DETERMINATION OF THE MINIMUM NUMBER OF SHARED PHASOR MEASUREMENTS FOR A NEW LINE OUTAGE DETECTION APPROACH IN EXTERNAL POWER NETWORK

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Security analysis is one of the most important functions employed by power system operators to prevent undesired cascading contingencies leading to a blackout, in an ultimate phase. To improve the security analysis of an internal power network, the accurate modeling of the external network is important in an interconnected power system. In this paper, a new methodology is proposed to identify the line outage in an external power system by using the minimum PMU measurements shared by the external system. This method is organized in several steps. First, the branches of an external power system that their outages have the considerable effect on the flow of tie-lines are identified. These branches are called critical lines. Then, based on a sensitivity analysis technique, the most sensitive measurements are identified with respect to the outage of critical lines. After that, an algorithm is proposed to prioritize these measurements to determine the minimum number of the required measurements. All of these steps are done with the help of a new artificial neural network-based approach. The proposed method is tested on a real power network which is a part of Iranian power system. Simulation results show the effectiveness of the proposed method.

Keywords: Interconnected Power System, Phasor Measurement Unit, Artificial Neural Network, Security Analysis

1. Introduction

Security analysis is one of the most important functions employed by power system planners and operators to prevent cascading contingencies leading to the system blackout in an ultimate phase. Nowadays, by the rapid increase in demands; the growth of the power generation; the disproportional expansion of the

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transmission network; power system restructure and some other similar circumstances, the power level transmitted through transmission lines is increased. This causes the stability margins of power networks to be degraded intensively [1-4]. Accordingly, power systems are operating close to their instability boundaries for a long period in a day. This shows the importance of the contingency analysis, which is a key component of the security assessment. The main objective of this analysis is to ensure that all elements of the power system are operating under allowable thermal restrictions without violating the node voltages from the predefined desired ranges [5].

In the interconnected power systems, operators and planners have accurate and on-line information on the status of the circuit breakers as well as the operating conditions of the system under their management. However, their information on the neighboring power systems, aggregately called the external network, includes the off-line data or limited to the virtual measurements obtained from the load forecasting estimations or power generation scheduler functions. In other words, the real-time data shared by the inter-utility real-time measurement exchange system are restricted [6].

Having no on-line access to the external power network topology is one of the most effective factors which leads to a wrong security analysis of the internal power system. Hence, updating the topology of the external power network considerably improves the precision of the internal power network studies and occasionally the power system security analysis. In this regard, it should be noted that the lack of awareness of the external system topology was identified as one of the most important reasons in the North American blackout in 2003 [7]. Therefore, many researchers and power system engineers concentrate on the problem of power system line outage detection. However, this problem can be divided into two different categories including internal system line outage detection and external system line outage identification. Here, the latter is investigated. Although many researches are carried out in the field of the internal system line outage detection [8-15], the line outage identification in the external system is less inspected by authors and researchers [16-20].

To detect a line outage in the external power systems, in [16] a method is proposed based on the deviations observed in the phase angle of the node voltages measured by the PMUs installed in the external network. To achieve the acceptable accuracy in this method, obtaining measurements from a large number of PMUs installed in the external system are needed. The method proposed in [17] is based on the partial factorization of the Jacobian matrix. In this method, several sets of tie-line powers are calculated and compared with those measured in internal power network. The configuration associated with the set calculated with a minimum difference compared to the measured set determines the line outage. This method needs a huge amount of calculations. In [18], the problem of line outage identification in external power network is formulated as a mixed-integer programming problem. The selection of PMUs in external power network for sharing the measured data is based on a trade-off method. In other words, no specific procedure is presented for choosing the mentioned PMUs among the PMUs installed in the external network. To solve the problem, methods based on sparse signal reconstruction are proposed in [19] and [20]. In these methods, the phase angles of all node voltages in the external system should be available prior to the line outage. As mentioned above, online access to these quantities is usually impossible for the internal network operator. Obtaining these quantities, based on either off-line studies or virtual measurements, may decrease the chance of these methods to be successful.

The aim of this paper is to identify the outage of lines in external network of an interconnected power system with a significant effect on the flow of tie-lines. Hereafter, these lines are called critical lines. To identify the outage of these lines, a method is proposed to find the minimum number of PMUs needed to be shared by the external power network. Moreover, a new Artificial Neural Network (ANN) based approach is recommended to identify the outage of critical lines. In doing so, the measurements with the highest sensitivity with respect to the outage of critical lines are selected to be shared by the external power network. Hence, a better separation is yielded in the input data of the ANN, which improves its ability to identify the outage of critical lines.

The remainder of this paper is organized as follows: in section 2, an overview on the proposed ANN-based approach for the identification of the line outage in external power system is presented. The method used for the identification of the critical lines in external power system is introduced in section 3. To identify the critical lines outages by the ANN, it is required to have a good separation in the inputs of the ANN. Hence, the sensitivity technique employed to determine the most sensitive phasor measurements in the external power system will be described in section 4. In section 5, a prioritizing algorithm is proposed to select the minimum number of measurements as a part of the ANN inputs. The method proposed for the identification of the critical lines outages in the external power system based on the ANN is presented in section 6. In section 7, numerical simulations are conducted to show the efficiency of the proposed methodology in this paper. Ultimately, the concluding remarks are presented in section 8.

2. An Overview of the Proposed Approach for the Identification of the Line Outage in External System based on ANN

In Fig. 1, a hypothetical interconnected power system comprising one internal and one external power network is depicted. The external power network, in turn, may include a number of neighboring power systems.

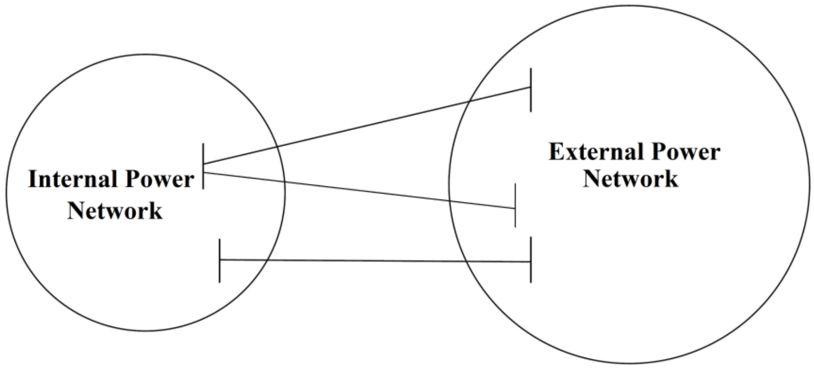

Fig.1. A hypothetical interconnected power system

For security analysis in internal power networks, the accurate modeling of external power networks is very important. However, the on-line accessibility to the signals measured in the external power network is limited. Therefore, it is valuable to use the minimum number of the most sensitive phasor measurements shared by the external power network. In doing so, a new method is presented in this paper to determine the minimum number of PMU measurements shared by the external power network. Therefore, at first, the critical lines in the external power network are defined from the viewpoint of the internal system. The critical lines are those by which the outage causes flow variation in at least one of the tie-lines to be higher than a selected threshold value. By the outage of critical lines, it is necessary to update the external network model used by the internal power system analyzer when the security analysis is taken into account. However, when the outages of the non-critical lines take place, it is not necessary to update the model because the variations in the external system are negligible from the viewpoint of internal system. Therefore, by the use of the pre-fault model, the resultant error in security analysis is not significant. Then, since the line outage identification is carried out, based on a sensitivity analysis technique, the most sensitive measurements are identified with respect to the outage of critical lines. After that, a cumulative sensitive technique is proposed to prioritize these measurements. All of these are considered as inputs for two different ANNs which are employed to work in sequence for the identification of critical line outage in external power networks. In fact, the cumulative sensitive technique produces better inputs for the ANNs, which in turn improves their abilities to determine the minimum number of the required measurements of the external power system. Actually, the main feature of the proposed methodology is the good separation yielded by using sensitivity analysis and the proper prioritization of phasor measurements.

The implementation of the above-mentioned approach can be outlined in sequential steps as follows:

- Identifying the critical lines in external power network;
- Determining the most sensitive measurements in external power network and prioritizing them to select the optimal (minimum) number of measurements as a part of ANN inputs;
- Selecting a proper structure for the ANN; and then providing the required patterns to train and to test the ANN.

All of these steps are described in details in the following sections.

3. Identification of Critical Lines in External Power Network

To determine the critical lines, the concept of the sensitivity of line loading with respect to the power level in the line outage is employed. It is supposed that line ℓm is out and the variation of the flow through line *jk* is expected. In this regard, the line outage distribution factor, $\tau_{jk,\ell m}$, is defined as follows:

$$\tau_{jk,\ell m} = \frac{\Delta \bar{S}_{jk}}{\bar{S}_{\ell m}}\Big|_{\ell m \ is \ out} \tag{1}$$

where $\Delta \bar{S}_{jk}$ is the variation of the complex power through line *jk* and $\bar{S}_{\ell m}$ is the complex power through line ℓm.

To indicate the distribution factor $\tau_{jk,\ell m}$ defined above, another distribution factor should be first defined, which indicates the variations of a line loading with respect to the variations of the injection to a specific node. For example, consider the variations of the power flow through line jk with respect to the injection at bus *n*. The power transfer distribution factor, $\rho_{jk,n}$, is defined by (2).

$$\rho_{jk,n} = \frac{\partial \bar{S}_{jk}}{\partial \bar{S}_n} \tag{2}$$

where $\bar{S}_{jk}$ is the complex power flow through line *jk* and $\bar{S}_n$ is the complex power injected to the node *n*.

The factor $\rho_{jk,n}$ can be calculated as follows [21]:

$$\rho_{jk,n} = \left(\frac{(Z_{bus})_{jn} - (Z_{bus})_{kn}}{\bar{z}_{jk}} \right)^* \tag{3}$$

where $(Z_{bus})_{jn}$ is the entry on the *jth* row and the n^{th} column of the power system nodal impedance matrix and $\bar{z}_{jk}$ is the series impedance of line *jk*.

Now, by using a technique known as compensation theorem, the following relationship is used to calculate the line outage distribution factor defined in (1):

$$\tau_{jk,\ell m} = \frac{1}{\rho_{\ell m,m}} \left(\rho_{jk,m}^{out\ \ell m} - \rho_{jk,m} \right) \tag{4}$$

where $\rho_{jk,m}^{out\ \ell m}$ implies the variations of the power flow through line jk with respect to the injection at bus m when the line is out. This value can be calculated either by using (3), if the nodal impedance matrix is corrected after line ℓm is out, or by using the associated relations presented in [21].

In order to determine the critical lines, it is supposed that line *jk* is one of the tie-lines connecting the internal and external networks and line ℓm is an arbitrary line in the external network. The percentage of power deviations across line *jk* by the outage of line ℓm can be calculated as follows:

$$\left| \frac{\Delta \bar{S}_{jk}}{\bar{S}_{jk}} \Big|_{\ell m\ is\ out} \right| \% = \left| \tau_{jk,\ell m} \times \frac{\bar{S}_{\ell m}}{\bar{S}_{jk}} \right| \times 100\% \tag{5}$$

where $\bar{S}_{\ell m}$ and $\bar{S}_{jk}$ are complex powers through lines ℓm and *jk*, respectively. These values change based on the power system operating point as well as configuration. However, the complex powers obtained at the basic operating condition can be substituted in (5) as an approximation.

Finally, if the percentage of power deviations in at least one line is higher than that of a predefined little value by the outage of a specific line in the external network, this line is considered as a critical line.

4. Determination of the Most Sensitive Measurements in External Power Systems

As mentioned in section 2, the goal is to identify the outage of critical lines in an external system based on the minimum number of on-line phasor measurements obtained from the external power network by the use of ANN. Hence, the phasor measurements with the highest sensitivities or, in other words, with the highest relative differentiations with respect to the outage of critical lines should be selected for this purpose.

By installing a PMU on a system node, all current phasors of the lines adjacent to that bus are also measured. Therefore, if line ℓm is one of the critical lines in the external network, $\bar{I}_{pq}$ is the measured phasor current of line *pq* in the external network and $\overline{V_i}$ is the measured phasor voltage of the i^{th} bus in external network; then the sensitivity of the current of line *pq* with respect to the outage of the critical line ℓm, and the voltage of node *i* with respect to the outage of the critical line ℓm can be calculated by the following two equations, respectively:

$$SI_{pq,\ell m}\% = \left| \frac{\Delta \bar{I}_{pq}}{\bar{I}_{pq}} \Big|_{\ell m \ is \ out} \right| \times 100\% \tag{6}$$

$$SV_{i,\ell m}\% = \left| \frac{\Delta \bar{V}_i}{\bar{V}_i} \Big|_{\ell m \ is \ out} \right| \times 100\% \tag{7}$$

where $\Delta \bar{I}_{pq}$ and $\Delta \bar{V}_i$ are the variations of the current phasor of line *pq* and that of the voltage phasor of node *i*, respectively. Also, $\bar{I}_{pq}$ and $\bar{V}_i$ are the current phasor of line *pq* and the voltage phasor of node i, respectively; both of them before the outage of line ℓm.

Then, new formulas are obtained to calculate equations (6) and (7), by generalizing the concepts and quantities mentioned in section (3).

A) Calculating the Sensitivity of a Measured Line Current with Respect to a Critical Line Outage

In order to calculate the sensitivity of line current $\bar{I}_{pq}$ with respect to the outage of the critical line ℓm, $SI_{pq,\ell m}\%$, a new variable should be defined as follows:

$$r_{pq,n} = \frac{\partial \bar{I}_{pq}}{\partial \bar{I}_n} \tag{8}$$

where variable $r_{pq,n}$, in the above expression is the conjugate of $\rho_{pq,n}$ defined in (3). In other words, there will be:

$$r_{pq,n} = \left(\frac{(Z_{bus})_{pn} - (Z_{bus})_{qn}}{\bar{z}_{pq}} \right) \tag{9}$$

where the quantities appeared in (9) are exactly the same as those defined in equation (3). However, it should be noted that the value obtained for $\rho_{pq,n}$ based on equation (3) includes the approximation, while (9) gives the exact value of $r_{pq,n}$ defined in (8).

Now, by using the same technique applied to obtain the line outage distribution factor in (4), i.e. the compensation theorem, we will have:

$$\frac{\Delta \bar{I}_{pq}}{\bar{I}_{\ell m}} \Big|_{\ell m \ is \ out} = \frac{1}{r_{\ell m,m}} \left(r_{pq,m}^{\ell m \ out} - r_{pq,m} \right) \tag{10}$$

where $\bar{I}_{\ell m}$ is the current phasor through the line ℓm before its outage. Moreover, $r_{pq,m}^{out \ \ell m}$ can be calculated either based on the entries of the nodal impedance matrix when it is updated considering the outage of line ℓm or based on the equations presented in [21] by converting the variable ρ to *r*.

After the calculation of (10), the sensitivity of the line current $\bar{I}_{pq}$ with respect to the outage of the critical line ℓm, defined in (6), can be calculated as follows:

$$SI_{pq,\ell m}\% = \left| \frac{1}{r_{\ell m,m}} \left(r_{pq,m}^{\ell m\ out} - r_{pq,m} \right) \right| \times \left| \frac{\bar{I}_{\ell m}}{\bar{I}_{pq}} \right| \times 100\% \tag{11}$$

where $\bar{I}_{\ell m}$ and $\bar{I}_{pq}$ are the current phasors through lines ℓm and *pq*, respectively. These values vary according to the power system operating points as well as the configuration. However, the current phasors at the basic operating condition, obtained from off-line studies, can be substituted in (11) as an approximation.

B) Calculating the Sensitivity of a Measured Node Voltage with Respect to a Critical Line Outage

In order to calculate the sensitivity of the node voltage V_i with respect to the outage of the critical line ℓm, $SV_{i,\ell m}\%$, it is sufficient to use the following expression derived by Ohm's law.

$$\frac{\Delta \bar{V}_i}{\bar{I}_{\ell m}} \Big|_{\ell m\ is\ out} = \sum_{\{k\}} \left(\bar{z}_{ik} \frac{\Delta \bar{I}_{ik}}{\bar{I}_{\ell m}} \Big|_{\ell m\ is\ out} \right) \tag{12}$$

where *{k}* is a set of nodes connected to bus *i* and $\bar{z}_{ik}$ is a series impedance of the branch between buses *i* and *k*. Likewise, $\bar{I}_{\ell m}$ is the phasor current through line ℓm. Hence, by the use of (10), the equation (12) can be rewritten as:

$$\frac{\Delta \bar{V}_i}{\bar{I}_{\ell m}} \Big|_{\ell m\ is\ out} = \sum_{\{k\}} \left(\frac{\bar{z}_{ik}}{r_{\ell m,m}} \left(r_{ik,m}^{\ell m\ out} - r_{ik,m} \right) \right) \tag{13}$$

Finally, the sensitivity of the node voltage V_i with respect to outage of the critical line ℓm, defined in (7), is obtained by (14).

$$SV_{i,\ell m}\% = \left| \sum_{k} \left(\frac{\bar{z}_{ik}}{r_{\ell m,m}} \left(r_{ik,m}^{\ell m\ out} - r_{ik,m} \right) \right) \right| \times \left| \frac{\bar{I}_{\ell m}}{\bar{V}_i} \right| \times 100\% \tag{14}$$

In (14) $\bar{I}_{\ell m}$ and $\bar{V}_i$ are the current phasor through line ℓm and phasor voltage of the node *i*, respectively, both of them before the outage of the line ℓm. These quantities vary based upon the operating conditions as well as the topology of the power system. However, the values at basic operating conditions can be used as an approximation in (14).

5. Proposed Method for Prioritizing the Most Sensitive Measurements for Identification of Critical Lines Outage by Using the Minimum Number of These Measurements

As mentioned earlier, the goal is to use the minimum number of measurements obtained from the external network to detect the outage of critical lines. Therefore, it is necessary to properly prioritize the sensitive measurements determined in the previous section. For this purpose, first, the most sensitive measurement with respect to the outage of every critical line is specified. In other words, by the outage of every critical line, equations (11) and (14) should be evaluated for every phasor line current and phasor node voltage measured in the external system, respectively.

Now, the concept of cumulative sensitivity for a specific phasor measurement is introduced as the summation of sensitivities obtained with respect to the outage of all critical lines. In other words, for every most sensitive measurement with respect to a critical line determined at the first step, sensitivities with respect to the outage of other critical lines should be calculated and be added together to specify cumulative sensitivity. Then, the most sensitive measurements are sorted based on their cumulative sensitivity values. In other words, the higher cumulative sensitivity obtained for a specific measurement, the higher priority for that measurement is considered.

The above descriptions can be outlined in the flowchart depicted in Fig. 2. In this flowchart, N_{cr} is the number of the critical lines in external power network determined by the use of the criterion proposed in section 3.

To determine the required optimal number of the measurements, a sequential addition procedure is proposed. In this procedure, first, the measurement with the highest priority is considered as the input of the ANN. Then, the associated ANN is trained and the error percentage in the output of the ANN is evaluated. If the error percentage is not lower than the small desired threshold value, the sensitive measurement with the next priority is added to previous input of the ANN. This process should be continued until the output error percentage reaches zero or a lower value than the mentioned threshold.

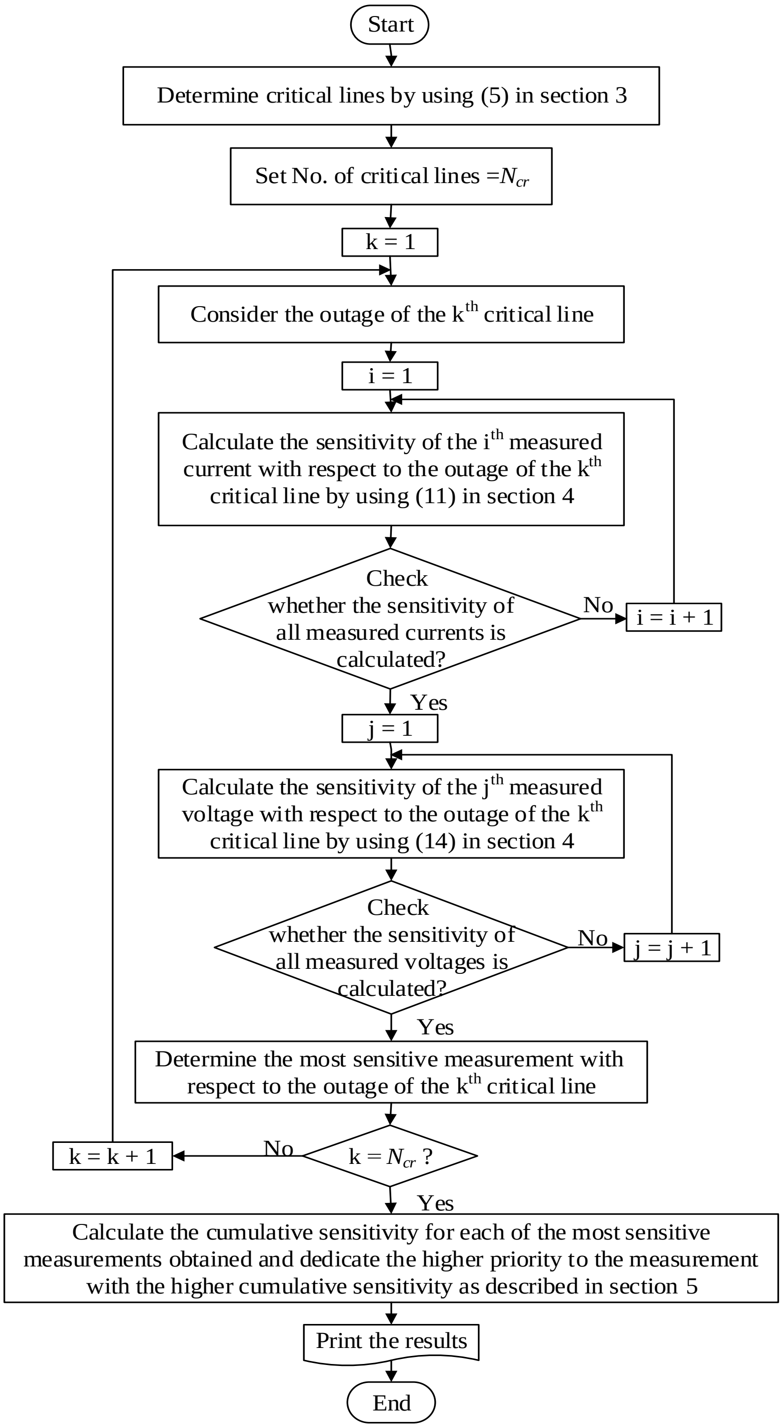

Fig.2. Flowchart used for prioritization of sensitive measurements

6. Proposed Method for Prioritizing the Most Sensitive Measurements for Identification of Critical Lines Outage by Using the Minimum Number of These Measurements

As mentioned before, the main goal in this paper is the on-line identification of the critical lines in the external power network. Therefore, it is valuable to use the minimum number of the most sensitive phasor measurements shared by the external power network. The identification of the lines which are out by the deterministic methods needs the full observability of the power network [16]. However, the on-line accessibility to the measurements in the external power network is limited so that a partial observability would not be yielded. In practice, it is expected that only partial on-line measurements along with some basic off-line data, e.g. the basic topology of the power system and the load and demand levels in the basic operating point be shared by the external system. Therefore, in this paper, ANN is used to identify the critical lines outage based on the minimum number of measurements shared by the external power network. Consequently, the specifications of the employed ANN including its inputs; the number of layers and neurons in every layer; the transfer function of layers; and the method used for training the ANN are described. Then, numerical simulations are conducted in which the efficiency of the proposed method in this paper is shown.

It is evident that in the external power network like every other power systems, the operating conditions; generations and demands; and the system topology change during the day. From a short-term point of view, there is a reasonable relationship between the seasonal weather variations and the changes stated above. Therefore, the correlation between the measured phasors and the outage of critical lines varies so that the ANN is not able to recognize the stated outage based on only the measured phasors. Hence, it is necessary to provide additional accessible information as the inputs of the ANN. In doing so, the ANN can estimate the changes in the load profile as well as the planned variations in the external power system topology brought about by weather fluctuations besides the outage of the critical lines. Thus, the following variables are considered as the inputs of the ANN for recognizing the outage of the critical lines:

a) The number of the days for every operating point
b) The time stamp of every operating point
c) The daily peak load of the internal as well as external network
d) The mean as well as the maximum daily temperature
e) The daily humidity
f) The real as well as imaginary part of the most sensitive measurements shared by the external network
g) The power flow of the tie-lines between the internal and external power networks measured in the internal power system

As mentioned before, the inputs (a) to (e) are used to recognize the load profile and the basic topology of the external power network. Moreover, the peak load is obtained by off-line studies for previous days and by load forecasting approaches for the days ahead. Likewise, the inputs (d) and (e) can be extracted from meteorological organization's reports for previous days and from the weather forecasting results for the days ahead.

In the case of a critical line outage, the ANN output should indicate the line which is out with a proper number. On the other hand, the ANN should distinguish the situation in which none of the lines in the external network are out (health condition) as well as the situation in which a non-critical line is out. Hence, the input (g), (i.e., the flow of the tie-lines) enables the ANN to recognize these three different situations.

Also, for more facilitation, two different ANNs are employed working in sequence with the same inputs (a) to (g) listed above. The first ANN distinguishes the three conditions, i.e. the health condition, outage of a non-critical line, and outage of a critical line. The second one is excited when critical line outage is recognized by the first ANN to indicate the critical line which is out.

As it can be understood from the above descriptions, the output of each of two above-mentioned ANNs is a number. Hence, there is one neuron in the output layer of the mentioned ANNs. In addition, the results obtained from a plenty of simulations indicate that one hidden layer is enough for both ANNs. Also, it is found that the optimal number of neurons in the hidden layer is equal to that of the conditions which are to be returned to the output of the ANN. It means that three neurons are required in the hidden layer of the first ANN. However, in the second ANN, the optimal number of neurons in the hidden layer is equal to that of critical lines in the external power network. The well-known back propagation method is used to train the ANNs. Therefore, the excitation functions of the layers should be differentiable. Simulations show that employing the logarithmic-sigmoid (Logsig in MATLAB software) and linear (Purelin in MATLAB software) transfer functions for the hidden layer and the output layer of each ANN, respectively, give the best results. Finally, the output of ANNs is rounded to the nearest integer.

7. Simulation Results

Here, it is appropriate to evaluate the proposed method for identification of critical lines outage by a limited number of phasor measurement shared by the external network. For this purpose, the proposed method is tested on two interconnected sub-networks of the Iranian power grid. Isfahan power network is considered as the internal and Khuzestan power network is the external power network. Then, the hourly load flow information during one month together with the number of days and the time stamp of every operating point are extracted from the associated regional power companies in Iran. It should be noted that these items of information are high. However, for example, the injection power and consuming power in the buses on a day when the load is peak are shown in Tables 1 and 2. Buses are not presented in these tables if their consuming and injection power is zero. Finally, the information is fed to MATLAB Software to perform numerical simulations. Fig. 3 depicts the single line diagram of the power network under study. Details of the power network can be found in [22].

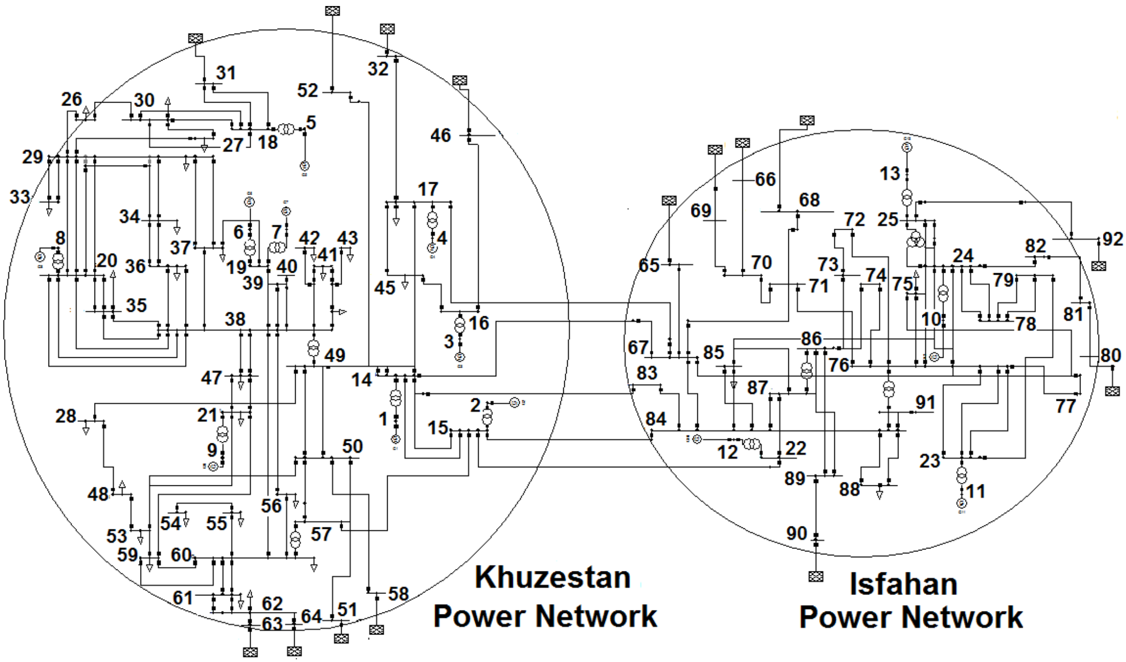

Fig.3. Single-Line diagram of the Isfahan-Khuzestan inter-connected power system

Table 1

Injected power in the buses on a day that the load was peak

Bus No.	Injected active power	Bus No.	Injected active power
2	150	8	147
3	34	9	39
4	86	10	56
5	52	11	49
6	20	12	74
7	6	13	72

Table 2

Consuming power in the buses on a day that the load was peak

Bus No.	Active power	Reactive power	Bus No.	Active power	Reactive power	Bus No.	Active power	Reactive power
17	10	5	42	2	1	60	16	10
21	8	3	43	2	1	61	14	10
26	12	6	44	9	4	62	24	13

27	8	5	45	38	22	63	-2	-6
28	16	7	46	18	1	64	5	-3
29	30	20	47	23	10	65	10	-3
30	35	20	48	29	15	66	-8	-5
31	2	6	51	45	2	68	14	4
32	20	2	52	21	1	69	-7	-6
33	12	5	53	18	10	75	18	9
34	27	11	54	1	0	80	6	-3
35	5	2	55	3	1	85	62	18
36	33	10	56	12	5	88	3	2
37	32	19	58	52	2	90	19	-2
40	4	2	59	4	1	92	59	-5
41	11	3						

Non-electrical inputs of the ANN including the mean as well as the maximum daily temperature and the humidity of the regions under study, as a part of ANN inputs, are extracted from Iranian meteorological organization's archives.

In order to determine the critical lines, the sensitivity of all tie-lines, as shown in Fig.3, is calculated with respect to the outage of every branch in external system. Then, the maximum sensitivity of all tie-lines is obtained. As mentioned in section 3, the branches in external power network which cause considerable changes in power flow of tie-lines when they are out, are critical lines. Hence, a threshold value should be selected to determine critical lines. Here, this value is selected to be 15%. Two criteria are allocated to this threshold value. The first criterion is that the changes in the power flow of the tie-lines should be significant. The second one is the gap observed between the maximum sensitivities obtained for the tie-lines by the outage of the external power system branches. The critical lines are identified and presented in Table 3.

Table 3

Numbering of critical lines in external power system

	End Nodes Numbers of Critical Lines							
	17-45	15-75	15-17	14-50	14-49	28-45	14-15	57-60
Critical Line No.	1	2	3	4	5	6	7	8

Now, the most sensitive measurements are determined based on the method presented in section 4. For this purpose, it is first necessary to know the locations of PMUs installed in the external power system. It should be noted that the main goal in the placement of PMUs is to locate them so that the full observability is provided. Therefore, the locations of PMUs under the supervision of the power system obtained by using the method proposed in [23] are presented in Table 4.

Table 4

Location of PMUs in Isfahan-Khuzestan inter-connected power network

Power Network	Location of PMUs
Isfahan (Internal)	23, 24, 67, 70, 76, 80, 84, 89
Khuzestan (External)	3, 7, 13, 17, 18, 21, 28, 29, 38, 41, 48, 51, 54, 62

Then, the sensitivity of every phasor measurement in the external power network is determined using (6) and (7). Next, by considering the obtained sensitivities, the most sensitive measurement with respect to the outage of each critical line is determined. Finally, by calculating the cumulative sensitivity based on the flowchart given in Fig. 2, the most sensitive measurements are prioritized. The priority of measurements with their absolute sensitivities with respect to the outage of the critical lines is given in Table 5.

Table 5

Most sensitive measurements in external power network with respect to the outage of critical lines and their prioritization based on the cumulative sensitivity values

Kind of Measurement	End Nodes Numbers (for Brach Currents) and/or Node Numbers (for Bus Voltages)	Critical Line Number								Cumulative Sensitivity	Priority of Measurement
		1	2	3	4	5	6	7	8		
Branch Current	48-53	2.6	2.0	0.4	**2.2**	**1.5**	1.6	0.0	2.3	12.6	1
Branch Current	15-17	**3.6**	1.5	**1.0**	0.5	0.9	**2.2**	0.6	0.5	10.8	2
Branch Current	38-47	0.7	0.7	0.1	0.6	0.8	0.4	0.1	**3.6**	7.1	3
Branch Current	28-45	0.6	**2.7**	0.3	0.3	0.5	0.1	**0.8**	0.3	4.9	4

In addition, the highest sensitivities obtained for every measurement with respect to the outage of the associated critical line are shown by bold letters in this Table. For instance, the current phasor of branches 38-47 with respect to the outage of critical line 8 has the most sensitivity with an absolute value of 3.6. Moreover, as shown in Table 3, it is possible that a particular measurement has the most sensitivity with respect to the outage of more than one critical line. For example, the phasor current of the branch 48-53 has the most sensitive measurement with respect to the outage of both critical lines 4 and 5. Also, the current phasor of the branch 15-17 has the most sensitivity with respect to the outage of critical lines 1, 3, and 6.

Implementation of the ANN

As mentioned earlier, the problem under consideration is divided into several steps. First, an ANN is trained to recognize one of the three possible conditions which can be considered in the power network. These conditions are the health condition, the outages of one critical line, and one non-critical line. Numbers 1, 2, and 3 show these three conditions, respectively. At the second step, if the outage of one critical line is identified by the first ANN, another ANN will be excited to find the critical line which is out. Hereafter, these two ANNs are called "the first ANN" and "the second ANN", respectively.

Moreover, it should be noted that to achieve the optimal specifications for these two ANNs, an ANN without a hidden layer is considered as the starting point. Then, the number of layers and the number of neurons in hidden layers are increased step by step. In addition, various transfer functions are tested for layers. Simulations results show that increasing the number of layers or the number of neurons in the hidden layers beyond what mentioned in section (6), does not involve a considerable improvement in the accuracy of ANNs.

Furthermore, the training time for ANNs grows exponentially with an increase in the number of layers as well as in the number of neurons in the hidden layers. Then, the training procedure of the two above-mentioned ANNs and the associated simulation results are presented.

A) ***Training and Testing "the first ANN"***

As mentioned earlier, in order to distinguish the conditions of the system, the first ANN is used. This ANN has one hidden layer with three neurons and one neuron in the output layer. To train and to test this ANN, besides the health conditions and the outage of critical lines, it is required to provide the electrical inputs when all non-critical lines are out by using the load flow technique. However, since the number of non-critical lines is usually high, if the outages of all the non-critical lines in every operating point of the network are considered, the required simulations will be highly time consuming. This prevents the on-line training of the ANN in real dimensional power networks. Hence, it is recommended that the outage of a partial number of non-critical lines be simulated in every operating point, randomly. A higher percentage of non-critical lines, whose outage is simulated in every operating point, leads to have a more precise identification of the power network conditions by the ANN.

To provide the required patterns, the electrical inputs of the ANN obtained from the load flow are combined with the weather information during one month. In doing so, the inputs of the patterns are prepared. Then numbers 1, 2, and 3 are dedicated to the output of the patterns based on the simulated power system condition, i.e. the health condition, the outage of a critical line, and the outage of a non-critical line. Finally, 75% of the patterns are selected as the trained patterns and the other 25% are considered as test ones, randomly. Simulation results are shown in Table 6.

Table 6

Simulation results for the power system condition identifying in "the first ANN"

Cond. No. 1: Health Condition Cond. No. 2: Outage of a Critical Line Cond. No. 3: Outage of a Non-Critical Line

Kind of Mismatched in Identification	**No. of Non-Critical Lines is Out in Every Operating Point**				
	1	2	3	4	5
Error in Identification of Cond. No. 1	0%	0%	0%	0%	0%
Error in Identification of Cond. No. 2	0%	0%	0%	0%	0%
Error in Identification of Cond. No. 3	1.1%	0%	0%	0%	0%
Error in Ident. of Cond. No. 2 Inst. of No. 1	0%	0%	0%	0%	0%
Error in Ident. of Cond. No. 2 Inst. of No. 3	1.1%	0%	0%	0%	0%
Absolute Identification Error Percentage	0.1%	0%	0%	0%	0%

As shown in Table 6, by simulating the outage of two non-critical lines at every operating point, a perfect accuracy is yielded in the power system. This good accuracy is obtained because of using the tie-lines power flow as a part of the ANN inputs. It should be noted that by the proper definition of critical lines, based on the power flow of tie-lines, a good separation is obtained between the three different conditions considered in the external power network. However, the number of the non-critical lines whose outages should be simulated in every operating point differs from case to case.

Moreover, in Table 6, "Error in Identification of Cond. No. 2 Instead of No. 3" means that the ANN identifies the outage of a non-critical line as the outage of a critical line. In other words, although there is no need to update the external system model, the ANN wrongly recognizes that the model update is necessary.

B) Training and Testing "the second ANN"

As mentioned earlier, in order to identify the critical line outage in the system, the second ANN is used. This ANN has one hidden layer with eight (equal to the number of the critical lines in the case study) neurons. The output of this ANN indicates the critical line number which is out. Hence, there is one neuron in its output layer. Inputs as well as training and testing procedures for this ANN are utterly the same as "the first ANN". To prepare the training and testing patterns, the electrical inputs of the ANN are obtained by using the load flow under the outage of each of critical lines at every operating point. Then, the electrical inputs are combined with the weather information during the one-month. Finally 75% of the patterns which are selected randomly, are used as the training set while the other 25% are considered as the testing set. The simulation results are presented in Table 7.

As shown in Table 7, by using just the most sensitive measurement, i.e. current phasor of branch 48-53 (from Table 5), there is a significant error in the detection of the critical line outage. But, by using two of the most sensitive measurements, i.e. current phasors of branches 48-53 and 15-17, the acceptable accuracy is yielded. Actually, it is shown that the proposed method has its priority over other existing methods in terms of the minimum number of shared phasor measurements and low amount of calculation. As mentioned in section 1, [16], [19], and [20] need a large number of phasor measurements for detecting the critical line outage in the external power network. Reference [17] needs a huge amount of calculation and in [18] there is no specific procedure for choosing PMUs in the external network. However, the results of Table 7 shows that by applying the method presented in this case study, it just needs two current phasor measurements for precise detection of the critical line outage in the external power network. In other words, Table 7 shows the effectiveness of the proposed method.

Table 7

Simulation results for detecting the critical lines outage by using the most sensitive current phasors

No. of Used Meas.	Error Percentage in Critical Outage Detection							
	1	2	3	4	5	6	7	8
1	3.74%	27.69%	25.61%	10.59%	10.15%	10.33%	34.04%	5.32%
2	0%	0%	0%	0%	0%	0%	0%	0%

8. Conclusions

In this paper, a new ANN-based method is proposed for identifying the line outage in the external network of an interconnected power system. For this purpose, first, the branches in external power network with a significant effect on the power flow of tie-lines, i.e. the critical lines, are specified. Then, to have a better separation in inputs of the ANN, the most sensitive phasor measurements are determined. In doing so, a sensitivity analysis technique is employed. Thereafter, a prioritizing algorithm is proposed to minimize the number of measurements needed to be shared by the external power network. Finally, the proposed methodology is tested on a part of Iranian power system. The mentioned power network includes two interconnected subsystems, i.e. Isfahan power system as the internal and Khuzestan power system as the external power networks. Numerical simulations show the accuracy of the ANN in the identification of critical lines outages by using a minimum number of phasor measurements shared by the external system. The good efficiency of the proposed methodology is because of the good separation yielded by using sensitivity analysis and the proper prioritization of phasor measurements.

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