IDENTIFICATION OF MULTI SIMULTANEOUS ANOMALIES BY INNOVATION GRAPH APPROACH

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Abstract – Blackouts often occur accompanied by network topology change as well as tripping loads or generators, and in many cases topology structure changes are the precursor of a blackout. It is very meaningful to identify multi simultaneous anomalies of bad data, sudden load change and topology error correctly to prevent blackout, especially where the measurements and status information are poor. The paper tries to solve this problem by innovation graph approach. The concept of sudden change loop can be used to identify sudden load or generation changes, and the identification problem of multi simultaneous anomalies is preliminary solved.

Key words: power system state estimation, topology error, sudden load change, innovation graph

1 INTRODUCTION

Blackouts often occur accompanied by network topology change as well as tripping loads or generators, and in many cases topology structure changes are the precursor of a blackout. In the process when a blackout develops, the static state estimation is sometimes not able to provide the system states, neither is the dynamic state estimation.

Generally, the state estimation with forecasting function is superior to static state estimation in handling bad data and topological error, because the innovation vector includes some helpful historical information. The innovation graph approach coming from innovation vector and network graph theory can identify simultaneous topological error and bad data [1-4], making greater improvement to topological error identification capability. However, when three anomalies of sudden load change (SLC), bad data and topological error appear simultaneously, the identification problem remains difficult, and further investigation is needed. This paper tries to give a preliminary discussion to this.

Sudden load change (called sudden state change in some papers) means unexpected systematic operational state change resulting from power injection change at a load or generation bus. Sudden load change may take place simultaneously with the topology change especially in the process that blackout develops. When the topological structure of the electric power system changes, it may cause the power injection change at a bus unexpected in most cases, for example, it may cut the load in a chain while tripping a branch.

When the unexpected sudden load change takes place, as it cannot be predicted, the prediction state deviates from the actual operation state. This results in many innovation vector elements far from zero. Bad data and topological change can also induce a lot of heavy absolute value of innovation vector elements. When sudden load change, bad data and topological structure change take place in a close place in electric distance at the same time, we called it three overlap case. In this case it is more difficult to identify, since the elements with large absolute values caused by each of them are mixed together. Up to date, we only see some papers handling the above anomalies individually, or detecting topology errors or sudden state changes with bad data [5-8].

This paper proposes a method to identify the three overlap of sudden load change, topological structure change and bad data by means of innovation graph. First, the much simpler overlap of two anomalies of topology error and sudden state change is studied assuming no bad data. The sudden change loop shown in the innovation difference graph is employed to identify the bus of SLC. The topology error can be identified after the SLC is detected and identified. Then, the overlap problem of multi anomalies is studied, by distinguishing the different characteristics of the bad data and SLC. After the bad data is identified, the three-overlap case turns to the two-overlap one and the problem is solved. The identification capability of the innovation graph has been improved notably.

2 INNOVATION DIFFERENCE VECTOR

Paper [1-4] proposed the innovation graph as a carrier of innovation vector to identify topology error. Employing the DC load flow model, the innovation graph has established a relationship, which follows the Kirchhoff's circuit law, among innovation elements. Therefore, bad data and topology error can be identified easily.

In the simplified innovation graph [4] without considering sudden load change, all injection innovation sources are considered to be equal to zero. A tree is selected by firstly choosing measured branches as links. This requirement is easy to be satisfied, since the number of the link branches is lower in the power network. Link values have the meaning of 'loop current' and the tree branch values have the meaning of 'branch current'. The branch current can be expressed as algebraic sum of certain loop currents. Putting the measured branch into link can make the loop current a known quantity given by its measurements. Therefore, the link reckoning innovation can be obtained by

$$\boldsymbol{P}_{\mathrm{RECKON}}=\boldsymbol{C}\boldsymbol{P}_{\mathrm{LINK}} \tag{1}$$

where $\boldsymbol{P}_{\mathrm{LINK}}$ is the active power innovation on the link with dimension b-n+1, $\boldsymbol{P}_{\mathrm{RECKON}}$ is the link reckoning innovation vector with dimension b, and $\boldsymbol{C}$ is the branch- loop incidence matrix of dimension $b\times(b-n+1)$.

The difference of active innovation vector with the link reckoning innovation vector is called innovation difference vector. Namely

$$\boldsymbol{P}_{\mathrm{INNVDIF}}=\boldsymbol{P}_{\mathrm{INNV}}-\boldsymbol{P}_{\mathrm{RECKON.m}} \tag{2}$$

where $\boldsymbol{P}_{\mathrm{INNVDIF}}$ is innovation difference vector, $\boldsymbol{P}_{\mathrm{INNV}}$ is the active power innovation vector corresponding to measurements, and $\boldsymbol{P}_{\mathrm{RECKON.m}}$ is part of the link reckoning innovation vector corresponding to the branch being measured.

3 IDENTIFICATION OF SLC AND TOPOLOGY ERROR

When an unknown SLC occurs at time interval between k and $k+1$, the load forecasting made at time k is impossible to predict it. Then the measured and the forecasted values of the injection power of the corresponding bus differ greater, so the innovation source at this bus deviates zero value obviously. It should remain in the innovation graph, not being neglected as in Paper [4].

In the 5 -node system of Fig.1, branch 3-4 is opened followed by load tripping at bus 4. The injection source of bus 4 should remain in Fig. 1(a), not being neglected as in other buses. It is expressed as an earthing (grounding) link and the earthing branch at swing bus is expressed as a tree branch. Supposing earthing bus is n_0, the bus of sudden load change is s and swing bus is n_{swing}, then the earthing link at bus 4 is s - n_0, and the earthing tree branch is n_{swing}- n_0. In this way, in an n-bus b branch network, the earth bus should be counted. The bus number adds 1, equal to $n+1$, and the tree branch number adds 1 correspondingly.

Fig.1 (a) lines out the innovation values of branch flows and bus injections under the condition of the SLC and topology error, and their measured values and forecasting values are listed in Table 1. In no bad data condition, the measurements reflect the real system state, so the innovation vector contains the information of SLC. However link reckoning innovation vector calculated from Equation (1) does not reflect the sudden state

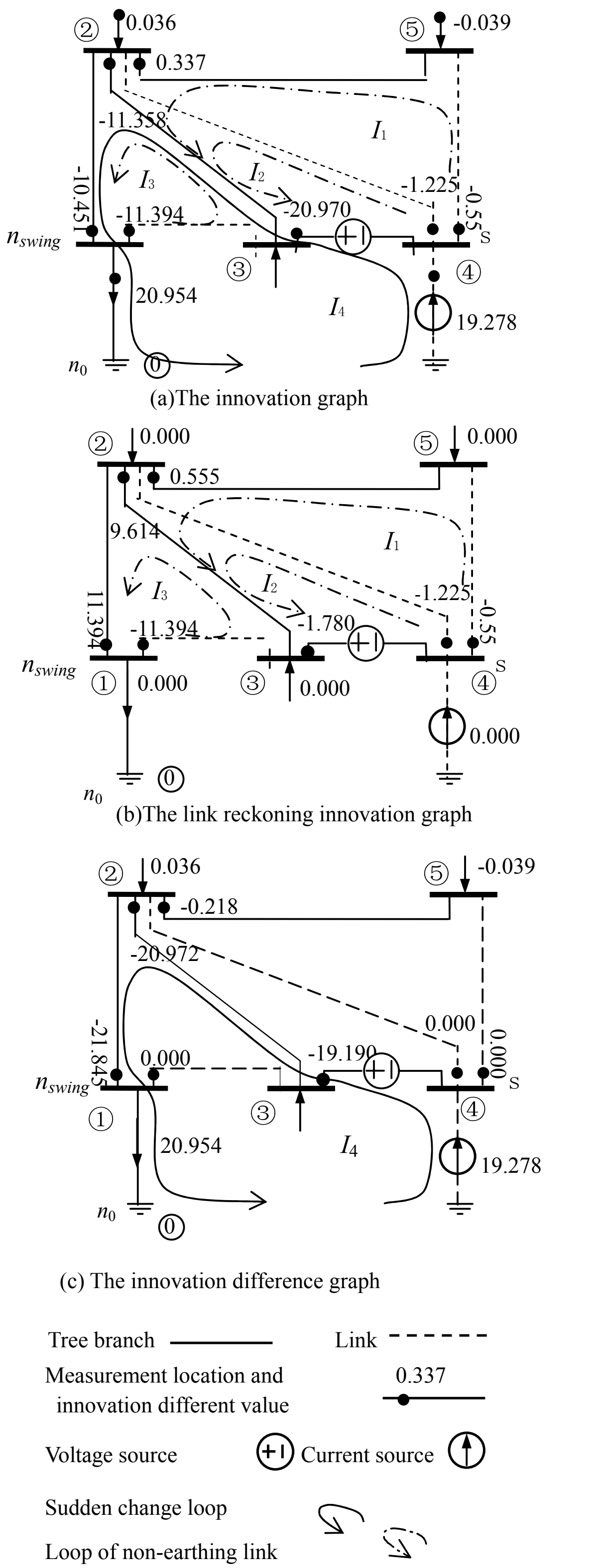


Fig. 1 The Innovation graph and innovation difference graph of IEEE-5 system under topology error and sudden load change /MW

since we suppose the innovation values of all bus injection powers being zero first, as shown in Fig. 1(b). In this way, the link reckoning innovation elements located at tree branches, first calculated under SLC condition, will inevitably deviate the actual value, but the deviation can be detected and identified from innovation difference graph.

The innovation difference graph is the carrier of the innovation difference vector, as shown in Fig.1(c). The innovation difference element values are marked on their corresponding branches. The values on branch 1-2, 2-3 and 3-4 are evidently large and relatively heavy closer around 20 MW in absolute values. Other absolute values are much smaller. It may still be seen that a circulation flow is formed by these large innovation difference values. The loop contains three tree branches, two earthing branches at swing bus and load change bus 4 respectively. This loop is named the loop of sudden change.

In innovation difference graph, the "loop current" I_4 in the sudden change loop is obviously nonzero, and other loop currents (I_1, I_2, I_3) are nearly zero. Therefore each branch current in sudden change loop is obviously nonzero. This has general meaning: it can be applied not only in 5-bus system, but also in a larger system.

In the innovation difference graph, after the loop of sudden change is detected and the sudden change bus is identified, the link reckoning innovation vector can be updated, and the error can be eliminated.

If a sudden load change occurs at one bus, the number of links is added by 1, so the loop number is increased by one also. Now, the innovation vector network is $n + 1$ bus, $b + 2$ branch system (+ 2 meaning an earthing tree branch and an earthing link have been increased). It has $b\text{-}n + 2$ links, that is to say $b\text{-}n + 2$ independent loops. The branch – loop incidence matrix is

$$\boldsymbol{C}' = \begin{pmatrix} 0 & 1 \\ \boldsymbol{C} & \boldsymbol{D} \\ 0 & 1 \end{pmatrix} \tag{3}$$

where $\boldsymbol{C}$ is the branch - loop incidence matrix without considering sudden load change, and $\mathbf{C}'$ is the branch - loop incidence matrix with dimension (b + 2) ×(b-n + 2) , taking into account sudden load change. The first row of matrix $\mathbf{C}'$ corresponds to the newly added swing earthing tree branch, and the last row corresponding to the earthing link of sudden load change. $\boldsymbol{D}$ is a vector of dimension b, the nonzero elements of which corresponds to the non-earthing tree branch in the sudden change loop. Let each innovation value of corresponding branch in Fig.1 (a) reduce with that in Fig.1 (b), we have

$$\boldsymbol{C}'\begin{pmatrix} \boldsymbol{P}_{LINK} - \boldsymbol{P}_{LINK} \\ P_s - 0 \end{pmatrix} = \boldsymbol{C}'\begin{pmatrix} 0 \\ P_S \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ \boldsymbol{C} & \boldsymbol{D} \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 0 \\ P_s \end{pmatrix} = \begin{pmatrix} P_S \\ \boldsymbol{D}P_S \\ P_S \end{pmatrix} \quad (4)$$

where P_s is the active power flow innovation value at the branch of sudden load change bus to earth, indicating the changed injection value at this bus. Equation (4) shows when there is a sudden load change, the innovation difference values are all P_s in the sudden load loop, which is composed by an earthing link and an earthing tree branch and all the tree branches corresponding to the nonzero elements of vector $\boldsymbol{D}$. Therefore after the link reckoning innovation is calculated, the innovation difference vector, locating at non earthing branch, is

$$\boldsymbol{P}_{INNVDIS} = \boldsymbol{P}_{INNV} - \boldsymbol{P}_{RECKON} = \boldsymbol{D}P_s \quad (5)$$

Equation (5) is a part of Equation (4) corresponding with non-earthing branches. It shows that when load sudden change of value P_s occurs, the link reckoning innovation vector calculated by Equation (1) missed the item $\boldsymbol{D}P_s$, so the calculation has deviated from actual value. However, we can make use of this deviation to find the sudden change bus. The sudden change loop indicated by $\boldsymbol{D}P_s$ in the innovation difference vector can show the SLC occurrence, and the earthing link in the loop indicates the location of the SLC bus.

Now, the link reckoning innovation vector has to be updated according to item $\boldsymbol{D}P_s$, to make it correct reflect the actual condition of load sudden change. The calculation results, after the deviation of link reckoning innovation vector been updated according to Equation (5), are shown in Table 1. The absolute values of innovation difference vector are all smaller, and the loop of sudden load change disappears. The link reckoning innovation vector correctly reflects the condition of load sudden change, and topological error can be identified by the ratio of corrective / predictive flow [4] defined in the innovation graphs. According to its lower ratio, topology error located in branch 3-4 can be identified. The corrective power flow equals to the sum of the link reckoning innovation value (after updating and getting rid of bad data) and the

Branch	Location of meas.	Measurement value (MW)	Forecast (MW)	Innovation (MW)	Link reckoning innovation (MW)	Innovation difference (MW)	Corrected load flow (MW)	Ratio of corrective / predictive
1-2	P_{12}	72.318	82.768	-10.451	-7.884	-2.567	74.885	0.9047
2-3	P_{23}	22.292	33.650	-11.358	-9.663	-1.694	23.986	0.7128
2-5	P_{25}	22.876	22.539	0.337	0.555	-0.218	23.093	1.0246
3-4	P_{34}	0.036	21.006	-20.970	-21.058	0.09	-0.052	0.0025
1-3	P_{13}	34.567	45.962	-11.394	-11.394	0.0 (link)	34.567	0.7521
4-2	P_{42}	-37.737	-36.512	-1.225	-1.225	0.0 (link)	-37.737	1.0336
4-5	P_{45}	-16.765	-16.211	-0.555	-0.555	0.0 (link)	-16.765	1.0342

Table 1 The results after the verifying the link reckoning innovation vector without bad data

predicting value, and the ratio of corrective/ predictive is the ratio of corrective power flow to the forecasting value [4].

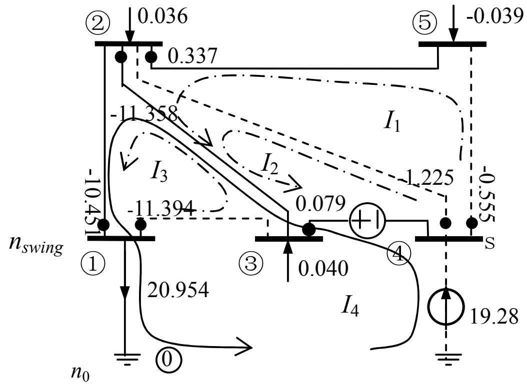
4 IDENTIFICATION OF MULTI ANOMALIES OF SUDDEN LOAD CHANGE, TOPOLOGY ERROR AND BAD DATA

When there are bad data in the measurements, isolated bad data or bad loop will show up in the innovation difference graph [4]. Here it is required to distinguish bad loop and the sudden change loop. Only after load sudden change and bad data are identified respectively, the topology error can be identified correctly.

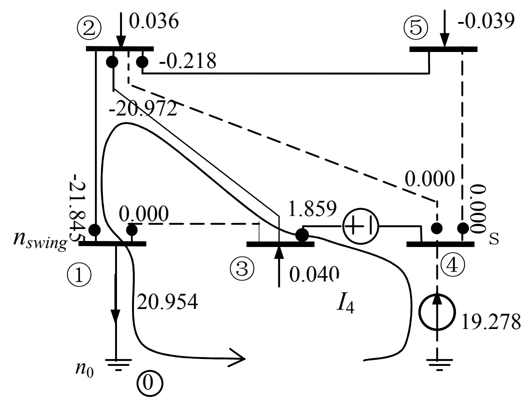
Fig. 2(a) shows the innovation value under the condition of simultaneous three anomalies. The difference from Fig. 1(a) lies in that the measured value in branch 3-4 is bad data. Then the innovation value of branch 3-4 is close to zero and it is hard for general method to discover its operation state change. The preliminarily calculated link reckoning innovation vector is the same as Fig. 1(b), since the bad data, located in the tree, does not affect reckoning results.

Innovation difference vector elements are shown in Fig. 2(b). Because of the appearance of bad data, two innovation difference vector elements with greater and equal absolute values correspond to tree branch 1-2 and 2-3. The sudden change bus is perhaps bus 3. However, the active injection power innovation value of bus 3 is more approximate to zero, and that of bus 4 is more approximate to the innovation difference value in the loop of sudden change.

Therefore, we know the measurement value of branch 3-4 is bad data, which has not turned into 0 along with the disconnection of the branch. Results of the updated link reckoning innovation vector (LRIN) elements according to Equation (5) are listed in Table 2. The table shows that the sudden change loop disappears and the link reckoning innovation vector have correctly contained the information of the load sudden change. From the elements of innovation difference vector, we know that the measurement of branch 3-4 is bad data, and the ratio of corrective/ predictive flow, of smaller value, indicates the topology error located in branch 3-4.



(a) The innovation graph



(b) The innovation difference graph

Fig. 2 An IEEE-5 bus example including sudden load change, topology error and bad data

The measurement redundancy required for identification of three anomalies is higher than two anomalies. On the one hand, we can use injection innovation value to identify branch bad data and sudden load change, as described in the above example. On the other hand, if the bus injection measurement becomes bad data, we can use the branch innovation difference values to identify sudden load change and the bad injection data according to the concept of sudden change loop. In

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4-5	P_{45}	-16.765	-16.211	-0.555	-0.555	0.0(link)	-16.765	1.0342

Table 2 The results after the verifying the LRIN with bad data load change，bad data and topology error /MW

addition, the innovation value of the swing bus injection is an indicator of a sudden load change.

In the above-mentioned example, bad data is located in the tree. When bad data is located in a link, a bad loop will show up in the innovation difference graph. Now the condition may be a little complex, but the method can still distinguish between the bad loop and the sudden change loop.

The difference of bad loop and the sudden change loop lies in whether the loop needs to pass the earthing bus n_0 to form a complete loop. The bad loop needs a non-earthing link to form complete loop, while the loop of sudden change contains an earthing tree at swing bus, and needs an earthing link at the bus of sudden change to form its complete loop.

After detecting a bad loop corresponding to a link data, the link can be alternated with a tree branch, i.e. the structure of the tree is changed. Then the link bad data will be turned into tree branch [1-4], the bad loop disappears, and the problem becomes the above discussed identification problem of sudden load change, topology error and bad data in the tree branch.

After identifying the bus of sudden load change, link reckoning innovation vector is updated according to Equation (5). Topology error and bad data can be identified by the method written in [1-4]. The bad data in tree branch can be identified according to the isolated innovation difference element; topology error can be identified according to the corrective/ forecast ratio.

The paper uses the five-bus system as an example, but the principle explained has general meaning: it is all the same and is suitable for a greater system. This method may be applied to the condition where bus load forecasting is not very accurate. When the prediction error in bus injection power is greater, link reckoning innovation, vector can also be modified and the influence of forecast error can be removed. So the requirement for forecasting value becomes lower.

5 CONCLUSION

Sudden change loop is the indicator of sudden load change. It differs from the bad loop in that it needs the grounding bus to form its loop in the assumption of one sudden load changes. The method first identifies bad data and sudden load change, and then, topology error can be identified. The poor condition of multi anomalies can be preliminarily solved. This is very significant for security supervisory and preventing blackout.

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