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A Simple Contingency Selection for Voltage Stability Analysis

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***Abstract*—The paper deals with a selection of potentially critical contingencies from the voltage stability view-point. Consideration of all contingencies is impractical. Before contingency analysis starts, one can state, that certain contingencies need not be taken into account. In the paper, after a short overview of the existing papers, in which the problem of the selection of contingencies is considered, the new method for selection of contingencies is presented. A selection of contingencies is based on results of testing of possible power transfers in a power network after the contingencies occur. During the tests, assessments of extreme values of active and reactive power flows, which change when power system state changes, are taken into consideration. In the paper, a computational example of utilization of the described method is given. At the end, the most important features of the method are pointed out.**

***Index Terms*—Load flow, power systems, power transmission, power system stability**

I. INTRODUCTION

One of the purposes of dispatcher is to ensure a secure operation of a power system. Among calculations made in a dispatcher centre to achieve this purpose there is also the contingency analysis, i.e. analysis of the loss/failure (L/F) of a small part of the power system (e.g. a transmission line), or L/F of individual equipment such as a generator or transformer [1].

The exhaustive investigations of contingencies (assuming consideration of all possible cases) are time-consuming. They comprise many cases of contingencies, which can be recognized as insignificant already at the beginning of investigation [1]. There exist many papers, in which the methods for contingency selection are presented [2]–[10]. Desired features of the contingency selection methods are high computation speed and effectiveness. The existing algorithmic methods are featured by short computation time but also by effectiveness, which is reduced by their drawbacks, e.g. dependence on masking effect of different contingencies. To overcome disadvantages of the algorithmic methods, different artificial intelligence techniques are used to develop more beneficial procedures for contingency selection, e.g. [7]–[9]. Analyzing existing papers, it can be noted, that new methods, which would be better from the view point of the mentioned desired features, are still searched.

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The aim of the paper is presentation of a new method for the contingency selection from the voltage-stability view point. In the paper, a new approach for the mentioned contingency selection is presented. It is an algorithmic one. It assumes examination of the necessary condition of fulfilment of power flow equations for a considered power system, what ensures possibility of detection of all critical contingencies.

II. GENERAL IDEA OF SEEKING CRITICAL CONTINGENCY IN A POWER NETWORK

For a stable power system, power flow equations are satisfied. In this paper, the necessary condition of that fact (further called *Condition N*) is formulated as: "The power delivered to a node is equal to the power received from it". When L/F of a branch in a power system occurs, the following cases can be distinguished: (i) there are changes of values of power flows in the power system but there are no changes of directions of these flows (*Case 1*), (ii) there are changes of values of power flows in the power system as well as at least some of directions of these flows (*Case 2*), (iii) there is no state of a power system for which power flow equations are satisfied (*Case 3*). In *Case 3*, there is no possibility to find solution of the power flow equations for the considered power system.

In the paper, it is assumed, that when L/F of any branch has place: (i) there are no changes of loads in the considered power system, (ii) *Case 1* is taken into account, (iii) a possibility of delivery of power to a node is examined with use of knowledge about extreme values of power flows on branches of a power system. The way of calculation of the mentioned extreme values of power flows is described in Section V.

If under earlier-given assumptions, for L/F of a branch, it is not possible to satisfy Condition N for at least one of the nodes with which the mentioned branch is connected, then the considered contingency is qualified as a candidate for the contingency analysis. In the set of such contingencies, there are L/Fs of branches for which in a power system, Case 2 or Case 3 can have place. However, in the paper, we follow the principle (further called as Principle G): "It is better to consider more contingencies in the contingency analysis than to ignore a critical contingency in this analysis".

III. IDEA OF SIMPLE SEEKING CRITICAL CONTINGENCY IN A POWER NETWORK

In a radial power network, if we observe L/F of an individual branch and in consequence there is not possibility to meet *Condition N*, such power as before cannot be delivered to the appropriate load nodes. In this situation, there is not possibility to find a state of a power system in which such powers as initially could be received from all load nodes. The mentioned L/F of a branch is a contingency, which should be taken into account in contingency analysis.

Generally, in a looped power network, one can point out such load nodes which are powered by more than one branch. In not all cases, L/F of an individual branch leads to unfulfillment of *Condition N* for the considered node. If there are several nodes which are connected with the examined load node (let us assume that it is the node N_x), then the power delivered to all these nodes should cover the power required by the node N_x and power losses on branches connecting the node N_x with neighboring nodes. Further, the last sentence is called as *Condition MN*. If from any reasons *Condition MN* is not fulfilled, then it is not possible to find a state of a power system in which such power, as before an event violating *Condition MN* occurs, can be received from the node N_x. If the earlier-mentioned event is L/F of the individual branch connected to any node (for example the node N_y) neighboring with the node N_x, then unfulfillment of *Condition MN* is a consequence of unfulfillment of *Condition N* for the node N_y. It should be underlined, that not always unfulfillment of *Condition N* for the node N_y leads to unfulfillment of *Condition MN*.

Searching for the set Ω, being a set of events which potentially cause unfulfillment of *Condition MN*, can be performed by examination of events causing unfulfillment of *Condition N* for all nodes which are neighbors to the node N_x,. In that situation, the set Ω can contain events, for which in fact *Condition MN* is fulfilled. According to *Principle G*, that idea is utilized in the paper. The set Ω is a set of contingencies which in this paper are proposed to consider in contingency analysis. The important feature of the mentioned idea of searching the set Ω is its simplicity.

The earlier-described idea of seeking events, which violate the condition of delivery of appropriate power to the node N_x, can be generalized for cases when the nodes, for which *Condition N* is examined, are not directly connected with the node N_x.

IV. INDICES USED FOR EXAMINATION OF THE CONDITION *N* FOR A DISTINGUISHED NODE

To find, that the required active power P or the required reactive power Q can occur on the branch between nodes i and j (i.e. the branch i-j) in a power system, we should know the extreme possible values of the active power or the reactive power for the branch i-j. These extreme values for particular branches are utilized during examination of *Condition N* for the nodes of the considered power system.

For the purposes of examination of *Condition N* for the node j, the following indices for particular branches connected with the mentioned node are tested:

$$\eta_{P,jl} = \begin{cases} \sum\limits_{i\in Jp+\backslash\{l\}} P_{ji,\max} - \sum\limits_{i\in Jp+} P_{ji}, & \text{when } l \in Jp+,\\ \sum\limits_{i\in Jp-} P_{ji} - \sum\limits_{i\in Jp-\backslash\{l\}} P_{ji,\min}, & \text{when } l \in Jp-, \end{cases} \qquad (1)$$

$$\eta_{Q,jl} = \begin{cases} \sum\limits_{i\in Jq+\backslash\{l\}} Q_{ji,\max} - \sum\limits_{i\in Jq+} Q_{ji}, & \text{when } l \in Jq+,\\ \sum\limits_{i\in Jq-} Q_{ji} - \sum\limits_{i\in Jq-\backslash\{l\}} Q_{ji,\min}, & \text{when } l \in Jq-, \end{cases} \qquad (2)$$

where J_p+, J_p- are the sets of the numbers of nodes connected with the j-th node by the branches, at which ends at the j-th node the active power flows are positive and negative, respectively; J_q+, J_q- are the sets of the numbers of nodes connected with the j-th node by the branches, at which ends at the j-th node the reactive power flows are positive and negative, respectively; l is the number of node connected with the j-th node by the branch, of which L/F is considered; P_{ji}, Q_{ji} are, respectively, active and reactive power flow on the branch i-j at the node j; $P_{ji,\max}$, $Q_{ji,\max}$ are, maximal values of P_{ji} , if $i \in J_P+$ and Q_{ji}, if $i \in J_Q+$, respectively; $P_{ji,\min}$, $Q_{ji,\min}$ are, minimal values of P_{ji} , if $i \in J_P$- and Q_{ji}, if $i \in J_Q$-, respectively.

If any of the earlier-defined indices is less than 0, then the branch l-j should be taken into account during the contingency analysis. L/F of that branch causes unfulfillment of *Condition N* for the node j.

V. EXTREME VALUES OF THE POWER FLOWS ON THE BRANCH

In a stable state of a power system, the power flow equations are satisfied. The mentioned statement means that for every branch, the active as well as reactive power flow does not exceed appropriate extreme value. The extreme value of active or reactive power flow on the considered branch can be found analysing equation of power flow for that branch.

In the paper, the pi-model of the branch is taken into consideration (Fig. 1).

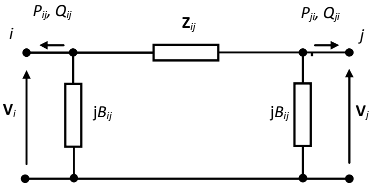

Fig. 1. The assumed pi-model of the branch. $Z_{ij} = R_{ij} + \mathrm{j}\, X_{ij}$, B_{ij} is a half of the capacitive susceptance of the branch.

The complex power flow on the branch i-j (Fig. 1) at the j-th node is as follows: $\mathbf{S}_{ji} = \mathbf{V}_j \mathbf{I}_{ji}^*$, where $\mathbf{I}_{ji} = (\mathbf{V}_i - \mathbf{V}_j)/\mathbf{Z}_{ij} - j0.5B_{ij}\mathbf{V}_j$.

Let us assume $\mathbf{V}_j = \mathbf{I}_{ji}\,\mathbf{Z}_j$. The active and reactive power flows on the branch i-j at the j-th node are as follows: $P_{ji} = S_{ji} \cos \varphi_j$, $Q_{ji} = S_{ji} \sin \varphi_j$, where:

$$S_{ji} = \frac{V_i^2}{Z_{ij}} \frac{Z_j}{Z_{ij}} \Bigg/ \left(\frac{A^2}{Z_{ij}^2} + \frac{B^2}{Z_{ij}^2} \right), \qquad (3)$$

$$A = \left(Z_{ij} \cos\theta_{ij} + Z_j \cos\phi_j - 0.5 B_{ij} Z_{ij} Z_j \sin\left(\theta_{ij} + \phi_j\right) \right)^2, \quad (4)$$

$$B = \left(Z_{ij} \sin\theta_{ij} + Z_j \sin\phi_j + 0.5 B_{ij} Z_{ij} Z_j \cos\left(\theta_{ij} + \phi_j\right) \right)^2, \quad (5)$$

where V_i is a magnitude of $\mathbf{V}_i$; Z_j, φ_j are a magnitude and an argument of $\mathbf{Z_j}$, respectively; Z_{ij}, θ_{ij} are a magnitude and an argument of $\mathbf{Z_{ij}}$, respectively.

The extreme values of P_{ji} and Q_{ji} with respect to Z_j are as follows: $P_{ji,\mathrm{extr}} = S_{ji,\mathrm{extr}} \cos\varphi_j$, $Q_{ji,\mathrm{extr}} = S_{ji,\mathrm{extr}} \sin\varphi_j$, where

$$S_{ji,\mathrm{extr}} = \frac{V_i^2}{Z_{ij}} \Big/ \left(\sqrt{D} + 2\cos\left(\theta_{ij} - \phi_j\right) - B_{ij} Z_{ij} \sin\phi_j \right), \quad (6)$$

where $D = 1 - B_{ij} Z_{ij} \sin\theta_{ij} + 0.25 B_{ij}^2 Z_{ij}^2$.

VI. Idea of Advanced Seeking Critical Contingency in a Power Network

If many branches deliver power to the considered node (e.g. the node j), *Condition N* can be fulfilled but in fact, L/F of certain branch (let us assume the branch l-j) from the mentioned ones is critical contingency. To reveal such contingency, testing branches on paths of delivery of required power to the node j, but not comprising the branch l-j, should be performed. During that test, possibility of transmission of the increased power by every considered branch is verified, using the following indices:

$$\eta_{P1,xy} = \begin{cases} P_{xy,\max} - \left(P_{xy} + \Delta P_{xy}\right), & \text{when } P_{xy} > 0, \\ \left(P_{xy} + \Delta P_{xy}\right) - P_{xy,\min}, & \text{when } P_{xy} < 0, \end{cases} \quad (7)$$

$$\eta_{Q1,xy} = \begin{cases} Q_{xy,\max} - \left(Q_{xy} + \Delta Q_{xy}\right), & \text{when } Q_{xy} > 0, \\ \left(Q_{xy} + \Delta Q_{xy}\right) - Q_{xy,\min}, & \text{when } Q_{xy} < 0, \end{cases} \quad (8)$$

where P_{xy}, Q_{xy} are, respectively, active and reactive power flow on the branch x-y at the node x before L/F of the branch l-j occurs; ΔP_{xy}, ΔQ_{xy} are, respectively, increase of the active and reactive power flow on the branch x-y at the node x as a result of L/F of the branch l-j.

It is assumed, that whole power delivered by the branch l-j to the node j is taken into account for calculation of ΔP_{xy} and ΔQ_{xy}. Hereby, in the paper, the worst conditions of a transfer of the power required at the node j are considered. If there is a path comprising branches, for which the indices $\eta_{P1,xy}$, $\eta_{Q1,xy}$ are positive and a generator feeding this path can deliver the required power then there is no basis to state that L/F of the branch l-j is a critical contingency.

If at least one of the indices $\eta_{P1,xy}$, $\eta_{Q1,xy}$ for a branch x-y is negative, then the appropriate power cannot be delivered by the considered path to the node j, i.e. for this path the test of possibility of delivery of the required power to the node j is negative. If for the node j, only such power delivery paths can be found, then L/F of the branch l-j is a critical contingency.

VII. Principle of the Method

The method comprises the following steps:

1. Calculation of extreme values of power flows at the ends of the branches of the considered power system.
2. Simple examination of fulfilment of *Condition N* for L/Fs of separate branches and creation of the set S_{cc}. The set S_{cc} is a set of contingencies proposed for taking into account in contingency analysis. If at least for one of terminal nodes of the branch *i-j*, its L/F entails unfulfillment of *Condition N*, then the mentioned contingency is qualified as a potentially critical one and it is inserted into the set S_{cc}.
3. Advanced examination of fulfilment of *Condition N* for L/Fs of separate branches for which the examination in the Step 2 does not give the base to ascertain that the considered contingency is potentially critical one. If contingency is recognized as potentially critical one, it is inserted into the set S_{cc}.

VIII. Computational Example

The example shows a part of calculations for the IEEE 118-bus test system. During the calculations, the modifications of loads in considered test system, which are shown in Table I, were assumed.

TABLE I. MODIFICATIONS OF LOADS IN THE CONSIDERED TEST SYSTEM.

Bus no.	P_{load}	Q_{load}	Bus no.	P_{load}	Q_{load}	Bus no.	P_{load}	Q_{load}
2	0.60	0.27	59	5.54	2.26	101	0.44	0.30
3	1.17	0.30	60	3.12	0.12	102	0.10	0.06
12	0.705	0.15	62	1.54	0.28	103	0.46	0.32
13	0.68	0.32	67	0.56	0.14	105	0.62	0.52
14	0.28	0.02	80	1.56	0.312	106	0.86	0.32
16	1.00	0.40	82	0.81	0.405	108	0.04	0.02
20	0.36	0.06	84	0.165	0.105	109	0.16	0.06
21	0.28	0.16	88	0.72	0.15	110	0.78	0.60
22	0.40	0.20	90	2.445	0.63	112	1.36	0.26
28	0.51	0.21	95	0.63	0.465	116	3.68	0.00
29	0.48	0.08	96	0.57	0.225	118	0.495	0.225
44	0.32	0.16	99	0.84	0.00			
45	1.06	0.44	100	0.74	0.36			

In this example, the part of the test system is considered (Fig. 2). The power flows at the ends of the branches shown in Fig. 2 are given in Table II. Positive value of an active power flow or an inductive reactive power flow indicates that this flow enters the node, at which it is considered.

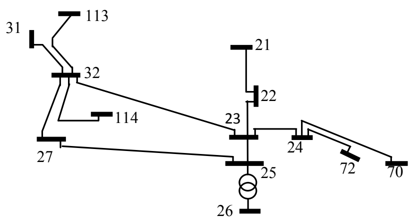

Fig. 2. The considered part of the test system.

In the example, L/Fs of the branches connected to the node 23 (Fig. 2) are taken into account.

At the beginning of the utilized procedure, the extreme values of power flows at the ends of branches of the test ystem (see Section V) are calculated. Results of these calculations are shown in the Table II.

The indices: $\eta_{P,ij}$, $\eta_{Q,ij}$, $\eta_{P,ji}$ and $\eta_{Q,ji}$ for branches connected to the node 23, which are shown in Table III, are calculated using the data from Table II. Analysing Table III, we can see that for each considered branch at least one of the mentioned indices is negative. In this situation, L/F of each branch given in Table III should be considered as potentially critical contingency.

TABLE II. POWER FLOW DATA.

Node *i*	Node *j*	P_{ji}	Q_{ji}	$P_{ji,extr}$	$Q_{ji,extr}$
22	23	-1,056	-0,306	-4,550	-1,320
24	23	1,588	-0,375	7,457	-1,759
25	23	1,061	0,582	2,656	1,458
32	23	-1,524	0,129	-4,131	0,349
21	22	-0,613	0,057	-4,617	0,427
23	22	1,013	0,143	1,833	0,259
23	24	-1,626	0,288	-8,612	1,525
70	24	0,955	-0,283	1,309	-0,389
72	24	0,801	-0,316	2,147	-0,847
23	25	-1,084	-0,609	-12,297	-6,912
27	25	-1,682	-0,312	-3,790	-0,704
26	25	0,565	0,195	10,016	3,452
23	32	1,448	-0,293	3,106	-0,629
31	32	-0,585	0,206	-3,554	1,250
27	32	0,047	0,059	1,656	2,082
113	32	-0,184	0,216	-0,804	0,943
114	32	-0,136	-0,009	-8,923	-0,571

TABLE III. RESULTS OF ANALYSES.

Nodes		Indices				n-1 analysis	
i	*j*	$\eta_{P,ij}$	$\eta_{Q,ij}$	$\eta_{P,ji}$	$\eta_{Q,ji}$	PCS	RCS
22	23	-1,013	0,227	1,551	1,078	NC	FP
24	23	-1,626	-0,288	0,007	0,639	NC	NC
25	23	1,024	-0,217	4,808	-0,362	CP	CP
32	23	-1,448	0,269	1,97	0,747	NC	CP

To verify effectiveness of the presented method, the n-1 contingency analysis for the test system has been realized. The results of that analysis for the considered part of the test system are in Table III, as well. The n-1 analysis was performed using the polar coordinate system (PCS) and the rectangular coordinate system (RCS) in power flow calculations. One can point out cases, when calculations in different coordinate systems give different results. We have the cases in which the results of power flow calculations: (i) are in a permissible area (PA), (ii) are close to the permissible area, (CP), (iii) are far from a permissible area (FP), (iv) can not be obtained, as the calculations are non-convergent (NC). In the cases PA, CP, FP, magnitudes of the node voltages differ from the nominal value not more than 10 %, 10-20 % and more than 20 %, respectively. The n-1 analysis shows that only L/Fs of branches 22-23 and 23-24 can be recognized as critical contingencies. When L/F of the branch 23-32 is taken into account, the result of the n-1 analysis cannot be considered as pointing to this contingency as a potentially critical one. In this case, the non-convergence of the power flow calculations in PCS should be treated as an effect of numerical problems.

Analysis of the whole test system allows noticing, that a number of branches, of which L/Fs are qualified by the described method as potentially critical contingencies is essentially less than total number of branches in the system. The mentioned number of potentially critical contingencies is about 67 %.

IX. CONCLUSIONS

The presented method allows a selection of contingencies (a contingency screening) for the voltage stability analysis, i.e. solving one of the problems existing before a contingency analysis, which are the contingency screening and the contingency ranking. The method is based on the original approach assuming utilization of the necessary condition of fulfilment of power flow equations for a power system, which is as follows: “The power delivered to a node is equal to the power received from it”. It is possible to make examination of particular L/F of branches from the view point of the mentioned necessary condition if extreme values of the power flows on the branches of a power system are known. In the paper, the formulas for these extreme power flows are derived assuming the pi-model of a branch. In other papers, a branch is characterized only by resistance and inductive reactance. The earlier-indicated formulas have been derived for a branch as the element of a looped power network and not as the element of a radial power network what is presented in the literature.

Utilization of the above-given necessary condition assures that a list of selected contingencies can be larger than the list of only critical contingencies, but the obtained list comprises all critical contingencies. That fact is an important feature of the presented method. Other feature of the method is that calculations are performed separately for particular branches using only relatively simple operations on results of load flow calculations.

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