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Reliability estimation of Iran's power network

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Abstract

Today, the electricity power system is the most complicated engineering system has ever been made. The integrated power generating stations with power transmission lines has created a network, called complex power network. The reliability estimation of such complex power networks is a very challenging problem, as one cannot find any immediate solution methods in current literature. In this paper, we advanced a new method for estimating the reliability of such networks, which is based on 1) decomposition of the whole network into sub-networks called islands, 2) estimating each island's reliability in exact form using the network reliability theory, and 3) assembling the islands back together to estimate the whole network reliability, again in exact form. We applied the new method on Iran's power network with 105 generation stations and 16460 kilometres of transmission lines.

Keywords: Reliability estimation, power network, network reliability, graph theory, complex systems

1-Introduction

Biological systems, power systems, social interactions and Internet are just a few examples of complex systems that have large number of dynamic components (Alipour, 2010) and (Boccaletti et al., 2006). They are often modelled as a network or graph with nodes and links. The reliability estimation of such networks is called *network reliability estimation*, which is combinatorial in nature, i.e, NP-hard (Leslie, 1979) and (Beichelt and Tittmann 2012). Reliability estimation of such complex system is a very challenging problem (Alipour, 2010). Researchers, in recent years, have contrived hard to find ways by which network reliability can be estimated efficiently (Solé et al, 2008), (Saniee Monfared et al., 2014), (Alipour et al., 2014) and (Saniee Monfared et al., 2013). The success rate is almost zero as none could apply the mathematical theory of reliability on estimating practical power networks.

In this study, we propose a new method by which the whole complete network can be divided into several islands, which each can be solved using the exact network reliability theory. The rest of this paper is organized as follows. In section 2, the new method is developed and applied to solve the reliability estimation of Iran's power network. In section 3, we perform some experiments to assess the sensitivity of our results. In section 4, further research directions are outlined.

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2-Methodology

Disruptions and fluctuations in country's electricity network cause a great amount of difficulties for residential, industrial and service sectors. To remedy this, one has to calculate the reliability of power grid first, which is now an impossible task, based on current methods in reliability theory. We apply the divide and conquer rule, in order to calculate the reliability of entire power network.

2-1-Calculation of network reliability considering equal reliability value for all links

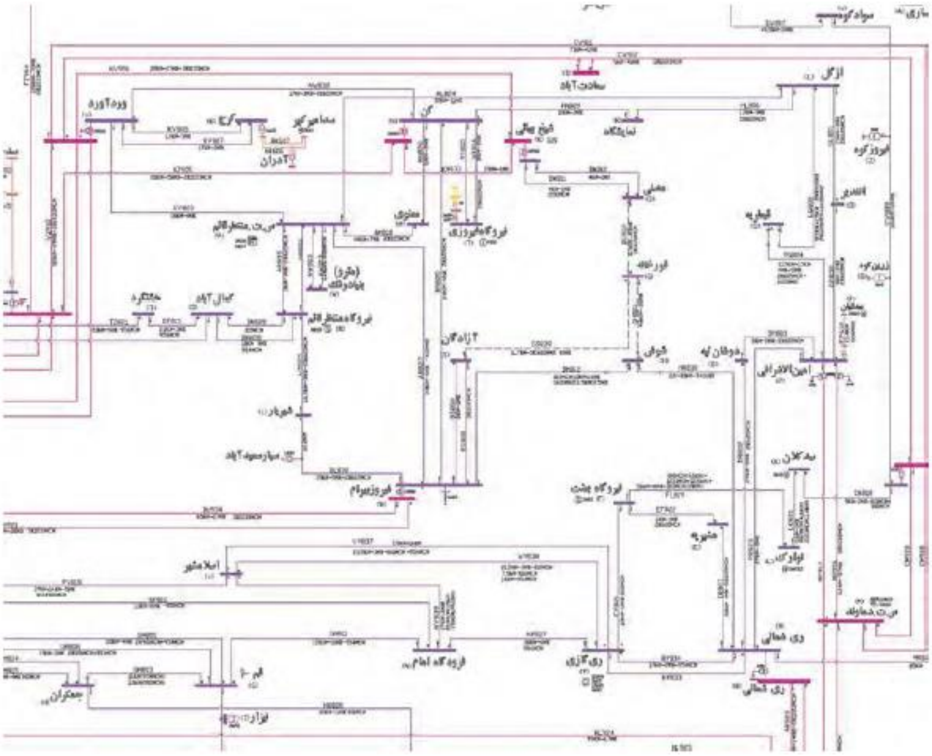


Fig1. Single line diagram of part of Iran's generation and transmission network [1]

As stated above, to calculate the reliability of entire electricity complex network, it is necessary to divide it into a number of subgraphs called islands. For this segmentation, it is necessary to cut a series of links with certain rules. We suggested the following rules to be applied to cut the links: 1) parallel links should be cut together; 2) each island should be of a certain graph forms such as stars, trees, etc. to enable its reliability calculation exactly, and 3) the size of each island should be chosen such that its exact network estimation becomes possible using the conventional network estimation algorithms.

Figure 2, which is based on Alipour (2010), illustrates the eight islands we cut in Iran's power network consisting of 105 nodes and 142 links and marked by A, B, ... ,H. We assumed that our node reliabilities are perfect, i.e., equal to 1 and link reliability is 0.9 for our first run of estimation. We consider equal link reliability now to put the emphasis on network structure and topology and not on link reliabilities. Later, in section 3 we adopt actual values for assessing link reliabilities impact on reliability estimation of our network.

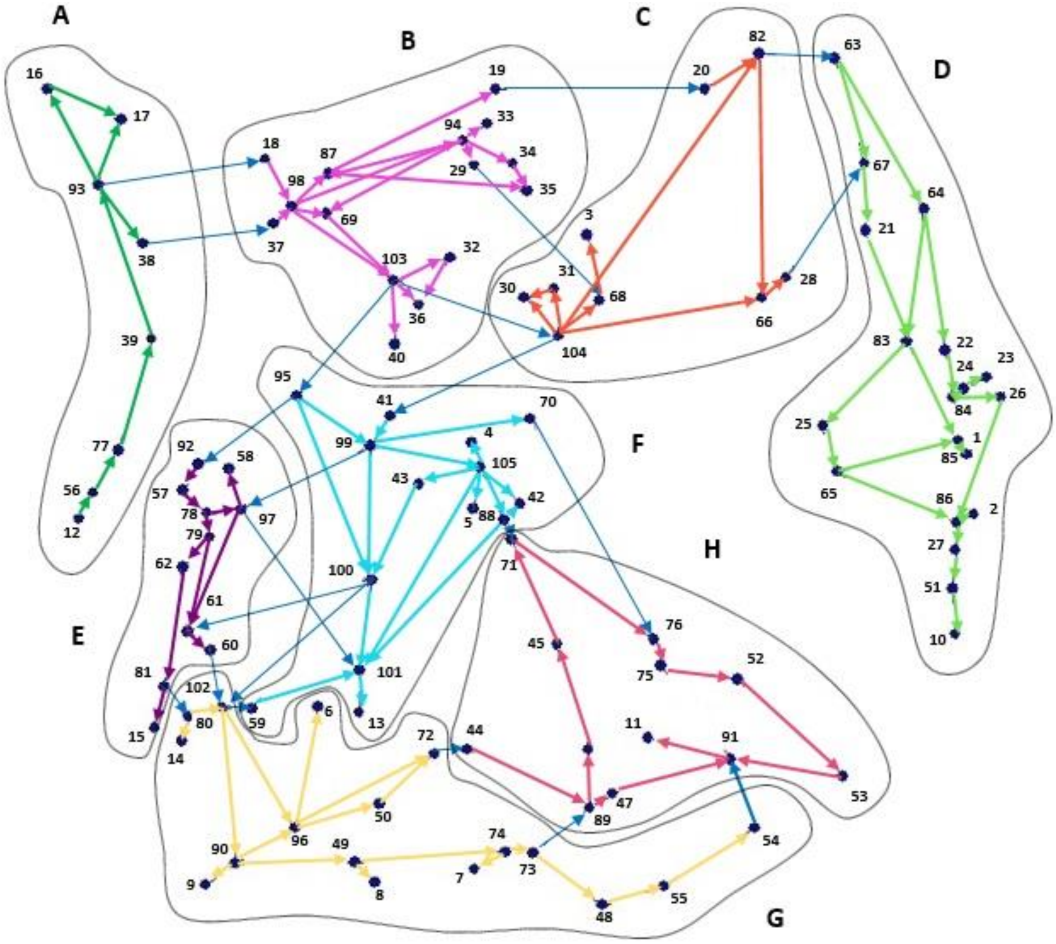
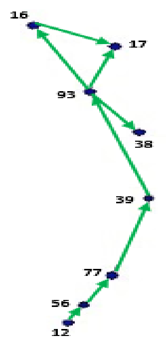
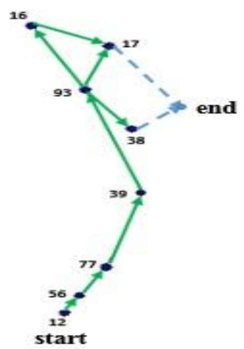
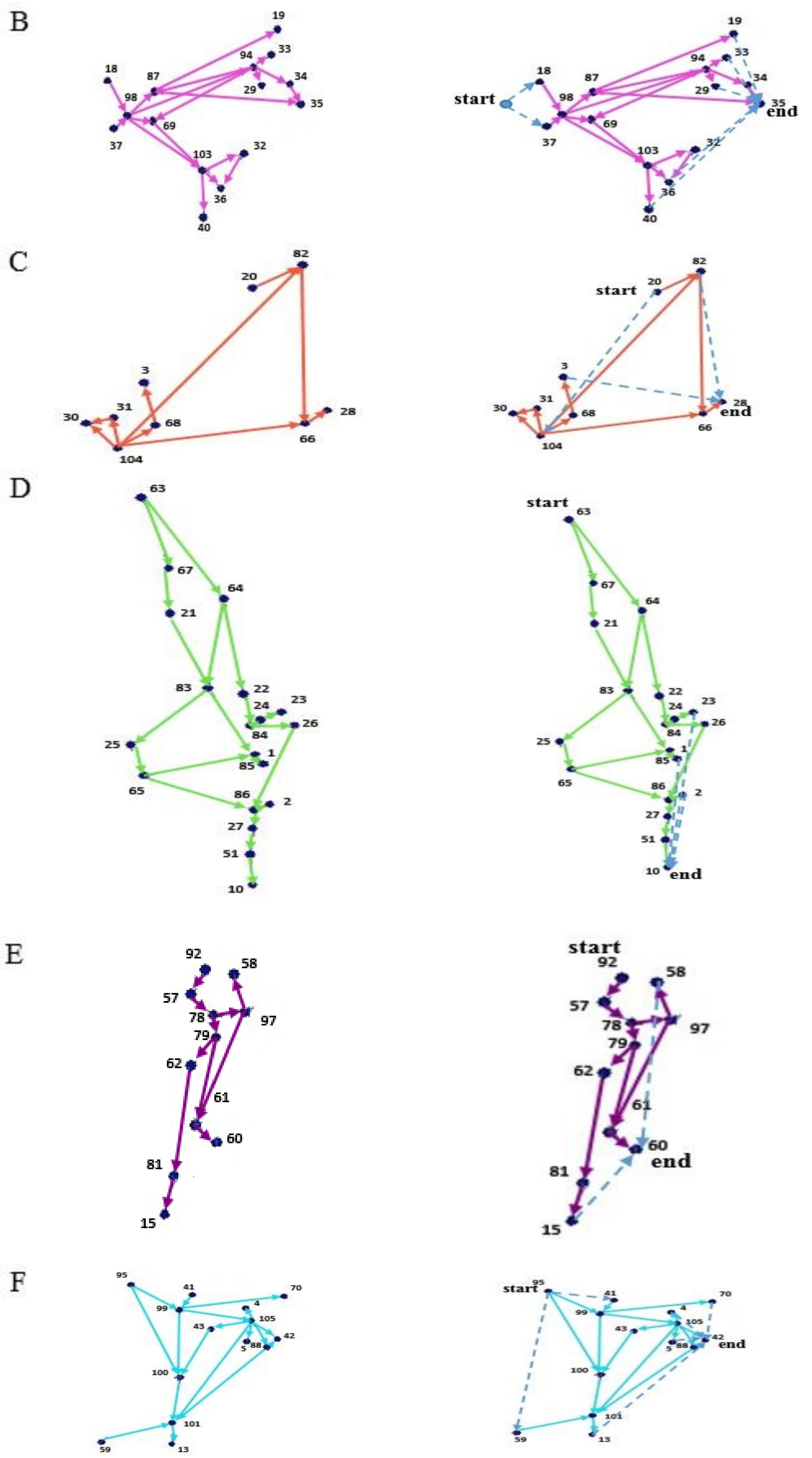


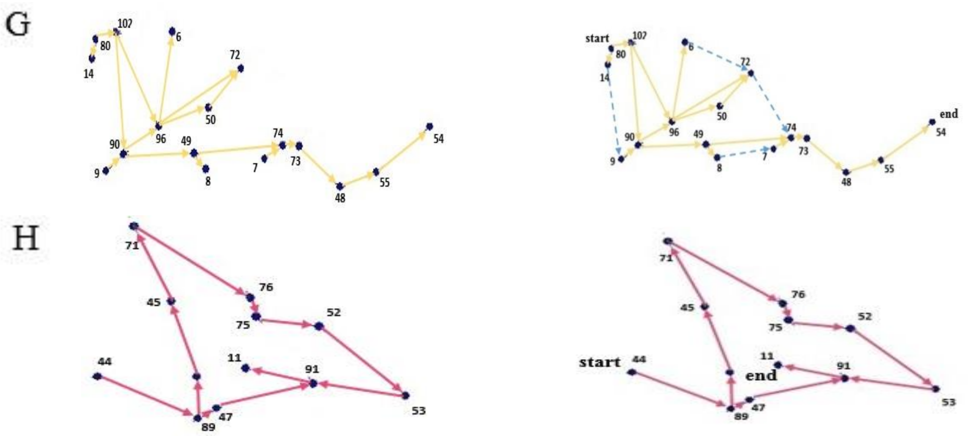
Fig 2. Cutting Iran's electricity network into 8 islands: A,B,..,H

In table 1, there are two columns in which the first column shows the islands and the second column shows each island's block diagram. Dummy links and nodes with reliability 1 have been added when necessary to help to make each block diagram a directed 2-terminal node network. Different methods have been developed to calculate the network reliability, e.g., path tracking method

Table 1. The 8 islands of Iran's power network

Island	Block diagram
A 	


B
start
end
C
start
end
D
start
end
E
start
end
F
start
end



Island A consists of 8 nodes, 1 *ring* and 1 *star/ tree*. The island's reliability is 0.6548.
Each island’s reliability was calculated using the path tracking method. For example, the reliability of island A is calculated as follows:

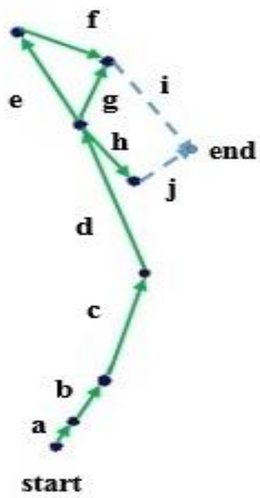


Fig 3. Island A

Given the figure 3, in order to get from the start point to the end point we have to go through at least one of the following three paths:

$\text{route1} = a \rightarrow b \rightarrow c \rightarrow d \rightarrow e \rightarrow f \rightarrow i$
$\text{route2} = a \rightarrow b \rightarrow c \rightarrow d \rightarrow g \rightarrow i$
$\text{route3} = a \rightarrow b \rightarrow c \rightarrow d \rightarrow h \rightarrow j$

The links i and j are dummy links. Therefore, they have reliability equal to 1 and have no effect on computation.
We use three specified routes to calculate the island's reliability:

$$\begin{aligned} R(\text{route1} \cup \text{route2} \cup \text{route3}) &= R(\text{route1}) + R(\text{route2}) + R(\text{route3}) - R(\text{route1} \cap \text{route2}) \\ &\quad - R(\text{route1} \cap \text{route3}) - R(\text{route2} \cap \text{route3}) + R(\text{route1} \cap \text{route2} \cap \text{route3}) \end{aligned}$$
$$R(\text{route1}) = R(a).R(b).R(c).R(d).R(e).R(f)$$

Since the reliability of each link is 0.9, then:

$\mathrm{R(route1)} = 0.9^6$
$\mathrm{R(route2)} = \mathrm{R(a).R(b).R(c).R(d).R(g)} = 0.9^5$
$\mathrm{R(route3)} = \mathrm{R(a).R(b).R(c).R(d).R(h)} = 0.9^5$

Since the paths are not independent and there are a number of links in common, we have:

$$\mathrm{R(route1 \cap route2)} = \mathrm{R(route1).R(route2|route1)} = \big(\mathrm{R(a).R(b).R(c).R(d).R(e).R(f)}\big).\mathrm{R(g)} = 0.9^7$$

$$\mathrm{R(route1 \cap route3)} = \mathrm{R(route1).R(route3|route1)} = \big(\mathrm{R(a).R(b).R(c).R(d).R(e).R(f)}\big).\mathrm{R(h)} = 0.9^7$$

$$\mathrm{R(route2 \cap route3)} = \mathrm{R(route2).R(route3|route2)} = \big(\mathrm{R(a).R(b).R(c).R(d).R(g)}\big).\mathrm{R(h)} = 0.9^6$$

$$\mathrm{R(route1 \cap route2 \cap route3)} = \mathrm{R(route1).R(route2|route1).R(route3|route1 \cap route2)} = \big(\mathrm{R(a).R(b).R(c).R(d).R(e).R(f)}\big).\mathrm{R(g).R(h)} = 0.9^8$$

Given the values we have:

$$\mathrm{R(route1 \cup route2 \cup route3)} = 0.9^6 + 0.9^5 + 0.9^5 - 0.9^7 - 0.9^7 - 0.9^6 + 0.9^8 = 0.6548$$

The rest of islands are calculated by the same method (path tracking method) via coding in MATLAB software. The input of the code is a matrix of how the links are connected to each other so that the paths can be identified by the software and ultimately the reliability of each island be calculated.

Island B consists of 15 nodes and 5 rings. The reliability of this is 0.9897. Island C consists of 9 nodes and has 2 *rings*. The island's reliability is found to be 0.9996. Island D consists of 19 nodes and 4 *rings*. The reliability of the island is found to be 0.9561. Island E consists of 11 nodes, 1 *ring*, and 2 *trees/ stars*. The reliability of the island is found to be 0.9107. Island F consists of 14 nodes and 5 *rings* with reliability of 0.9727. Island G consists of 17 nodes and 2 *rings* with reliability of 0.6410. Finally, Island H consists of 12 nodes and 2 *rings* with reliability of 0.7444.

In figure 4, we assembled again the broken islands into a full network, which is a complex structure, i.e., not a series-parallel structure. Number of links in figure 4 is different, showing the actual links in the original network of figure 1. For example, between A and B we had cut 2 links where 3 links were cut between B and C, such parallelism improves the reliability estimation of whole network.

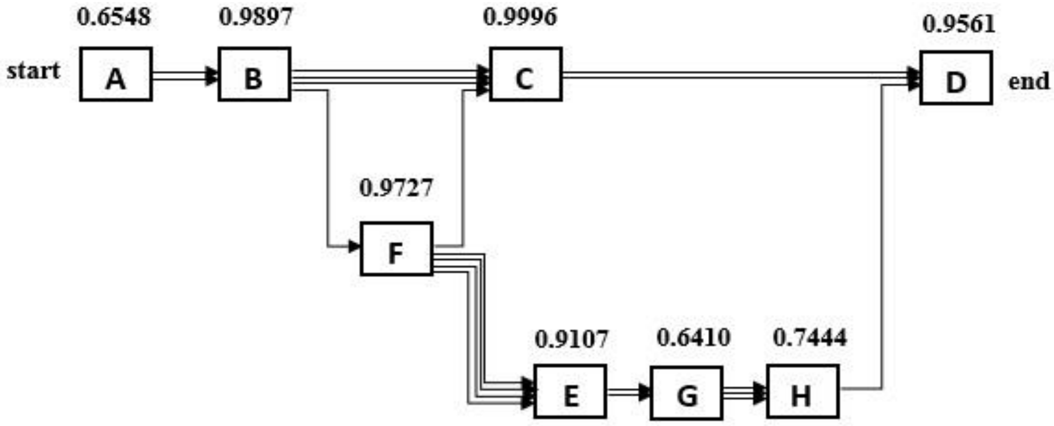


Fig 4. Connection islands back into a much simple network structure

Now, by assuming that island are independent of each other and by denoting reliability of A_i by $R(A_i)$ we can write:
For reliability of two, three and four parallel links we have:

$$\mathrm{R(A_1 \cup A_2)} = \mathrm{R(A_1)} + \mathrm{R(A_2)} - \mathrm{R(A_1)R(A_2)} = 0.9 + 0.9 - (0.9 \times 0.9) = 0.99$$

$$
\begin{aligned}
&R(A_1 \cup A_2 \cup A_3) \\
&\qquad = R(A_1) + R(A_2) + R(A_3) - R(A_1)p(A_2) - R(A_1)p(A_3) - R(A_2)p(A_3) \\
&\qquad + R(A_1)R(A_2)R(A_3) = 0.999
\end{aligned}
$$

and

$$
\begin{aligned}
&R(A_1 \cup A_2 \cup A_3 \cup A_4) \\
&\qquad = \binom{4}{1} R(A_1) - \binom{4}{2} R(A_1 \cap A_2) + \binom{4}{3} R(A_1 \cap A_2 \cap A_3) \\
&\qquad - \binom{4}{4} R(A_1 \cap A_2 \cap A_3 \cap A_4) = 0.9999
\end{aligned}
$$

In this stage, the final network reliability is calculated based on the path tracking method. There are three routes for the flow from start to end, as it was explained for the reliability calculation of island A. The calculation method is exactly same as Island A reliability calculation method.

However, using the MATLAB code gives the same result as well. The notable point is that in the final network, in addition to each island's reliability, the reliability of parallel links between the islands is also used in calculation of the ultimate reliability.

For more explain, any cluster of parallel links between islands can be considered as a component whose reliability is calculated above. For example, there are two parallel links between islands A and B and there is just one link between islands B and F. So the routes for the flow from start to end are as follows:

$$
\begin{aligned}
&\text{route1} = \text{A} \rightarrow \text{two parallel links} \rightarrow \text{B} \rightarrow \text{three parallel links} \rightarrow \text{C} \rightarrow \text{two parallel links} \rightarrow \text{D} \\
&\text{route2} = \text{A} \rightarrow \text{two parallel links} \rightarrow \text{B} \rightarrow \text{one link} \rightarrow \text{F} \rightarrow \text{one link} \rightarrow \text{C} \rightarrow \text{two parallel links} \rightarrow \text{D} \\
&\text{route3} = \text{A} \rightarrow \text{two parallel links} \rightarrow \text{B} \rightarrow \text{one link} \rightarrow \text{F} \rightarrow \text{four parallel links} \rightarrow \text{E} \\
&\qquad \rightarrow \text{two parallel links} \rightarrow \text{G} \rightarrow \text{three parallel links} \rightarrow \text{H} \rightarrow \text{one link} \rightarrow \text{D}
\end{aligned}
$$

Note: In this section the links values are the same and equal to 0.9. In section 3.1 the actual values of links reliability are considered which are proportional to the length of each link, but the solution method is quite similar to the method described in this section and only the numbers are different. (See figure 5 in section 3.1)

According to the calculated reliability values for each island and parallel links as well, total reliability of the network drawn in figure 4 was 0.609. Numbers are approximated to 4 decimals.

3-Sensitivity analysis

In this section, we undertake two different experiments. First, in order to assess the impact of topology on the network reliability, we attempt to remove islands one-by-one and as shown in table 3.

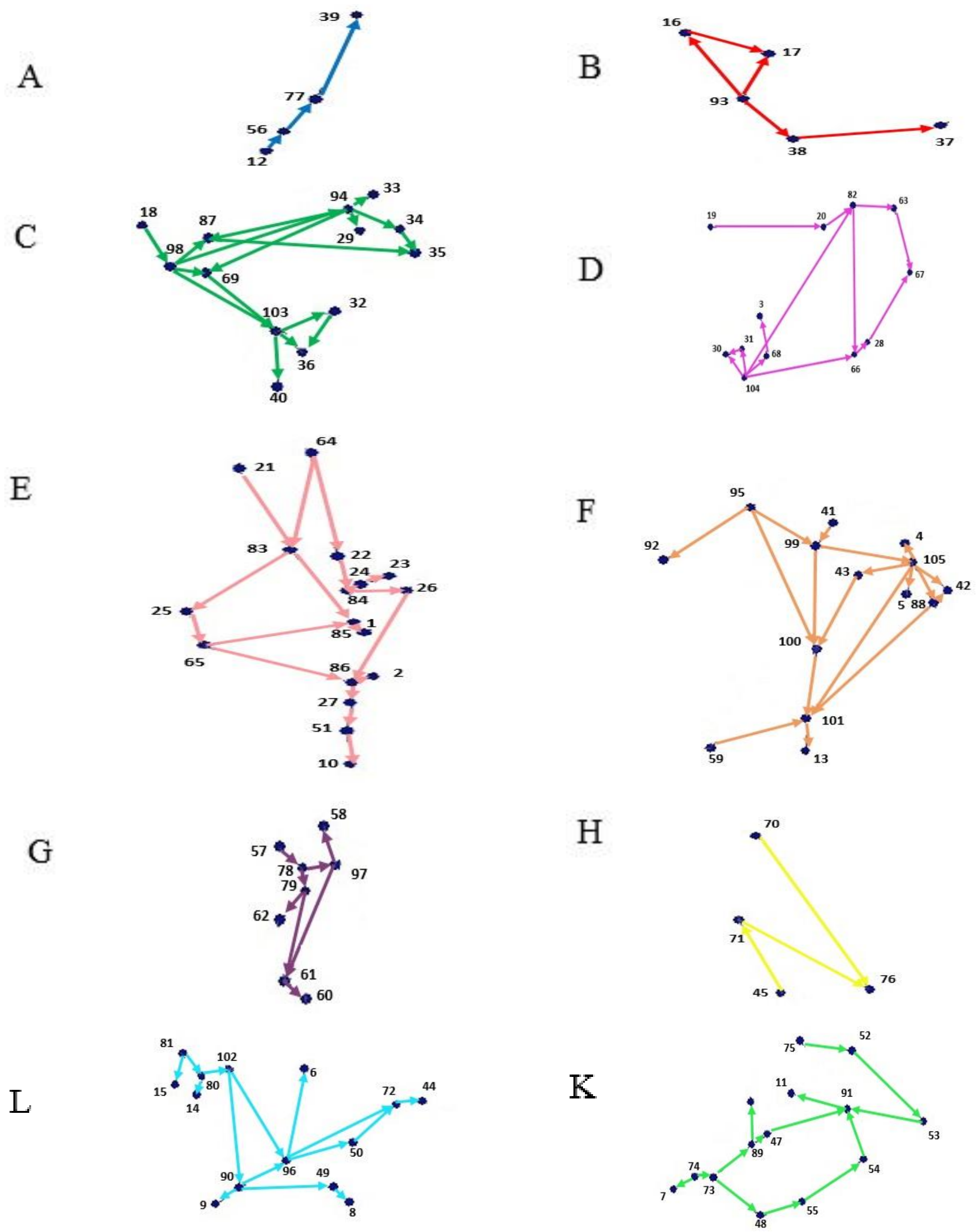
Table 3. The network reliability by missing an island (subgraph removal)

Removed island	A	B	C	D	E	F	G	H
R(network modified)	0	0	0.1971	0	0.6069	0.6064	0.6069	0.6069

It can be seen in table 3 that if islands A, B or D are removed, the reliability value gets zero, because as shown in figure 4, removing each of these three islands would cut off the flow route from the entrance to the outlet. Removing any of the other islands is seen to reduce the reliability value relative to total reliability. One or two flow routes from the entrance to the outlet would be cut off by removing any of these islands (C, E, F, G or H), thereby the ultimate reliability value reduces.

The second experiment we perform is that we assess how the number of island we have chosen could affect the reliability estimation of our power network. To do so, we divide the power network into 10 islands instead of 8 island considered earlier. Divisions are made according to the rules discussed above in Section 2. The results for 10 new islands are shown in table 4:

Table 4. The 10 islands of Iran's power network



By repeating the estimation process explained before, we achieve R(network)= 0.6266, i.e., higher than the earlier estimation. The tolerance between two estimated values is very low at about 0.0176. Perhaps, one can conclude that the approach we have developed here is promising.

3-1- Estimating network reliability using actual link reliabilities

In this section, we consider actual link reliabilities. Link length and its failure modes vary from one place to a different place. Age, technology, environment, load fluctuations, etc. are important. The estimation of link reliabilities is shown in table 5. Realizing the fact that for a link denoted as *ij* the failure rate is $\sum \lambda_{ij}$ and then $r_{ij} = e^{-\sum \lambda_{ij} T}$ where T is the period of time, in our case one year. $\sum \lambda_{ij}$ is set equal to 1.0858 occurrences per year for 100 km for Iran's system (Cadini et al., 2010). In table 5 is part of this calculation (See Alipour (2010), for full calculations).

Table 5. Calculation of Iran's grid reliability at 400 KV level

from (node number)	To (node number)	Distance (km) between nodes (link)	Failure rate of 1.0858 occurrences per year for 100 km	Reliability $R = e^{-\lambda T}, T = 1\ year$
Amin eshragh (3)	Comb. Damavand (68)	62	0.673196	0.51
Narivaran (20)	Shahid salimi power plant (82)	91	0.988078	0.3723
Miami (21)	Sarbedaran (83)	186	2.019588	0.1327
Comb. Shirvan (22)	Comb. Ferdosi (84)	162	1.758996	0.1722
Rei (north) (30)	Varamin (31)	25	0.27145	0.7622
Mahalat (41)	Golpaigan (99)	76	0.825208	0.4381
Folad mobarake (42)	Chehel soton (88)	11	0.119438	0.8874
Comb. Kazeron (50)	Molk malekan (72)	88	0.955504	0.3846
Sefid abe (51)	Nabovat (10)	154	1.672132	0.1878
Ali abad (63)	Comb. Shahrod (67)	107	1.161806	0.313
Shahid montazeri power plant (70)	Golpaigan (99)	134	1.454972	0.2334
Comb. Jonoob Esfahan (71)	Sormagh (45)	200	2.1716	0.114
Mahshahr (80)	Omidiye2 (102)	55	0.59719	0.5503
Milad (81)	Comb. Khoramshahr (15)	7	0.076006	0.9268
Choghadak (90)	Omidiye2 (102)	257	2.790506	0.0614
Sirjan (91)	Yazd1 (75)	296	3.213968	0.0402
Jalal (104)	Mahalat (41)	252	2.736216	0.0648
Tiran (105)	Folad mobarake (42)	43	0.466894	0.627

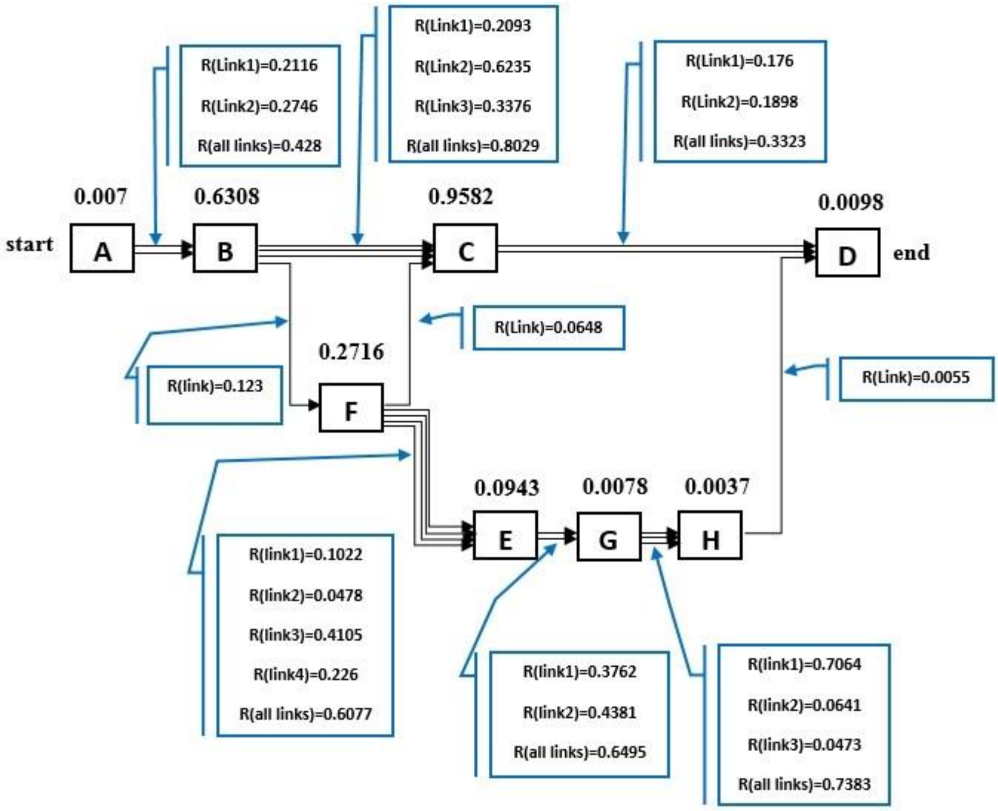


Fig 5. Network structure with actual link and node reliabilities

In figure 5, the reliability of the islands and the parallel links connecting them together is illustrated. In previous diagrams, only node reliabilities were available while here we need to take both node and link reliabilities into considerations. This is not difficult as we can replace link reliability with new node reliability boxes. For instance, between A and B in figure 5 we will have a new node box say AB whose reliability is 0.428. Hence, the A-B part of figure 5 will be replaced by A-AB-B, i.e., 3 nodes in series. Again, between F and E, we will have a new node called FE with node reliability of 0.6077. Following this procedure, we will end up with a new block diagram, which is not shown here, but can be calculated easily using the path tracking method described completely in section 2.1. Accordingly, the network reliability was found to be4.732×10^{-6}, i.e., far less than the previous reliability value of 0.6266. This is not an unexpected result considering the complexity of actual power network with many links in *series structure*. The accuracy of our estimation can be checked against actual data using the annually published data set by power authorities, as will considered in future researches.

4- Conclusion

Power networks are the most complex and vital engineering systems man has ever experienced by any country, worldwide. Connections between power generating stations and consumers are built through transmission system which is itself a complex system. Power failure is detrimental to our life so that any breakdown or even fluctuation in electricity supply to subscribers produce serious crisis. This means that power system reliability should be modelled properly to become manageable. However, theoretical foundations for accurate reliability estimation are now lacking. Our attempt in this paper was to propose a working model by which reliability estimation of power network becomes possible. We did that by proposing a method to breakdown a power network into islands or a graph into subgraph. The islands are made in a way that its exact computation is possible using the network theory of reliability, a new branch of reliability theory. We have investigated Iran's electricity power network at 400 kV level with 105 power generating stations (as nodes) and 142 transmission lines (as links) The entire network reliability was analysed in two cases. In the first case, reliability was estimated when all links were set equal to 0.9. In the second case, reliability of links was set according to their physical and failure properties. Further research will be undertaken to check the validity of our estimation method against the power failure data and improve the model thereafter.

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