{Xy}$, $U_{Xy} = F_{Xy}$
Model: incorrect switching-on a branch at one end (at the node x) and incorrect switching-off the branch at second end System: the branch is switched off at one end (at the node x) and switching-on the branch at second end	$W_{Xxy} = \Gamma_{Xxy}$, $W_{Xyx} = \Gamma_{Xyx}$	$W_{Xxi} = \gamma_{Xxi}$, $W_{Xix} = \gamma_{Xix}$ $W_{Xyi} = \Gamma_{Xyi}$, $W_{Xiy} = \Gamma_{Xiy}$	$W_{Xx} = U_{Xx}$, $U_{Xx} = 0$	$W_{Xy} = U_{Xy}$, $U_{Xy} = F_{Xy}$
Correct modeling of nodes (the nodes x and y can be result of splitting a node)	$W_{Xxy} = 0$, $W_{Xyx} = 0$	$W_{Xji} = \gamma_{Xji}$, $W_{Xij} = \gamma_{Xij}$	$W_{Xx} = 0$	$W_{Xy} = 0$
Node-split error (the nodes x and y are result of splitting a node)	$W_{Xxy} = 0$, $W_{Xyx} = 0$	$W_{Xji} = \Gamma_{Xji}$, $W_{Xij} = \Gamma_{Xij}$	$W_{Xx} = U_{Xx}$, $U_{Xx} = F_{Xx}$	$W_{Xy} = U_{Xy}$, $U_{Xy} = F_{Xy}$
Node-merging error (the nodes x and y are the merged nodes)	$W_{Xxy} = 0$, $W_{Xyx} = 0$	$W_{Xji} = \gamma_{Xji}$, $W_{Xij} = \gamma_{Xij}$	$W_{Xx} = 0$	$W_{Xy} = 0$

$x, y \in \{k, l\}$, $x \neq y$, , $j = x, y$; $i = i_1^j, i_2^j, \ldots, i_{nj}^j$, $\{i_1^j, i_2^j, \ldots, i_{nj}^j\} = I_j - \{j^*\}$, $j^* = y$ if $j = x$ or $j^* = x$ if $j = y$, $W_{Xi} = 0$,

$$F_{Xx} = \begin{cases} -P_{xy} & \text{when } X = P \\ -Q_{xy} & \text{when } X = Q \end{cases}, \quad \gamma_{Xuv} = \begin{cases} R_{uv} B_{uv}^2 V_u^2 & \text{when } X = P \\ X_{uv} B_{uv}^2 V_u^2 - W_{uv}^V & \text{when } X = Q \end{cases}, \; u, v \in \{x, y\} \text{ or } u, v \in \{i, j\},\; u \neq v,$$

$$\Gamma_{Xvu} = \begin{cases} -U_{Xv} + R_{vu} \left[U_{Pv}^2 + \left(U_{Qv} + B_{vu} V_v^2 \right)^2 \right] / V_v^2 & \text{when } X = P \\ -U_{Xv} - W_{vu}^V + X_{vu} \left[U_{Pv}^2 + \left(U_{Qv} + B_{vu} V_v^2 \right)^2 \right] / V_v^2 & \text{when } X = Q \end{cases}, \; u = x,\; v = y \text{ or } v = j,\, u = i,$$

$$\Gamma_{Xuv} = \begin{cases} -U_{Xv} + R_{vu} B_{vu}^2 V_u^2 & \text{when } X = P \\ -U_{Xv} - W_{vu}^V + X_{vu} B_{vu}^2 V_u^2 & \text{when } X = Q \end{cases} \quad u = x,\, v = y \text{ or } u = i,\, v = j.$$

and branches in the areas A^k and A^l as in the case *G*. The here-considered situation is very like to the situation in the case *D*. However, in the case *D* we can expect larger values of the moduli of the unbalance indices for the branch *k-l* and for the branches connected with the node, at which the branch *k-l* is switched on in the system, than it is in the case considered in this subsection.

I. Correct Modeling of Nodes

The errors of modeling nodes can be considered in the process of identification of TEs, if the appropriate topology model of a power network is utilized. If a node can be splitted into certain number of nodes (e.g. two nodes), not one but the appropriate number (e.g. two) of nodes should occur in the topology model and they should be connected each other through a zero-impedance branches.

If we consider a possibility of splitting a node into two nodes, let us call one of them as the node *k* and the second one as the node *l*. The branch between the mentioned nodes is a zero-impedance branch.

When there are no TEs, for each node in the areas A^k and A^l the unbalance indices are equal to zero. For any branch in the considered areas but other than the branch *k-l* the unbalance indices are different from zero and moduli of their values are relatively small. For the branch *k-l* the unbalance indices are equal to zero.

J. Node-Split Error

When there is the node-split error, the unbalance indices are the same as in the case of the branch-exclusion error, if the nodes *k* and *l* are two nodes, which are introduced into the topology model instead of the splitted node.

K. Node-Merging Error

It should be underlined, that the node-merging error can be considered as the branch-inclusion error. In this situation, after the node-merging error occurs, the unbalance indices for all nodes and all branches in the areas A^k and A^l are the same as in the case of correct modeling the power system (subsection *I*).

L. Conclusion from the Carried out Analysis of the Different Cases of Topology Error Identification

Analyzing values and relations among these values of the unbalance indices for all nodes and all branches in the areas A^k and A^l, in which there is the considered branch, we can ascertain that the case *B*, i.e. the case of the branch exclusion error can be easily identified.

When we recognize that a branch is switched off at one end in a topology model and we perform artificial disconnection of the branch at the second end from a terminal node then, in fact, in the case *D*, we have such a situation as in the case *B* and therefore we can determine which TE occurs. Using the mentioned way we can ascertain that we have the case *D*, i.e. there is incorrect switching-off a branch at one end in a topology model when in the system the branch is in operation.

Considering correctness of modeling nodes in a topology model we can state that the identification of TE in the case *J* is also simple.

Analysis of the sets of values of the unbalance indices for all nodes and all branches in the areas A^k and A^l shows that one can determine a characteristic set of these values for each of the following groups of cases:

(i) *A*, *C*, *E*, *F*,
(ii) *G*, *H*,
(iii) *I*, *K*.

The mentioned fact means that it is not possible to unequivocally distinguish the cases belonging to the earlier-given groups.

IV. Real Conditions of Topology-Error Identification

In real cases, measurement data are burdened with errors. There can not also exclude existence of multiple TEs. In these conditions, TE identification is a more complex problem. The possible solution of such problem is utilization not only unbalance indices but also ANNs as it was done in [15].

V. Principle of the Method

The method for TE identification consists of the following steps:

(i) testing connections of branches with nodes in a topology model - if there is switching-off of the branch only at one end, performing disconnection of the branch from the node at its second end,
(ii) calculation of unbalance indices for nodes and branches,
(iii) pre-processing of unbalance indices,
(iv) local classification,
(v) global classification.

The steps (ii) - (v) are described more extensively in [15].

The first step of the method allows increasing the number of cases in which the TE identification is possible.

The pre-processing standardisation of each unbalance index is realized using RBF unit with Gaussian transfer function:

$$f(x) = \exp\left(-x^2/2\sigma^2\right), \tag{5}$$

where σ is a parameter calculated on the base of:

(i) standard deviations of data of the active or reactive power flows in the case of unbalance indices for nodes for active or reactive powers respectively,
(ii) the parameters σ calculated for the nodal unbalance indices in the case of the branch unbalance indices.

The pre-processing standardisation allows keeping input values for local classifiers in the range (0; 1].

The purpose of the local classifiers is classification of correctness of modelling branches of a power system using RBF Networks. One local classifier corresponds to one node of a considered power network. If the considered node has the number *k* then inputs for a local classifier, that corresponds to this node, are the results of the pre-processing of active and reactive power unbalance indices for all nodes and branches in the area A^k. The number of outputs of a local classifier is equal to the number of the branches in the area A^k.

During the global classification, final decisions on correctness of modelling the individual branches are produced on the basis of the decisions of the local classifications.

VI. Case Study

A. Description of the Considered Power System

The method has been tested using the IEEE 14-bus test system. The part of the tests is presented in this case study.

In the case study, the part of the IEEE 14-bus test system, which is presented in Fig. 2, is taken into account. Parameters of the branches of the part of the test system from Fig. 2 are shown in the Table II. In Table III, the results of the load flow calculations for different considered cases are gathered. The state, in which all branches are in operation, is an initial one.

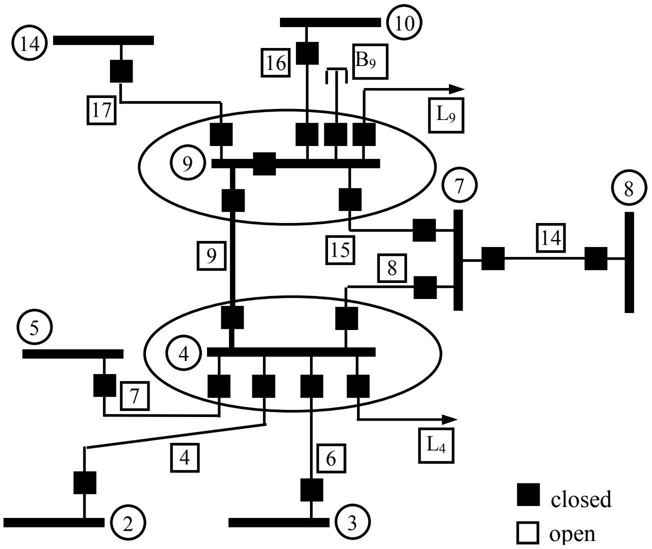

Fig. 2. The part of the IEEE 14-bus test system considered in the case study.

TABLE II
PARAMETERS OF THE BRANCHES
IN THE CONSIDERED PART OF THE TEST SYSTEM

i	j	R_{ij} p.u.	X_{ij} p.u.	B_{ij} p.u.
2	4	0.0581	0.1763	0.0374
3	4	0.0670	0.1710	0.0346
4	5	0.0133	0.0421	0.0128
4	7	0.0000	0.2045	0.0000
4	9	0.0000	0.5389	0.0000
7	8	0.0000	0.1761	0.0000
9	10	0.0318	0.0845	0.0000
9	14	0.1271	0.2703	0.0000

The identification of TEs for different cases of modeling the branch 9 (the branch 4-9, i.e. the branch between the nodes 4 and 9) and the node 9 (Fig. 3) is described in this section. During the calculations the assumptions are made that one considers:

(i) the cases in which the branch 9 (the branch 4-9) is in operation as well as the cases in which it is out of operation,

(ii) the cases in which there is a split of the node 9 and also the cases in which there is no a split of this node.

Inputs for the procedure of the identification of TEs are results of load flow calculations for the test system with noise representing existence of small errors with which measurement data are normally burdened.

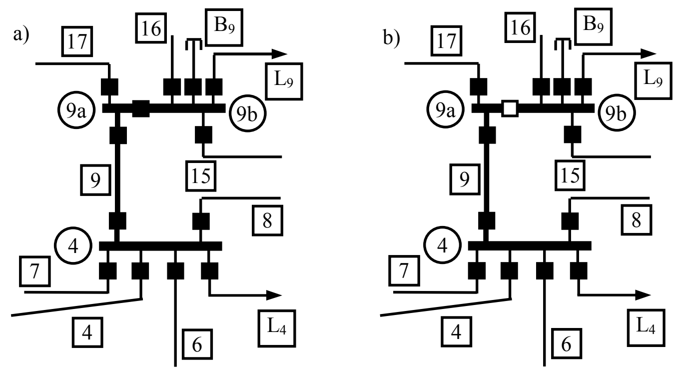

Fig. 3 . Different cases of modeling the node 9: a) there is no a split of the node 9, b) there is a split of the node 9.

B. Incorrect Modeling of only the Branch 9

Considering incorrect modeling of only the branch 9 (the branch 4-9), two possible cases can be distinguished:

(i) in the system the branch 9 is in operation but it is not included in the topology model,

(ii) in the system the branch 9 is out of operation but it is included in the topology model.

For both the mentioned cases the unbalance indices for nodes and branches in the areas, which are taken into account by ANNs related to the nodes 4 and 9, are gathered in Table IV. ANN related to the node 4 takes into account the area A^4, which comprises: (i) the node 4 and nodes: 2, 3, 5, 7, 9, (ii) the branches: 4, 6, 7, 8, 9.

ANN related to the node 9 takes into account the area A^4, which comprises: (i) the node 9 and nodes: 4, 7, 10, 14, (ii) the branches: 9, 15, 16, 17.

In Table IV, apart from the unbalance indices also identification decisions taken on the base of outputs of ANNs are presented. In Table IV and in other tables, D denotes a decision, B - the decision "The branch is incorrectly modeled", N - the neutral decision, i.e. refraining from decision making.

Analyzing unbalance indices for the area A^9 (i.e. unbalance indices for all the nodes and all the branches in the area A^9) in the first part of Table IV, we can observe that the mentioned unbalance indices create the set of values, which is characteristic for the error of exclusion of the branch 9. The same situation is, analyzing unbalance indices for the area A^4. ANN for the node 9 and also ANN for the node 4 allows to take the decision that the branch 9 is incorrectly modeled.

TABLE III
ACTIVE AND REACTIVE POWERS AND VOLTAGES MAGNITUDES AT THE NODES IN THE CONSIDERED PART OF THE TEST SYSTEM

i	*j*	P_{ij}	Q_{ij}	P_{i_inj}	Q_{i_inj}	P_{i_load}	Q_{i_load}	V_i
		p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.
All the branches are in operation								
2	4	-0.557	0.023	0.400	0.424	-0.217	-0.127	1.045
3	4	0.237	-0.028	0.000	0.234	-0.942	-0.190	1.014
4	2	0.546	-0.034	0.000	0.000	-0.478	0.039	1.019
4	3	-0.237	0.055					
4	5	0.613	-0.155					
4	7	-0.287	0.093					
4	9	-0.160	0.003					
5	4	-0.623	0.130	0.000	0.000	0.000	0.000	1.020
7	4	0.280	-0.111	0.000	0.000	0.000	0.000	1.062
7	8	0.000	0.172					
7	9	-0.280	-0.058					
8	7	0.000	-0.174	0.000	0.174	0.000	0.000	1.090
9	4	0.162	-0.016	0.000	0.000	-0.295	0.046	1.056
9	7	0.281	0.050					
9	10	-0.053	-0.043					
9	14	-0.095	-0.036					
10	9	0.052	0.042	0.000	0.000	-0.090	-0.058	1.051
14	9	0.094	0.034	0.000	0.000	-0.149	-0.050	1.036
The branch 9 (the branch 4-9) is out of operation								
2	4	-0.556	0.011	0.400	0.443	-0.217	-0.127	1.045
3	4	0.233	-0.048	0.000	0.254	-0.942	-0.190	1.010
4	2	0.541	-0.025	0.000	0.000	-0.478	0.039	1.017
4	3	-0.239	0.052					
4	5	0.569	-0.151					
4	7	-0.389	0.085					
4	9	0.000	0.000					
5	4	-0.576	0.130	0.000	0.000	0.000	0.000	1.019
7	4	0.389	-0.115	0.000	0.000	0.000	0.000	1.060
7	8	0.000	0.181					
7	9	-0.392	-0.066					
8	7	0.000	-0.187	0.000	0.186	0.000	0.000	1.090
9	4	0.000	0.000	0.000	0.000	-0.295	0.046	1.054
9	7	0.388	0.052					
9	10	-0.018	-0.054					
9	14	-0.073	-0.043					
10	9	0.018	0.053	0.000	0.000	-0.090	-0.058	1.049
14	9	0.072	0.042	0.000	0.000	-0.149	-0.050	1.034
All the branches are in operation and there is a split of the node 9								
2	4	-0.557	0.013	0.400	0.440	-0.217	-0.127	1.045
3	4	0.231	-0.047	0.000	0.253	-0.942	-0.190	1.010
4	2	0.553	-0.028	0.000	0.000	-0.478	0.039	1.017
4	3	-0.237	0.051					
4	5	0.613	-0.155					
4	7	-0.329	0.108					
4	9a	-0.116	-0.016					
5	4	-0.623	0.130	0.000	0.000	0.000	0.000	1.019
7	4	0.330	-0.129	0.000	0.000	0.000	0.000	1.064
7	8	0.000	0.158					
7	9b	-0.322	-0.027					
8	7	0.000	-0.161	0.000	0.162	0.000	0.000	1.090
9a	4	0.113	0.009	0.000	0.000	0.000	0.000	1.043
9a	14	-0.115	-0.009					
9b	7	0.330	0.016	0.000	0.000	-0.295	0.046	1.062
9b	10	-0.032	-0.064					
10	9b	0.032	0.064	0.000	0.000	-0.090	-0.058	1.056
14	9a	0.114	0.005	0.000	0.000	-0.149	-0.050	1.028

TABLE IV
UNBALANCE INDICES FOR THE AREAS TAKEN INTO ACCOUNT BY ANNS RELATED TO THE NODES 4 AND 9 AND IDENTIFICATION DECISIONS, WHEN THE BRANCH 9 (THE BRANCH 4-9) IS INCORRECTLY MODELED

i	*j*	W_{Pi}	W_{Qi}	W_{Pj}	W_{Qj}	W_{Pij}	W_{Qij}	W_{Pji}	W_{Qji}	*D*
		p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	
In the system the branch 9 is in operation and only it is incorrectly modeled										
4	2	0.156	-0.002	0.004	-0.002	-0.159	-0.032	-0.161	-0.029	*N*
	3			0.006	0.000	-0.160	-0.029	-0.162	-0.033	*N*
	5			0.014	-0.003	-0.170	-0.007	-0.170	-0.008	*N*
	7			-0.001	0.002	-0.156	0.005	-0.156	-0.000	*N*
	9			-0.162	0.016	0.006	-0.001	0.006	-0.001	*B*
9	4	-0.162	-0.162	0.016	-0.002	0.006	-0.001	0.006	-0.001	*B*
	7			-0.001	0.002	0.163	-0.019	0.163	-0.016	*N*
	10			-0.001	0.000	0.164	-0.014	0.163	-0.016	*N*
	14			0.000	0.000	0.165	-0.010	0.162	-0.017	*N*
In the system the branch 9 is out of operation and only it is incorrectly modeled										
4	2	0.005	0.000	-0.010	0.005	0.005	-0.044	0.005	-0.044	*N*
	3			-0.001	0.000	-0.004	-0.035	-0.004	-0.035	*N*
	5			0.006	0.001	-0.011	-0.013	-0.011	-0.013	*N*
	7			-0.002	-0.001	-0.002	0.001	-0.002	0.001	*N*
	9			0.002	0.001	-0.007	-0.000	-0.007	-0.001	*N*
9	4	0.002	0.001	0.005	0.000	-0.007	-0.000	-0.007	-0.001	*N*
	7			-0.002	-0.001	0.000	-0.000	0.000	-0.000	*N*
	10			0.000	0.000	-0.002	-0.001	-0.002	-0.001	*N*
	14			0.000	0.000	-0.001	-0.001	-0.001	-0.001	*N*

For other branches, we cannot state, whether the branch is correctly modeled, whether there is the inclusion error.

In the second part of Table IV, the unbalance indices for the area A^9, and also for the area A^4, create a set, that is also observed in the case of a completely correct topology model. In this situation, the reasonable identification decisions are neutral decisions.

C. Modeling Multiple Topology Errors

In the case of multiple TEs, the patterns of different TEs overlap each other. Such case is observed in the area A^4, in which there are two errors (Table V). In A^4, there are two incorrectly modeled branches, i.e. the branch 6 (the branch 3-4) and the branch 9 (the branch 4-9).

In this situation, identification of TEs is much more complex problem than identification of single TEs. However, also in this case, when in the system both considered branches (i.e. the branches 6 and 9) are in operation, decisions taken on the bases of outputs of the utilized ANNs are correct. When in the system, the branch 9 is out of operation (the second part of Table V), it is impossible to distinguish the error of inclusion of the branch into topology model from the correct modeling of this branch.

D. Incorrect Modeling of only the Node 9

The following cases of incorrect modeling of a node can be distinguished:

(i) incorrect splitting of a node,
(ii) incorrect merging of nodes.

TABLE V
UNBALANCE INDICES FOR THE AREAS TAKEN INTO ACCOUNT BY ANNS RELATED TO THE NODES 4 AND 9, AND IDENTIFICATION DECISIONS, WHEN THE BRANCHES 6 (3-4) AND 9 (4-9) ARE INCORRECTLY MODELED

i	*j*	W_{Pi}	W_{Qi}	W_{Pj}	W_{Qj}	W_{Pij}	W_{Qij}	W_{Pji}	W_{Qji}	*D*
		p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	
All the Branches are in Operation and the Branches 6 and 9 are Incorrectly Modeled										
4	2	0.393	-0.057	0.004	-0.002	-0.398	0.019	-0.389	0.046	*N*
	3			-0.231	0.028	-0.158	0.003	-0.152	0.019	*B*
	5			0.014	-0.003	-0.405	0.053	-0.407	0.047	*N*
	7			-0.001	0.002	-0.393	0.086	-0.393	0.055	*N*
	9			-0.162	0.016	-0.231	0.123	-0.231	0.054	*B*
9	4	-0.162	0.016	0.393	-0.057	-0.231	0.123	-0.231	0.054	*B*
	7			-0.001	0.002	0.163	-0.019	0.163	-0.016	*N*
	10			-0.001	0.000	0.164	-0.014	0.163	-0.016	*N*
	14			0.000	0.000	0.165	-0.010	0.162	-0.017	*N*
In the test system only the branch 9 is out of operation and the branches 9 and 6 are incorrectly modeled										
4	2	0.244	-0.052	-0.010	0.005	-0.234	0.007	-0.231	0.018	*N*
	3			-0.233	0.049	-0.006	-0.022	-0.006	-0.022	*B*
	5			0.006	0.001	-0.249	0.041	-0.250	0.038	*N*
	7			-0.002	-0.001	-0.241	0.065	-0.241	0.053	*N*
	9			0.002	0.001	-0.245	0.083	-0.245	0.051	*N*
9	4	0.002		0.244	-0.052	-0.245	0.083	-0.245	0.051	*N*
	7			-0.002	-0.001	0.000	-0.000	0.000	-0.000	*N*
	10			0.000	0.000	-0.002	-0.001	-0.002	-0.001	*N*
	14			-0.001	0.000	-0.001	-0.001	-0.001	-0.001	*N*

TABLE VI
UNBALANCE INDICES FOR THE AREAS TAKEN INTO ACCOUNT BY ANNS RELATED TO THE NODES 9A AND 9B, AND IDENTIFICATION DECISIONS WHEN THE NODE 9 IS INCORRECTLY MODELED

i	*j*	W_{Pi}	W_{Qi}	W_{Pj}	W_{Qj}	W_{Pij}	W_{Qij}	W_{Pji}	W_{Qji}	*D*
		p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	
In the test system there is no a split of the node 9 but such split is in the model										
9a	4	0.068	-0.051	-0.004	0.001	-0.065	0.053	-0.065	0.050	*N*
	9b			-0.067	0.053	-0.001	-0.002	-0.001	-0.002	*B*
	14			0.002	0.002	-0.069	0.050	-0.070	0.048	*N*
9b	7	-0.067	0.053	-0.001	0.002	0.067	-0.055	0.067	-0.054	*N*
	9a			0.068	-0.051	-0.001	-0.002	-0.001	-0.002	*B*
	10			-0.001	0.000	0.068	-0.052	0.068	-0.053	*N*
In the test system there is a split of the node 9 but there is no such split in the topology model										
9a	4	-0.002	0.000	0.006	0.000	-0.004	-0.000	-0.004	-0.000	*N*
	9b			0.003	-0.002	-0.002	0.002	-0.002	0.002	*N*
	14			0.002	0.000	0.000	-0.000	0.000	-0.000	*N*
9b	7	0.003	-0.002	0.008	0.003	-0.011	-0.001	-0.011	-0.001	*N*
	9a			-0.002	0.000	-0.002	0.002	-0.002	0.002	*N*
	10			0.000	0.000	-0.003	0.002	-0.003	0.002	*N*

In the case study, different cases of incorrect modeling of the node 9 are considered. Instead of the node 9 the nodes 9a and 9b occur (Fig. 3) and between them there is a zero-impedance branch (the branch 9a-9b). In this situation the problem of modeling the node 9 is treated as the problem of modeling the branch 9a-9b.

When there is the incorrect split of the node 9, in the first part of Table VI, we can see that values of the unbalance indices (for the area A^{9a} as well as for the area A^{9b}) create the characteristic sets for the case of error of exclusion of the branch 9a-9b.

When there is the incorrect merging of the nodes 9a and 9b, the method does not allow to distinguish the considered case from the case of correct modeling of the node 9 (the second part of Table VI).

E. Incorrect Modeling the Node 9 and the Branch 16

Cases of incorrect modeling the node 9 and the branch 16 (the branch 9-10) can be analyzed as the cases from subsection *C*, taking into account, that instead of the node 9 we have the nodes 9a and 9b and between the nodes 9a and 9b there is the zero-impedance branch.

TABLE VII
UNBALANCE INDICES FOR THE AREAS TAKEN INTO ACCOUNT BY ANNS RELATED TO THE NODES 9A AND 9B, AND IDENTIFICATION DECISIONS, WHEN THE NODE 9 AND THE BRANCH 16 (9-10) ARE INCORRECTLY MODELED

i	*j*	W_{Pi}	W_{Qi}	W_{Pj}	W_{Qj}	W_{Pij}	W_{Qij}	W_{Pji}	W_{Qji}	*D*
		p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.	
In the test system, there is no a split of the node 9 and the branch 16 is in operation. In the model there is a split of the node 9 and the branch 16 is switched off.										
9a	4	0.068	-0.051	-0.004	0.001	-0.065	0.050	-0.065	0.053	*N*
	9b			-0.014	0.096	-0.054	-0.045	-0.054	-0.045	*B*
	14			0.002	0.002	-0.070	0.048	-0.069	0.050	*N*
9b	7	-0.014	0.096	-0.001	0.002	0.015	-0.098	0.015	-0.097	*N*
	9a			0.068	-0.051	-0.054	-0.045	-0.054	-0.045	*B*
	10			-0.053	-0.043	0.067	-0.052	0.067	-0.053	*B*
In the test system there is a split of the node 9 and the branch 16 is in operation. In the topology model there is no a split of the node 9 and the branch 16 is switched off.										
9a	4	-0.002	0.000	0.006	0.000	-0.004	-0.000	-0.004	-0.000	*N*
	9b			0.035	0.062	-0.034	-0.062	-0.034	-0.062	*N*
	14			0.002	0.000	0.000	-0.000	0.000	-0.000	*N*
9b	7	0.035	0.062	0.008	0.003	-0.044	-0.065	-0.044	-0.064	*N*
	9a			-0.002	0.000	-0.034	-0.062	-0.034	-0.062	*N*
	10			-0.032	-0.064	-0.004	0.002	-0.004	0.002	*B*

VII. CONCLUSIONS

The described method is the method of topology-error identification based on the utilization of unbalance indices and ANNs. The method is very efficient in a case of single and multiple TEs, when there occur such errors as:

(i) branch-exclusion error,
(ii) node-split error,
(iii) error of switching off branch at one end when in a power system this branch is in operation.

The method does not distinguish the case of error of inclusion of a branch from the case of correct modeling this branch. The method does not distinguish the case of the incorrect merging of the nodes from the case of correct modeling these nodes, as well. The method will be further developed to eliminate these disadvantages. However, it should be also noted that when the method could not distinguish the earlier-mentioned cases it refrains from decision making, i.e. it takes the neutral decision.

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IX. Biographies

Dr Robert Lukomski was born in Ostrow Wielkopolski, Poland, in 1974. He received the M. Sc. degree in Electronic Engineering from Wroclaw University of Technology in 1999. He joined the Electric Power System Group in Institute of Electrical Power Engineering (Wroclaw University of Technology). He received the Ph.D. degree in 2002. His special fields of interest include modeling of power systems, especially real time modeling of power systems.

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